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Musicians Experience Less Age-Related Decline in Central Auditory Processing

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Age-related decline in auditory perception reflects changes in the peripheral and central auditory systems. These age-related changes include a reduced ability to detect minute spectral and temporal details in an auditory signal, which contributes to a decreased ability to understand speech in noisy environments. Given that musical training in young adults has been shown to improve these auditory abilities, we investigated the possibility that musicians experience less age-related decline in auditory perception. To test this hypothesis we measured auditory processing abilities in lifelong musicians ($N = 74$) and nonmusicians ($N = 89$), aged between 18 and 91. Musicians demonstrated less age-related decline in some auditory tasks (i.e., gap detection and speech in noise), and had a lifelong advantage in others (i.e., mistuned harmonic detection). Importantly, the rate of age-related decline in hearing sensitivity, as measured by pure-tone thresholds, was similar between both groups, demonstrating that musicians experience less age-related decline in central auditory processing.

Keywords: aging, musician, auditory processing

Auditory-based communication problems are prevalent in the elderly. Worldwide estimates indicate that by age 60, 10–30% of people meet the diagnostic criteria for moderate hearing loss; by age 80, as many as 60% of adults meet this criteria (Mathers, Smith, & Concha, 2000). Age-related decline in auditory perception can vary substantially between individuals and often include difficulties understanding speech in adverse listening situations (Frisina & Frisina, 1997; Pichora-Fuller, Schneider, & Daneman, 1995); increased thresholds for detecting mistuning in a harmonic complex (Alain, McDonald, Ostroff, & Schneider, 2001; Grube, von Cramon, & Rubsamen, 2003), which is important for segregating simultaneous sounds; and a reduced ability to detect brief gaps in an otherwise continuous sound (Gordon-Salant, Yeni-Komshian, Fitzgibbons, & Barrett, 2006; Heinrich & Schneider, 2006; Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994; Strouse, Ashmead, Ohde, & Grantham, 1998), which is important for distinguishing speech phonemes. These age-related changes in auditory perception are thought to reflect bilateral sensorineural hearing loss due to physical changes in the inner ear (Gates & Mills, 2005; Stenklev & Laukli, 2004) as well as changes in the central auditory system (Alain, Dyson, & Snyder, 2006; Murphy, Daneman, & Schneider, 2006; Schneider, Pichora-Fuller, & Daneman, 2010). Given the prevalence, and negative outcomes of age-related decline in hearing abilities, finding ways to prevent, mitigate, or delay these changes is of utmost importance.

There is increasing evidence that lifestyle choices can have a significant impact on successful aging. For instance, older adults who engage in cognitively stimulating activities later in life show slower rates of cognitive decline, independent of early education levels (Ghisletta, Bickel, & Lovden, 2006). Other research suggests that higher educational and occupational achievements contribute to delayed onset of age-related cognitive decline (Qiu, Backman, Winblad, Aguero-Torres, & Fratiglioni, 2001; Stern et al., 1994). In a recent review of the literature, Middleton and Yaffe (2009) reported that engaging in cognitively demanding activities (e.g., reading, learning, or game playing) and being physically or socially active can delay or prevent dementia. Furthermore, being bilingual has also been shown to delay the onset of dementia (Bialystok, Craik, & Freedman, 2007). In addition, professional musicians, compared to nonmusicians and amateur musicians, exhibit less age-related decline in speeded motor tasks related to music performance (Krampe & Ericsson, 1996). Finally, chess abilities in chess experts, as measured by the Elo rating, decline with age, but overall the ratings remained high (Elo, 1965). These findings suggest that early educational or occupational achievement create a "cognitive reserve" that can delay age-related cognitive change, and continued engagement in stimulating activities can maintain or enhance this reserve.

When examining the lifelong influence of expertise on task performance, two age-related trends may emerge from the data. The first is differential preservation, which is characterized by interactions between age and expertise, where the rate of age-related decline on a given task is slower in experts (Salthouse, 2006). The second is a preserved differentiation, which is characterized by main effects of expertise without interactions with age

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(Salthouse, 2006). Here experts perform better than nonexperts, but the difference is equal across the life span. Importantly, only differential preservation can be indicative of a protective effect of expertise because it demonstrates that lifelong expertise increases the cognitive benefit or mitigates the cognitive decline (Salthouse, 2006). A pattern of preserved differentiation could indicate a protective effect of expertise, but could also reflect predispositions.

Differential preservation, therefore, suggests an accumulation of cognitive reserve over the life span. This hypothesis was supported through computational modeling that simulated aging. Using neural network models Mireles and Charness (2002) demonstrated that aging could be simulated by progressively adding noise to the network, while increasing knowledge of the problem (in the network) improved performance of the network to a greater degree with age (demonstrating differential preservation). This model suggests that expertise and continued training could offset age-related declines in auditory perception.

Musicians are one group of people that have highly developed auditory abilities. Compared to nonmusicians, they are better at detecting mistuning in a harmonic complex (Koelsch, Schroger, & Tervaniemi, 1999; Zendel & Alain, 2009), detecting a short silent gap (Rammsayer & Altenmuller, 2006), and discriminating pure tone frequencies (Micheyl, Delhommeau, Perrot, & Oxenham, 2006; Schellenberg & Moreno, 2010). Musicians also show superior performance in general cognitive domains including auditory working memory (Lee, Lu, & Ko, 2007), general cognitive abilities as measured by the WISC–III (i.e., IQ; Schellenberg, 2004), and the identification of speech embedded in multitalker babble (Parbery-Clark, Skoe, Lam, & Kraus, 2009). Moreover, cross-sectional studies using neuroimaging techniques have shown that being a musician is associated with enhancements in the auditory brainstem (Bidelman & Krishnan, 2010; Musacchia, Sams, Skoe, & Kraus, 2007; Parbery-Clark, Skoe, & Kraus, 2009; Wong, Skoe, Russo, Dees, & Kraus, 2007) and auditory cortex (Hyde et al., 2009; Koelsch et al., 1999; Pantev et al., 1998; P. Schneider et al., 2002; Shahin, Bosnyak, Trainor, & Roberts, 2003; Zendel & Alain, 2009). Longitudinal studies have yielded similar findings, suggesting that the differences between musicians and nonmusicians are due to experience-dependant plastic brain changes rather than self-selection due to preexisting genetic differences (Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006; Hyde et al., 2009). It is, therefore, likely that the influence of musicianship on age-related change to auditory processing abilities is due to both enhancements in perceptual processing of acoustic features, as well as higher-order cognitive interpretations of those features. Hence, musicians are one group of experts that could demonstrate an age-by-expertise interaction on tasks that tap into central auditory processes.

Here, we tested the general hypothesis that playing a musical instrument throughout the life span mitigates age-related decline in auditory perception. Musicians and nonmusicians ranging in age from 18 to 91 completed four hearing tests: pure-tone thresholds, mistuned harmonic detection thresholds, gap-detection thresholds, and the QuickSIN test (Speech-In-Noise; Etymotic Research, Version 1.3, 2001; Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004). These four tests were chosen because performance on all these tasks declines with age (Alain et al., 2001; Frisina & Frisina, 1997; Gordon-Salant et al., 2006; Grube et al., 2003; Heinrich & Schneider, 2006; Pichora-Fuller et al., 1995; Schneider et al., 1994; Stenklev & Laukli, 2004; Strouse et al., 1998). At the same time, performance on gap detection, mistuned harmonic detection, and speech-in-noise perception have been shown to be enhanced in young adult musicians (Koelsch et al., 1999; Parbery-Clark, Skoe, Lam et al., 2009; Rammsayer & Altenmuller, 2006; Zendel & Alain, 2009). More importantly, these tests assess disparate aspects of auditory processing, with pure-tone thresholds reflecting the functioning of the peripheral auditory system (Mazelova, Popelar, & Syka, 2003; Nelson & Hinojosa, 2006), gap-detection reflecting the ability to detect fine temporal details, mistuned harmonic detection reflecting the ability to detect fine spectral details, and speech-in-noise detection reflecting realistic auditory situations.[1] These distinctions are important because we hypothesize that the rate of age-related decline on tasks that require central processing will be slower in musicians, while peripheral processing (cochlear transduction) should decline at similar rates in both musicians and nonmusicians.

Method

Participants

A total of 163 native English speakers took part in the study and provided formal informed consent in accordance with the joint Baycrest Centre-University of Toronto Research Ethics Committee. Seventy-four participants were musicians (age 19–91, 35 females), while 89 were nonmusicians (18–86, 51 female). Here we defined a musician as someone who started musical training by the age of 16, continued practicing music until the day of testing, and had an equivalent of at least six years of formal music lessons. The sample of musicians included both professional and amateur musicians; however, the distinction between professional and amateur musician was not directly quantified because of the difficulty in distinguishing them. For example, some "amateur" musicians had other (nonmusical) careers, but occasionally taught students part-time or performed for payment during their lifetime; others earned their main income through music for a few years, but then went on to a different career; others had retired, and no longer performed professionally, but continued to practice and perform for their own enjoyment. Clearly the distinction between amateur and professional is difficult to pin down, and therefore the sample of musicians was not quantified into "amateur" and "professional" subgroups. Nonmusicians had no more than two years of formal or self-directed lessons throughout their lifetime, and did not play any musical instrument. These criteria excluded many people with intermediate levels of musical achievement (e.g., took piano lessons in childhood and stopped playing, or learned guitar in college and played in a band for a few years). Participants for this study were initially recruited for other studies in our lab. Preliminary analyses of the data from these participants revealed a trend that

[1] Auditory information is integrated over time, thus resolving spectral details requires the encoding of precise timing information. Alternatively, we could describe fine spectral resolution as resolving the relationship of phase information between simultaneously occurring stimuli. However, for the purpose of clarity, we will refer to this as fine spectral resolution throughout.

musicians had age-related advantages on some auditory assessments. This led to the recruitment of lifelong musicians and nonmusicians to confirm that the original trends were real. In the final sample, musicians and nonmusicians were matched in terms of years of education (16.9 vs. 16.2, respectively, $t(161) = 1.36$, $p > .05$), and age (45.3 vs. 49.3, $t(161) = 1.21$, $p > .05$). In addition, for the musicians, we collected the age of musical training onset, and the average hours per week in practicing their instrument (in the year the participant was tested) to correlate with task performance. Older participants were screened for age-related psychological disorders including dementia before they participated. No participants wore hearing aids during the testing, and no participants used hearing aids on a regular basis.

Stimuli and Task

All stimuli were presented through ER 3A insert earphones (Etymotic Research, Elk Grove, U.S.A.), while participants were seated in a soundproof room. Before the experiment began, participants were familiarized with the stimuli and response methods for each task. Furthermore, stimuli for the gap detection, mistuned harmonic detection and speech-in-noise tasks were presented well above hearing thresholds for all participants; no participant reported any difficulty hearing the stimuli.

Pure-tone thresholds. Pure-tone thresholds were collected for each octave between frequencies of 250 to 8000 Hz binaurally using an audiometer (model GSI 61). Participants were instructed to press a button if they detected a tone. The procedure began by presenting a 1000 Hz tone to the left ear at 40 dB HL. If the participant indicated that they heard the tone, the amplitude was reduced by 5 dB HL. This continued until the participant no longer responded to the tone. The amplitude of the tone was then increased by 5 dB HL; if a response was recorded the amplitude was lowered again by 5 dB HL; if there was no response the amplitude of the tone was increased by 5 dB HL, and that amplitude was recorded as the pure-tone threshold for the frequency and ear of presentation. If the participant could not hear the initial tone at 40 dB HL, the amplitude was increased in 5 dB steps until the amplitude was 10 dB HL above where the participant first detected the tone. The procedure then continued as stated above. Each tone was presented at an irregular time interval to prevent false positive responses. The same procedure was repeated for each frequency octave in each ear.

Gap detection. Stimuli were tone pips produced by multiplying a 1-kHz pure tone by a temporal window created by summing a series of Gaussian envelopes spaced 0.5 ms apart (Schneider et al., 1994). Two 10-ms tones marked the beginning and end of the gap. The duration of the gap, Δt, was defined as the time between the last Gaussian in the leading marker and the first Gaussian of the lagging marker. The comparison stimulus (a tone whose duration and energy are equal to that of the two markers defining the gap) was created by filling in the missing Gaussians between the two markers. The initial gap size was 31 ms, and stimuli were presented in a two-alternative forced-choice (2AFC) paradigm, with a 3 down 1 up tracking procedure to determine the 79.4% accuracy point on the psychoacoustic curve (Levitt, 1971). All stimuli were presented binaurally at 75 dB SPL. In each trial, two stimuli were presented sequentially (order was varied randomly), and the listener identified which of the two sounds contained a gap by pressing a button on a response box. For the first reversal, the size of the gap was reduced by 8 ms after three correct responses, or increased by 8 ms after one incorrect response. The amount of change in gap size was reduced by 50% after each reversal to a minimum of 0.5 ms. Each block of trials lasted until there were 12 reversals. The threshold was determined by averaging the last 8 reversals. This procedure was repeated three times, and the final gap threshold was the average of these three blocks. Feedback about the correctness of the response was given to participants after each trial to ensure that each participant achieved his or her lowest possible threshold.

Mistuned harmonic detection. Stimuli were harmonic complexes made up of 12 pure tones at equal intensity levels with a fundamental frequency of 200 Hz at 75 dB SPL. Stimulus duration was 200 ms including a 10 ms rise and fall time. The second harmonic (600 Hz) of the complex was mistuned from its original value, with a starting value of 696 Hz (16% above its original value). As in the gap-detection task, we used a 2AFC procedure to estimate the thresholds in detecting a mistuned harmonic. In each trial, two stimuli were presented sequentially, one of which contained the mistuned harmonic component (order was varied randomly). Participants were asked to identify which sound had the mistuned component by pressing a button on a response box. Feedback about the correctness of the response was given to participants after each trial to ensure that each participant achieved his or her lowest possible threshold. The amount of mistuning was reduced by 50% after three correct responses (i.e., from 16% of the original value to 8% of the original value); a single incorrect response resulted in an increase of mistuning by 32% on the next trial. After the first two reversals, the amount of mistuning decreased by 24% after three correct responses. Thresholds were an average of the last eight reversals. This procedure was repeated three times, and the final threshold was the average of the three blocks.

Speech-in-noise. The effects of age and musical training on listeners' ability to process speech in noise were assessed using the QuickSIN test (Speech-In-Noise; Version 1.3). Participants were presented with five lists of six sentences with five key words per sentence embedded in four-talker babble noise. The sentences were presented at a combined amplitude of 70 db SPL using prerecorded signal-to-noise ratios (SNRs) which decreased in 5-dB steps from 25 dB (*very easy*) to 0 dB (*very difficult*). Thresholds were defined as the SNR needed to identify 50% of the target words for the five lists. Participants were asked to repeat back the target sentence, and were given a single point for each of five "key words" in each sentence, for a possible 30 points on each list. The SNR loss was determined by subtracting the total number of words correct from 25.5. This number represents the SNR the participant needs to correctly identify 50% of the key words in the target sentences (Killion, 1997). The standardization procedure of this test can be found in Killion et al., (2004).

Data Analysis

Each hearing assessment was analyzed separately using multiple linear regressions. Due to experimenter error, data loss, or participants' fatigue, SIN thresholds were not available for five participants, and gap and mistuned harmonic thresholds were not available for nine participants. Three factors were used in each analysis:

age, musical training (coded as 0.5 and −0.5 for musicians and nonmusicians, respectively), and the age by musical training interaction. Regression analyses were used because they allowed us to test the effects of aging and lifelong musicianship. More importantly, the regression analysis allows us to determine whether the advantages for musicians, if any, were due to preserved differentiation (characterized by main effects of musicianship) or differential preservation (characterized by age by musicianship interactions). For the analysis, 18 years were subtracted from every participant's age so the comparisons between groups would compare intercepts in the regression lines that matched with the youngest participants in the study. Note that all figures show participants' real age. In addition, for the musician group, correlations with the age at which musical training began, and the number of hours per week of music practice (in the year the participant was tested) were calculated, while controlling for the effect of age. Age was included as a covariate because performance on each of the hearing tests significantly declined with age, and the purpose of calculating these correlations was to determine if hours of practice or age of training onset was related to task performance independent of age. Finally, correlations were calculated between pure-tone thresholds at the stimulus frequencies for gap-detection thresholds (1000 Hz), and mistuned harmonic detection thresholds (250, 500, and 1000 Hz) to determine if pure-tone thresholds were related to task performance. Again, age was included as a covariate because the influence of age on all hearing assessments was significant, and we wanted to determine if there was a relationship independent of the effect of age. Only significant correlations are reported.

Results

Pure-Tone Thresholds

The mean response for both ears and all pure-tone frequencies (all-tone average) was analyzed in a single regression analysis. The overall regression model was significant for the all-tone average (see Table 1, Figure 1). Importantly, the only significant factor was age. No significant effects of musical training or its interaction with age were found. In separate analyses, not shown here, this pattern was stable for each octave tested (250, 500, 1000, 2000, 4000, and 8000 Hz). The only difference between the frequency octaves was the rate of age-related change (i.e., slope of the regression line) increased at higher frequencies. Furthermore, the

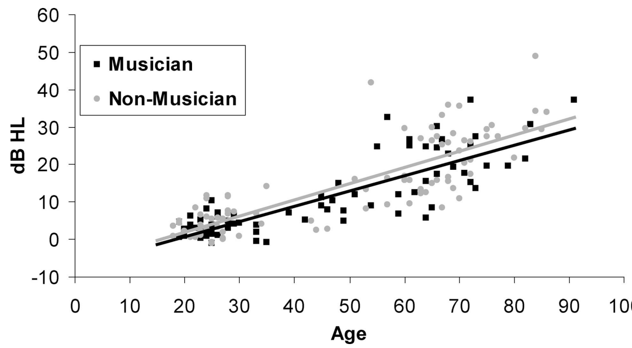

Figure 1. Pure-tone thresholds in musicians and nonmusicians as a function of age. The data on the figure represent individual participants' averaged pure-tone thresholds across each octave frequency from 250 to 8000 Hz for both ears (all-tone average). The solid black and gray lines reflect the best-fit linear trend for the age-related changes in musician and nonmusicians, respectively.

average left and right thresholds were compared in each participant to ensure participants were free of retrocochlear pathology. Two participants exceeded the 15 dB difference between the left and right ears. All further analyses (below) were run with and without these participants, and no difference in the pattern of results was found, thus they were included in all analyses.

Gap-Detection Thresholds

The overall regression model for gap-detection thresholds was significant (see Table 2, Figure 2). The beta weights for the age and the age by musical training factors were significant, but the beta weight for the musical training factor was not significant. That is, gap-detection thresholds increase with age; however, the rate (slope of the regression line) at which gap-detection thresholds increase with age is slower in musicians compared to nonmusicians. Finally, gap-detection thresholds were not correlated with 1000-Hz pure-tone thresholds, while controlling for age ($r(157) = -0.061$, $p < .1$), suggesting that sensitivity at the tested frequency band is not related to the ability to detect a silent gap.

Mistuned Harmonic Detection Thresholds

The overall regression model for mistuned harmonic threshold was significant (see Table 3, Figure 3). In this regression, the beta

Table 1
Regression Analysis for Pure-Tone Thresholds

R statistic	*R* square	*df*		*F*
.831	.691	3, 159		118.51**
Variable	Unstd. beta	*SE*	Std. beta	*t* test
(Constant)	.581	.947		.613
Age	.481	.026	.818	18.22**
Musician	−1.19	1.89	−.05	−.63
Musician × Age	−.023	.053	−.034	−.444

Note. *df* = degrees of freedom; *SE* = standard error.
** $p < .01$.

Table 2
Regression Analysis for Gap-Detection Thresholds

R statistic	*R* square	*df*		*F*
0.356	.126	3, 150		7.239**
Variable	Unstd. beta	*SE*	Std. beta	*t* test
(Constant)	.732	.374		1.958
Age	.031	.011	.224	2.915**
Musician	.43	.748	.007	.058
Musician × Age	−.042	.021	−.257	−2.008*

Note. *df* = degrees of freedom; *SE* = standard error.
* $p < .05$. ** $p < .01$.

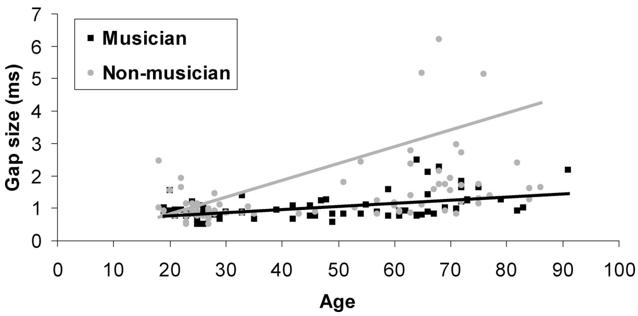

Figure 2. Gap-detection thresholds in musicians and nonmusicians as a function of age. The solid black and gray lines reflect the best-fit linear trend for the age-related changes in musician and nonmusicians, respectively.

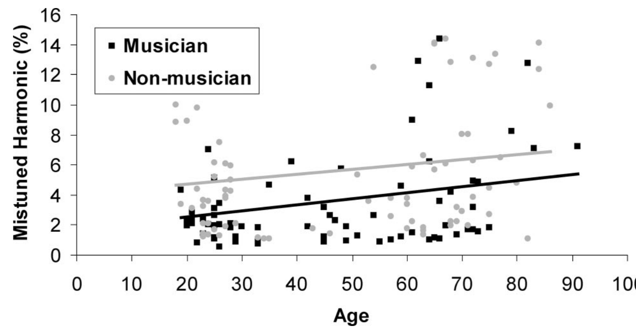

Figure 3. Mistuned harmonic thresholds in musicians and nonmusicians as a function of age. The solid black and gray lines reflect the best-fit linear trend for the age-related changes in musician and nonmusicians, respectively.

weights for both the age and the musical training factors were significant. That is, mistuned harmonic thresholds increase with age; however, musicians have lower thresholds compared to nonmusicians. In addition, we also found that mistuned harmonic threshold was correlated with pure-tone thresholds at 250, 500, and 1000 Hz, while controlling for age, ($r(157) = 0.163$ $p < .05$, 0.245 $p < .01$ & 0.182, $p < .05$, respectively) suggesting that pure tone thresholds at the frequencies used in the mistuned harmonic task may contribute to the ability to detect a mistuned harmonic. At the same time, in musicians, mistuned harmonic thresholds were negatively correlated with hours per week of musical practice while controlling for age ($r(60) = -0.313$, $p < .05$). That is, the more time a musician spent engaged in musical activities, the lower his or her mistuned harmonic threshold.

Speech-in-Noise Thresholds

The overall regression model for speech-in-noise threshold was significant (see Table 4, Figure 4). In this regression, the beta weights for both age and the age by musical training factors were significant. That is, speech-in-noise thresholds increased with age; however, the rate (slope of the regression line) at which speech-in-noise thresholds increase with age is slower in musicians compared to nonmusicians. One participant exceeded the pure tone threshold of 45 dB HL that required an increase in the amplitude of the stimulus to a level that was "loud but okay". The level was not adjusted in this case to maintain experimental control. For musicians, speech-in-noise thresholds were negatively correlated with hours per week of musical activities while controlling for age ($r(61) = -0.267$, $p < .05$). That is, the more time a musician spent engaged in musical activities, the lower his or her speech-in-noise threshold.

Discussion

The primary objective of this study was to examine whether age-related changes in peripheral and central auditory processing were mitigated in musicians. We observed that musicians experienced less age-related decline for both gap-detection and speech-in-noise thresholds. Moreover, musicians demonstrated a lifelong advantage in detecting a mistuned harmonic compared to nonmusicians. Performance on the mistuned harmonic and the speech-in-noise tasks were correlated with hours of music practice, that is, the more musicians practiced, the better they were at detecting a mistuned harmonic and understanding speech in noise. For speech in noise thresholds, the relationship between practice and performance suggests that the accumulation of practice over many years may result in preservation of this ability in musicians, as demonstrated by the interaction between age and musicianship for this test. Most importantly, no influence of being a musician was found for pure-tone thresholds, suggesting that aging can differentially influence central and peripheral stages of auditory processing, and that the advantage for musicians over nonmusicians was due to

Table 3
Regression Analysis for Mistuned Harmonic Detection Thresholds

R statistic	*R* square	*df*	*F*
.328	.108	3, 150	6.032**

Variable	Unstd. beta	*SE*	Std. beta	*t* test
(Constant)	3.583	.507		7.068
Age	.036	.014	.197	2.53*
Musician	−2.191	1.014	−.278	−2.162*
Musician × Age	.007	.029	.031	.242

Note. *df* = degrees of freedom; *SE* = standard error.
* $p < .05$. ** $p < .01$.

Table 4
Regression Analysis for Speech-in-Noise Thresholds

R statistic	*R* square	*df*	*F*
.595	.353	3, 154	28.061**

Variable	Unstd. beta	*SE*	Std. beta	*t* test
(Constant)	−.318	.239		−1.329
Age	.052	.007	.516	7.845**
Musician	.346	.478	.08	.724
Musician × Age	−.033	.013	−.279	−2.497*

Note. *df* = degrees of freedom; *SE* = standard error.
* $p < .05$. ** $p < .01$.

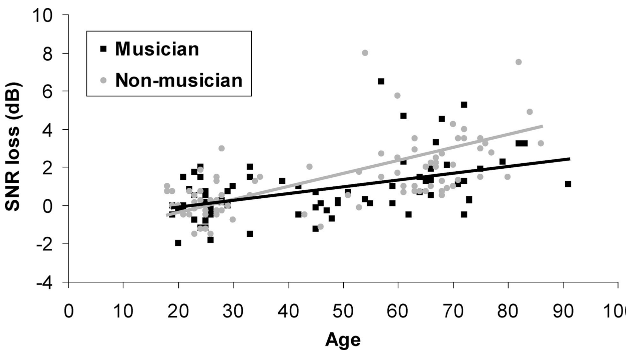

Figure 4. Speech-in-noise thresholds measured using the QuickSIN test in musicians and nonmusicians as a function of age. The solid black and gray lines reflect the best-fit linear trend for the age-related changes in musician and nonmusicians, respectively.

enhancements at the central level. Thus, being a musician may contribute to better hearing in old age by delaying some of the age-related changes in central auditory processing. Alternatively, it is also possible that musicians are self-selected based on inborn characteristics that endow them with enhanced auditory processing abilities.

Our findings are consistent with a growing body of literature demonstrating that staying mentally and physically active can prevent or delay age-related cognitive decline (e.g., Bialystok et al., 2007; Middleton & Yaffe, 2009). In the present study, we found that in musicians, amount of practice was correlated with the ability to detect mistuning and to understand speech in multitalker babble. This finding suggests that continued practice throughout life may alleviate some of the age-related decline in speech perception often experienced by older adults. One possibility is that continued practice of a musical instrument may enhance cognitive reserve, thereby freeing perceptual, attentional, and cognitive resources which could then be dedicated to the processing of auditory stimuli. Furthermore, enhanced cognitive reserve may allow for more effective and flexible strategies during auditory perceptual and cognitive tasks. Increased cognitive reserve would be particularly important in older adults who often experience audiometric threshold elevations, even when their hearing is within a clinically normal range. That is, the incoming acoustic signal is bound to be less accurate because of age-related changes to the inner ear, thus older adults need to compensate for such age-related changes in the peripheral auditory system through cognitive mechanisms.

The continued practice of a musical instrument may also result in greater neural efficiency, greater neural capacity, or the ability for compensation via the recruitment of additional brain regions during auditory processing. Indeed, evidence from cross-sectional and longitudinal neuroimaging studies in children and young adults have shown that musical training can have long-lasting effects on the central auditory system. For instance, using a cross-sectional design, Schneider et al. (2002) demonstrated that young musicians have enhanced gray matter density in the auditory cortex that was correlated with musical aptitude. Utilizing longitudinal designs, Hyde et al. (2009) showed that children who received 15 months of music lessons had structural brain changes that were correlated with performance on musical tasks. Fujioka et al. (2006) compared neuromagnetic brain activity in children before and after participating in music lessons over a one-year period, and found enhanced activity in musically trained children compared to matched controls who did not receive music lessons. Another study examining neuromagnetic brain activity demonstrated that in young adults, two weeks of musical training can yield reliable changes in central auditory processing (Lappe, Herholz, Trainor, & Pantev, 2008). Together, these studies provide converging evidence that musical training is associated with neuroplastic changes in the auditory cortex that is related to an enhanced ability to process auditory material.

The benefit of musical training spans from simple perceptual tasks that require detecting a single acoustic features (Micheyl et al., 2006; Rammsayer & Altenmuller, 2006; Schellenberg & Moreno, 2010), to higher order cognitive abilities that tap into both perceptual and cognitive functions such as language and memory (Lee et al., 2007; Parbery-Clark, Skoe, Lam et al., 2009; Schellenberg, 2004). Any task that requires processing of an acoustic input will engage the auditory cortex, including detection of a silent gap or a mistuned harmonic (Alain, 2007; Ross, Schneider, Snyder, & Alain, 2010). More complex auditory tasks, such as processing speech in the presence of background noise, will engage a more complex network that comprises the auditory, parietal, and prefrontal cortices (Wong et al., 2009). Interestingly, when processing speech in background noise, older adults, compared to younger adults, show increased activity in the fronto-parietal network, and decreased activity in the auditory cortex, suggesting that older adults automatically compensate for declining perceptual abilities with a more cognitive strategy (Wong et al., 2009). It is therefore possible that differential age-related decline in musicians for the speech-in-noise test observed in the current study indicates enhanced engagement of this fronto-parietal network. On the other hand, younger musicians demonstrate a more robust subcortical encoding of speech embedded in noise (Parbery-Clark, Skoe, & Kraus, 2009). This suggests that the differential age-related decline for the speech-in-noise task in the current study may reflect preserved early processing and encoding of speech sounds in the ascending auditory pathway, thereby providing older musicians with a more robust signal at the auditory cortex. Therefore, the benefit older musicians have in detecting a gap or mistuned harmonic may be due to enhanced subcortical processing and/or enhanced cognitive strategies. To clarify our findings, future experimental, longitudinal and neuroimaging research is needed to determine if musical training causes the enhancements observed in the current study, and to determine the neural locus of the benefit.

Another important question related to musical training and neural plasticity is of specificity. That is, does musical training provide general cognitive enhancements, or is the benefit of musical training specific to musical-type tasks. Laboratory-based auditory training, where human participants or nonhuman animals learn to distinguish between auditory stimuli that were previously undistinguishable, lead to enhancements to the neural circuitry involved in making that distinction (e.g., Recanzone, Schreiner, & Merzenich, 1993; van Wassenhove & Nagarajan, 2007; Alain, Snyder, He, & Reinke, 2007). Unlike laboratory training, musical training and lifelong musicianship also result in benefits to cognitive abilities not directly related to auditory processing (e.g., working memory: Lee et al., 2007; IQ: Schellenberg, 2004). It is therefore possible that lifelong musicianship may preserve or enhance brain structures and/or functions related to age-related cognitive decline. Few studies have addressed this issue directly. Krampe and Ericsson (1996) demonstrated that motor tasks related to music performance were relatively preserved in older expert musicians, while general processing speed was not. This suggests that the neural plasticity observed in musicians is specific to music-related tasks. Taken in concert with the current findings, it is likely that lifelong musicianship mitigates age-related decline to some cognitive functions (i.e., auditory processing and musical-type motor tasks), but not others (i.e., processing speed). Clearly, more research needs to be done to understand the scope of the age-related cognitive benefits and related neural plasticity of lifelong musicianship.

Being a musician is not a panacea in terms of preventing age-related cognitive decline; however, there are numerous benefits. Despite the scant data on aging and musicianship, the picture emerging is that lifelong musicianship mitigates age-related decline on cognitive tasks directly related to musical performance, in addition to mitigating cognitive decline on tasks peripherally related to musical performance (i.e., none of the stimuli used in the current study was "musical" but auditory processing is important for music performance). Being a musician is a highly demanding cognitive activity, in some cases requiring the coordination of 1800 notes per minute, thus requiring highly developed working and long-term memory, in addition to integrated and precise auditory, motor, sensory, and visual processing (Munte, Altenmuller, & Jancke, 2002). It is, therefore, likely that lifelong musicianship will influence age-related changes on some or all of these cognitive abilities. Given this hypothesis, it is not surprising that musicians experience less age-related decline in central auditory processing.

References

Alain, C. (2007). Breaking the wave: Effects of attention and learning on concurrent sound perception. *Hearing Research, 229,* 225–236. doi:10.1016/j.heares.2007.01.011

Alain, C., Dyson, B. J., & Snyder, J. S. (2006). Aging and the perceptual organization of sounds: A change of scene? In P. M. Conn (Ed.), *Handbook of models for human aging* (pp. 759–770). San Diego, CA: Elsevier Academic Press. doi:10.1016/B978-012369391-4/50065-5

Alain, C., McDonald, K. L., Ostroff, J. M., & Schneider, B. (2001). Age-related changes in detecting a mistuned harmonic. *Journal of the Acoustical Society of America, 109,* 2211–2216. doi:10.1121/1.1367243

Alain, C., Snyder, J. S., He, Y., & Reinke, K. S. (2007). Changes in auditory cortex parallel rapid perceptual learning. *Cerebral Cortex, 17,* 1074–1084. doi:10.1093/cercor/bhl018

Bialystok, E., Craik, F. I., & Freedman, M. (2007). Bilingualism as a protection against the onset of symptoms of dementia. *Neuropsychologia, 45,* 459–464. doi:10.1016/j.neuropsychologia.2006.10.009

Bidelman, G. M., & Krishnan, A. (2010). Effects of reverberation on brainstem representation of speech in musicians and non-musicians. *Brain Research, 1355,* 112–125. doi:10.1016/j.brainres.2010.07.100

Elo, A. E. (1965). Age changes in master chess performance. *Journals of Gerontology, 20,* 289–299.

Frisina, D. R., & Frisina, R. D. (1997). Speech recognition in noise and presbycusis: Relations to possible neural mechanisms. *Hearing Research, 106,* 95–104. doi:10.1016/S0378-5955(97)00006-3

Fujioka, T., Ross, B., Kakigi, R., Pantev, C., & Trainor, L. J. (2006). One year of musical training affects development of auditory cortical-evoked fields in young children. *Brain, 129,* 2593–2608. doi:10.1093/brain/awl247

Gates, G. A., & Mills, J. H. (2005). Presbycusis. *Lancet, 366,* 1111–1120. doi:10.1016/S0140-6736(05)67423-5

Ghisletta, P., Bickel, J. F., & Lovden, M. (2006). Does activity engagement protect against cognitive decline in old age? Methodological and analytical considerations. *Journals of Gerontology: Psychological Sciences and Social Sciences, 61,* P253–P261.

Gordon-Salant, S., Yeni-Komshian, G. H., Fitzgibbons, P. J., & Barrett, J. (2006). Age-related differences in identification and discrimination of temporal cues in speech segments. *Journal of the Acoustical Society of America, 119,* 2455–2466. doi:10.1121/1.2171527

Grube, M., von Cramon, D. Y., & Rubsamen, R. (2003). Inharmonicity detection. Effects of age and contralateral distractor sounds. *Experimental Brain Research, 153,* 637–642. doi:10.1007/s00221-003-1640-0

Heinrich, A., & Schneider, B. (2006). Age-related changes in within- and between-channel gap detection using sinusoidal stimuli. *Journal of the Acoustical Society of America, 119,* 2316–2326. doi:10.1121/1.2173524

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., & Schlaug, G. (2009). The effects of musical training on structural brain development: A longitudinal study. *Neurosciences and Music III: Disorders and Plasticity: Annals of the New York Academy of Sciences, 1169,* 182–186.

Killion, M. C. (1997). Hearing aids: Past, present, future: Moving toward normal conversations in noise. *British Journal of Audiology, 31,* 141–148. doi:10.3109/03005364000000016

Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., & Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *Journal of the Acoustical Society of America, 116,* 2395–2405. doi:10.1121/1.1784440

Koelsch, S., Schroger, E., & Tervaniemi, M. (1999). Superior pre-attentive auditory processing in musicians. *Neuroreport, 10,* 1309–1313. doi:10.1097/00001756-199904260-00029

Krampe, R. T., & Ericsson, K. A. (1996). Maintaining excellence: Deliberate practice and elite performance in young and older pianists. *Journal of Experimental Psychology-General, 125,* 331–359. doi:10.1037/0096-3445.125.4.331

Lappe, C., Herholz, S. C., Trainor, L. J., & Pantev, C. (2008). Cortical plasticity induced by short-term unimodal and multimodal musical training. *Journal of Neuroscience, 28,* 9632–9639. doi:10.1523/JNEUROSCI.2254-08.2008

Lee, Y., Lu, M., & Ko, H. (2007). Effects of skill training on working memory capacity. *Learning and Instruction, 17,* 336–344. doi:10.1016/j.learninstruc.2007.02.010

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49,* 467. doi:10.1121/1.1912375

Mathers, C., Smith, A., & Concha, M. (2000). Global burden of hearing loss in the year 2000. In *Global burden of disease 2000* (pp. 1–30). Geneva, Switzerland: World Health Organization.

Mazelova, J., Popelar, J., & Syka, J. (2003). Auditory function in presbycusis: Peripheral vs. central changes. *Experimental Gerontology, 38,* 87–94. doi:10.1016/S0531-5565(02)00155-9

Micheyl, C., Delhommeau, K., Perrot, X., & Oxenham, A. J. (2006). Influence of musical and psychoacoustical training on pitch discrimination. *Hearing Research, 219,* 36–47. doi:10.1016/j.heares.2006.05.004

Middleton, L. E., & Yaffe, K. (2009). Promising strategies for the prevention of dementia. *Archives of Neurology, 66,* 1210–1215. doi:10.1001/archneurol.2009.201

Mireles, D. E., & Charness, N. (2002). Computational explorations of the influence of structured knowledge on age-related cognitive decline. *Psychology and Aging, 17,* 245–259. doi:10.1037/0882-7974.17.2.245

Munte, T. F., Altenmuller, E., & Jancke, L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews Neuroscience, 3,* 473–478.

Murphy, D. R., Daneman, M., & Schneider, B. A. (2006). Why do older adults have difficulty following conversations? *Psychology and Aging, 21,* 49–61. doi:10.1037/0882-7974.21.1.49

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings of the National Academy of Sciences of the United States of America, 104,* 15894–15898. doi:10.1073/pnas.0701498104

Nelson, E. G., & Hinojosa, R. (2006). Presbycusis: A human temporal bone study of individuals with downward sloping audiometric patterns of hearing loss and review of the literature. *Laryngoscope, 116*(9 Pt 3 Suppl 112), 1–12. doi:10.1097/01.mlg.0000236089.44566.62

Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L. E., & Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature, 392,* 811–814. doi:10.1038/33918

Parbery-Clark, A., Skoe, E., & Kraus, N. (2009). Musical experience limits the degradative effects of background noise on the neural processing of sound. *Journal of Neuroscience, 29,* 14100–14107. doi:10.1523/JNEUROSCI.3256-09.2009

Parbery-Clark, A., Skoe, E., Lam, C., & Kraus, N. (2009). Musician enhancement for speech-in-noise. *Ear and Hearing, 30,* 653–661. doi:10.1097/AUD.0b013e3181b412e9

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *Journal of Acoustical Society of America, 97,* 593–608. doi:10.1121/1.412282

Qiu, C. X., Backman, L., Winblad, B., Aguero-Torres, H., & Fratiglioni, L. (2001). The influence of education on clinically diagnosed dementia incidence and mortality data from the Kungsholmen project. *Archives of Neurology, 58,* 2034–2039. doi:10.1001/archneur.58.12.2034

Rammsayer, T., & Altenmuller, E. (2006). Temporal information processing in musicians and nonmusicians. *Music Perception, 24,* 37–47. doi:10.1525/mp.2006.24.1.37

Recanzone, G. H., Schreiner, C. E., & Merzenich, M. M. (1993). Plasticity in the frequency representation of primary auditory cortex following discrimination training in adult owl monkeys. *Journal of Neuroscience, 13,* 87–103.

Ross, B., Schneider, B., Snyder, J. S., & Alain, C. (2010). Biological markers of auditory gap detection in young, middle-aged, and older adults. *Plos One, 5,* e10101. doi:10.1371/journal.pone.0010101

Salthouse, T. A. (2006). Mental exercise and mental aging: Evaluating the validity of the "use it or lose it" hypothesis. *Perspectives on Psychological Science, 1,* 68–87. doi:10.1111/j.1745-6916.2006.00005.x

Schellenberg, E. G. (2004). Music lessons enhance IQ. *Psychological Science, 15,* 511–514. doi:10.1111/j.0956-7976.2004.00711.x

Schellenberg, E. G., & Moreno, S. (2010). Music lessons, pitch processing, and g. *Psychology of Music, 38,* 209–221. doi:10.1177/0305735609339473

Schneider, B., Pichora-Fuller, M. K., & Daneman, M. (2010). Effects of senescent changes in audition and cognition on spoken language comprehension. In S. Gordon-Salant, D. R. Frisina, A. N. Popper & R. R. Fay (Eds.), *Springer handbook of auditory research: The aging auditory system (vol. 34,)*. New York: Springer.

Schneider, B. A., Pichora-Fuller, M. K., Kowalchuk, D., & Lamb, M. (1994). Gap detection and the precedence effect in young and old adults. *Journal of the Acoustical Society of America, 95,* 980–991. doi:10.1121/1.408403

Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., & Rupp, A. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature Neuroscience, 5,* 688–694. doi:10.1038/nn871

Shahin, A., Bosnyak, D. J., Trainor, L. J., & Roberts, L. E. (2003). Enhancement of neuroplastic P2 and N1c auditory evoked potentials in musicians. *Journal of Neuroscience, 23,* 5545–5552.

Stenklev, N. C., & Laukli, E. (2004). Presbyacusis: Hearing thresholds and the ISO 7029. *International Journal of Audiology, 43,* 295–306. doi:10.1080/14992020400050039

Stern, Y., Gurland, B., Tatemichi, T. K., Tang, M. X., Wilder, D., & Mayeux, R. (1994). Influence of education and occupation on the incidence of Alzheimers disease. *Journal of the American Medical Association, 271,* 1004–1010. doi:10.1001/jama.271.13.1004

Strouse, A., Ashmead, D. H., Ohde, R. N., & Grantham, D. W. (1998). Temporal processing in the aging auditory system. *Journal of the Acoustical Society of America, 104,* 2385–2399. doi:10.1121/1.423748

van Wassenhove, V., & Nagarajan, S. S. (2007). Auditory cortical plasticity in learning to discriminate modulation rate. *Journal of Neuroscience, 27,* 2663–2672. doi:10.1523/JNEUROSCI.4844-06.2007

Wong, P. C. M., Jin, J. X. M., Gunasekera, G. M., Abel, R., Lee, E. R., & Dhar, S. (2009). Aging and cortical mechanisms of speech perception in noise. *Neuropsychologia, 47,* 693–703. doi:10.1016/j.neuropsychologia.2008.11.032

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

Zendel, B. R., & Alain, C. (2009). Concurrent sound segregation is enhanced in musicians. *Journal of Cognitive Neuroscience, 21,* 1488–1498. doi:10.1162/jocn.2009.21140

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