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Effects of Varying Reverberation on Music Perception for Young Normal-Hearing and Old Hearing-Impaired Listeners

Paul N. Reinhart[1] and Pamela E. Souza[2,3]

Abstract
Reverberation enhances music perception and is one of the most important acoustic factors in auditorium design. However, previous research on reverberant music perception has focused on young normal-hearing (YNH) listeners. Old hearing-impaired (OHI) listeners have degraded spatial auditory processing; therefore, they may perceive reverberant music differently. Two experiments were conducted examining the effects of varying reverberation on music perception for YNH and OHI listeners. Experiment 1 examined whether YNH listeners and OHI listeners prefer different amounts of reverberation for classical music listening. Symphonic excerpts were processed at a range of reverberation times using a point-source simulation. Listeners performed a paired-comparisons task in which they heard two excerpts with different reverberation times, and they indicated which they preferred. The YNH group preferred a reverberation time of 2.5 s; however, the OHI group did not demonstrate any significant preference. Experiment 2 examined whether OHI listeners are less sensitive to (e, less able to discriminate) differences in reverberation time than YNH listeners. YNH and OHI participants listened to pairs of music excerpts and indicated whether they perceived the same or different amount of reverberation. Results indicated that the ability of both groups to detect differences in reverberation time improved with increasing reverberation time difference. However, discrimination was poorer for the OHI group than for the YNH group. This suggests that OHI listeners are less sensitive to differences in reverberation when listening to music than YNH listeners, which might explain the lack of group reverberation time preferences of the OHI group.

Keywords
music perception, reverberation, preference, sensitivity, hearing impairment

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Introduction

Musical performance venues are designed to use acoustic features, such as reverberation, to enhance the listening experience for those in attendance. Reverberation is the persistence of sound due to repeated acoustic reflections off features in an environment after the source has ceased. While there are many physical parameters of reverberation that affect perception including direct-to-reverberant ratio, interaural cross correlation, and lateral energy fractions, the reverberation time remains the most common metric for quantifying reverberation (International Organization for Standardization, 1997). Reverberation time is frequently calculated as the time required for the sound level to decrease by 60 dB relative to its initial level (Sabine, 1927).

Reverberation is commonly considered as a source of distortion with respect to speech. Longer reverberation times challenge speech perception more than short reverberation times by smearing the acoustic content of words and phonemes to a greater extent (Nábělek, Letowski, & Tucker, 1989; Reinhart, Souza, Srinivasan, & Gallun, 2016). However, for the enjoyment of music, a certain amount of reverberation is desirable because it embellishes the direct sound and adds qualities of fullness, warmth, and cohesion to the musical piece. As such,

[1]Department of Communication Sciences and Disorders, University of South Florida, Tampa, FL, USA
[2]Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL, USA
[3]Knowles Hearing Center, Evanston, IL, USA

Corresponding author:
Paul N. Reinhart, Department of Communication Sciences and Disorders, University of South Florida, Tampa, FL 33605, USA.
Email: reinhart@usf.edu

the reverberation time of a music venue is one of the most important acoustic parameters affecting listener perception and enjoyment of the music (Giménez, Cibrián, & Cerdá, 2012; Lokki, Pätynen, Kuusinen, & Tervo, 2012; Prodi, Pompoli, Martellotta, & Sato, 2015; Schroeder, Gottlob, & Siebrasse, 1974; Yamaguchi, 1972).

Due to the important effect of reverberation on music perception, reverberation time has become a critical acoustic parameter in venue design (e.g., Adelman-Larsen, Thompson, & Gade, 2010; Ando, 2007; Kuhl, 1954; Sakai, Setoguchi, & Ando, 1998; Winckel, 1962). If the reverberation time is too short, music can sound unblended and disconnected. In contrast, if the reverberation time is too long, the dynamic contrasts, articulation, and rhythm of the music may sound distorted. Tsolias and Davies (2014) summarized previous research and determined that the optimal reverberation time for music listening environments ranges from 1 to 4 s. This recommended reverberation time range is so wide because optimal reverberation time varies based on musical style, tempo, and other inherent aspects of the music. For music with lyrical content, listeners prefer moderate reverberation times of approximately 1 s (Ando, 2007; Sakai et al., 1998), so as to enhance the perceived quality of the music without overly distorting the transmission of lyrical speech information. For music without lyrical content, longer reverberation times are generally preferred. Kuhl (1954) examined the preferred amount of reverberation for classical, romantic, and modern music in a sample of 370 musicians and engineers. It was found that the preferred reverberation time varied from approximately 1.5 to 2.1 s. Similarly, Ando (2007) summarized that the preferred reverberation time for some classical orchestral music varies from approximately 2 to 3 s. Overall, these previous studies have shown that the preferred reverberation time when listening to music has high test–retest reliability and low intersubject variability for a given type of music when testing younger listeners with normal hearing (Kuhl, 1954; Sakai et al., 1998).

However, these previous studies have predominantly been conducted using samples of young normal-hearing (YNH) listeners with many studies only partially reporting the age and hearing status of their participants. These samples may not represent the range of listeners, including older listeners with hearing impairment, who may be more likely to attend certain types of concerts. This may be particularly true for classical music. An estimated 50% of classical music concert attendees are over 50 years of age and are likely to experience some degree of age-related hearing impairment (Kolb, 2001; Lee et al., 2012). Due to the potential prevalence of aging and hearing impairment in the classical music attendee population, it is important to consider how advanced age and hearing impairment may affect perception of reverberant classical music. Previous studies investigating the preferred amount of reverberation for classical music listening have not examined old hearing-impaired (OHI) listeners and thus may not reflect the classical music attendee population.

Previous work has identified that OHI listeners experience degraded spatial auditory processing and perceive reverberation differently than YNH listeners. Akeroyd, Gatehouse, and Blaschke (2007) found that OHI listeners show deficits in the ability to use reverberation as a cue for distance perception compared with YNH listeners (Akeroyd et al., 2007). It is also well known that OHI listeners have significantly different perception of reverberation in speech than YNH listeners (Duquesnoy & Plomp, 1980; Gordon-Salant & Fitzgibbons, 1993, 1995). This difference in perception of reverberant speech persists even when audibility is accounted for. Thus, it is hypothesized that age and sensorineural hearing impairment fundamentally change the way in which OHI listeners perceive reverberation (Dobreva, O'Neill, & Paige, 2011; Reinhart & Souza, in press; Zahorik & Brandewie, 2011). That is, the OHI auditory system encodes reverberation differently than the normal auditory system, irrespective of audibility. If true, then it is likely that OHI listeners also perceive reverberant music differently than the YNH listeners on which previous studies have exclusively focused. If OHI listeners prefer a different amount of reverberation when listening to music than YNH listeners, then it is possible that the acoustic criteria used in modern concert venue design do not reflect the perceptual needs of OHI listeners because those criteria are based on research in YNH listeners.

Experiment 1

The purpose of Experiment 1 was to examine whether OHI listeners and YNH listeners prefer different amounts of reverberation for listening to classical music. For this experiment, both YNH listeners and OHI listeners listened to excerpts from three classical music recordings processed across a range of reverberation times. Stimuli were presented in a round-robin paired-comparisons task in which listeners selected which of the recordings in a pair they preferred. Results were compiled across listeners in each group to construct a relative preference scale, and group results were compared.

Methods

Participants. Thirteen YNH listeners and 14 OHI listeners enrolled in the study. Audiometric thresholds were measured in all listeners at octave frequencies from

.25 to 8 kHz and interoctaves at 3 and 6 kHz. All listeners in the YNH group had air conduction thresholds ⩽ 20 dB HL across the test frequencies. Listeners in the OHI group additionally had their bone conduction thresholds tested at octave frequencies from .5 to 4 kHz. Results of the bone conduction testing confirmed that the etiology of hearing loss for the OHI listeners was sensorineural in nature (air-bone threshold gaps ⩽ 10 dB). Listeners also had symmetrical hearing loss (pure-tone average threshold difference across the ears ⩽ 10 dB). Audiometric results for both groups can be seen in Figure 1. A cutoff of 40 years of age between YNH and OHI groups was used based on evidence that age-related hearing changes occur as early as 40 years (Grose, Hall, & Buss, 2006). Additional relevant participant information for each group is summarized in Table 1. Because music typically occurs over a wider frequency bandwidth than speech (Chasin, 2003), degree of hearing loss was quantified as the 6-frequency pure-tone average (average thresholds at octaves 250–8000 Hz).

Because the tasks in the current study involve music perception, it is possible that musical experience may have some impact on performance. While the effect of musical experience on perception of reverberation in music was not a research question of the current study, we sought to include approximately equal numbers of musicians in both listener groups. This was done to avoid musical experience as a significant confound by having one listener group dominated by musicians. For the current study, musicianship was defined as having greater than 3 years of formal music training (Bidelman, Gandour, & Krishnan, 2009; Bidelman & Krishnan, 2010). All of the listeners reported good general health at the time of testing. Listeners completed an informed consent process and were compensated for their time.

Stimuli and processing. Music stimuli included excerpts from three classical symphonic compositions:

1. Beethoven's Symphony no. 7, I movement, bars 1–53
2. Bruckner's Symphony no. 8, II movement, bars 1–61
3. Mahler's Symphony no. 1, IV movement, bars 1–85

These stimuli were recorded by Lokki, Pätynen, and Pulkki (2008) to provide a set of open-source anechoic classical symphony recordings for academic research. From the composite recordings, we isolated an 8 to 10 s excerpt that comprised a coherent musical line without too abrupt a start or finish, consistent with musical phrasing. Excerpts were gated with a 0.5-s cosine-squared ramp. The spectral and temporal characteristics of the three excerpts are similar. The long-term magnitude spectra of the signals across octave bands are depicted in Figure 2. The tempos for the Beethoven, Bruckner, and Mahler excerpts were 125, 120, and 105 beats per minute, respectively. Overall, these stimuli were selected due to the anechoic nature of the recordings.

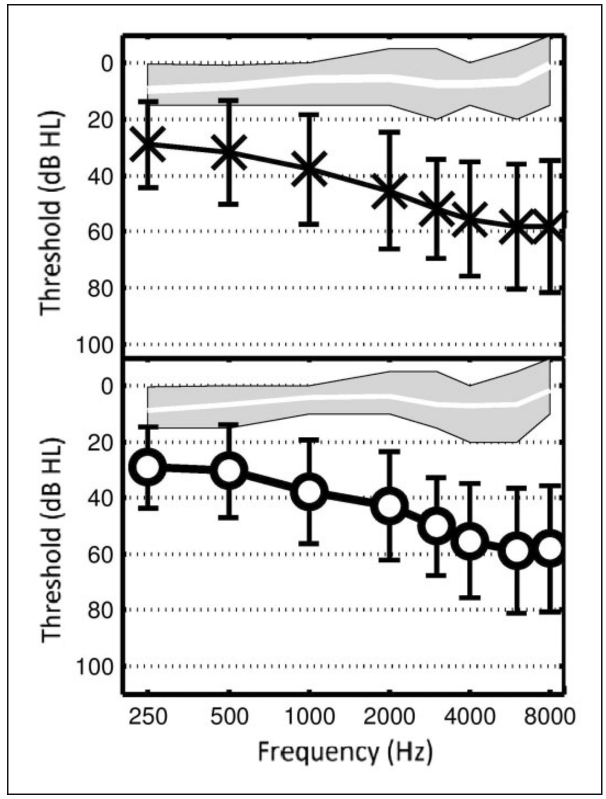

Figure 1. Participant audiograms for Experiment 1 for the left and right ear. The shaded area represents the range for the YNH group, and the white line represents the mean. The symbols represent mean threshold for the OHI group with error bars representing ± 1 standard deviation.
YNH = young normal-hearing; OHI = old hearing-impaired; dB HL = decibels hearing level.

Table 1. Participant Characteristics for Experiment 1 for the YNH and OHI Groups.

	Young normal-hearing group *N* = 13	Old hearing-impaired group *N* = 14
Six-Frequency PTA (dB HL)	*M* = 6.0	*M* = 45.5
	SD = 2.7	*SD* = 12.5
	Range: 0.8–10.4	Range: 25.8–70.0
Age (years)	*M* = 26.5	*M* = 68.2
	SD = 5.8	*SD* = 11.9
	Range: 22–39	Range: 41–83
No. of Musicians	5	4
Sex	5 Male, 8 Female	7 Male, 7 Female

Note. YNH = young normal-hearing; OHI = old hearing-impaired; PTA = pure-tone average; dB HL = decibels hearing level.

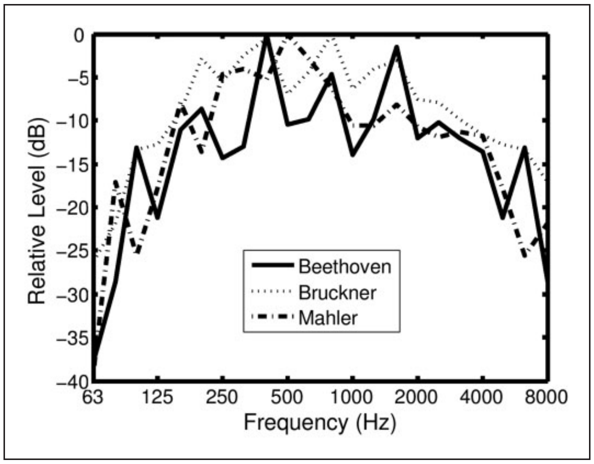

Figure 2. Long-term magnitude spectra in octave bands for the musical excerpts. Each spectrum has been normalized to its maximum value.
dB = decibel.

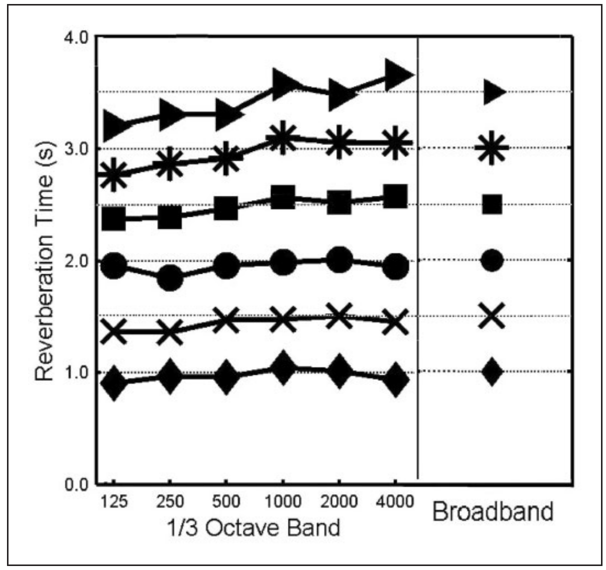

Figure 3. Final broadband reverberation time as well as reverberation time as a function of octave bands for the six processed reverberation conditions.

This allowed us to control the exact amount of reverberation without having to compensate for the uncontrolled amount of reverberation that would otherwise be incorporated into studio and live recordings.

Musical excerpt stimuli were then processed using a virtual reverberation simulator implemented in MATLAB (Zahorik, 2009) to yield reverberant music stimuli processed across a range of reverberation times typical for a concert hall. In total, six broadband reverberation time conditions were simulated ranging from 1.0 to 3.5 s in 0.5-s intervals. A three-dimensional room (15 m × 30 m × 10 m) that is typical of a medium-sized performance venue was simulated (e.g., Orlowski, 2014), and the absorptive properties of the room were varied to yield the desired broadband reverberation times. In brief, the simulation method uses an image model to compute the early reflections and the direct stimulus path (Allen & Berkley, 1979). In the current model, the source was set 3 m from the wall with the receiver spatialized 15 m away in a more central position in the room. Independent Gaussian noise samples were used to statistically simulate the late reverberant energy using exponential decay functions in octave bands from 125 to 4000 Hz, and original stimuli were zero-padded as needed for the duration of reverberant decay. These components were spatially rendered using nonindividualized head-related transfer functions to produce binaural room impulse responses. Lastly, the binaural room impulse responses were convolved with the excerpts to produce the final reverberant stimuli. Final broadband reverberation times, as well as the individual octave band reverberation times for each of the six conditions can be seen in Figure 3. Overall, the relationship between the overall reverberation time and octave band values is comparable to that measured in real-world performance spaces of similar size (Beranek, 2012; Orlowski, 2014).

Preference task. Preference for reverberation time was measured using a pairwise comparison task. The task consisted of 90 trials in a round-robin comparison format. In each trial, the participants listened to two versions of the same musical excerpt processed at different reverberation times. For the round-robin comparison format, 15 comparisons were required to compare each of the six reverberation time conditions to all of the others (number of comparisons $= N \times (N-1)/2$, where N is the total number of conditions). Two trials for each possible reverberation time comparison were conducted to counterbalance the order of presentation of the different reverberation times. All of these comparisons were conducted for each of the three symphonic compositions for the total of 90 trials (15 comparisons × 2 orders × 3 compositions). The order of the trials was individually randomized for each participant.

In each trial, listeners were asked to select whichever sample they preferred. Listeners did not have to listen to the entire duration of the second stimulus if they knew which they preferred after a few seconds. Listeners were required to indicate a response even if they were unable to determine a preference. To test for the presence of order selection bias, data were collected on how frequently listeners selected either the first or second stimulus in the trial. Listeners from both groups had a slight order bias toward selecting the second stimulus of a pair (53.0% for YNH group and 55.3% for OHI group).

Procedure. Testing took place in a double-walled soundproofed booth. Stimulus presentation and data recording for the preference task were controlled using a custom MATLAB program. Listeners logged their responses using a computer interface. Digital signals were converted to analog by Tucker-Davis Technologies equipment (Alachusa, FL) and played through Etymotic-ER2 insert phones (Elk Grove Village, IL). These headphones were chosen due to their flat frequency response at the tympanic membrane. The music stimuli were presented at 75 dB sound pressure level, as this level reasonably approximates the average intensity of symphonic music performed in a small auditorium (Royster, Royster, & Killion, 1991). It was a methodological choice not to provide any frequency shaping or compensation for loss of audibility to the listeners in the OHI group. We believe that this approach most closely imitates the perception of reverberation and music by OHI listeners in the real world. Approximately 80% of OHI listeners do not use any form of amplification (Kochkin, 2007). While some concertgoers may be of higher socioeconomic status and be more likely to own hearing aids (Nieman, Marrone, Szanton, Thorpe, & Lin, 2016), they may nevertheless opt not to use their hearing aids during music listening due to distortions introduced by hearing aid signal processing (Chasin, 2003; Madsen & Moore, 2014). This may be especially true for individuals with milder degrees of hearing impairment for whom the unamplified live music signal is sufficiently audible. Therefore, it is ecologically valid to investigate music perception in OHI listeners without providing amplification. All procedures were approved by the Northwestern University Institutional Review Board.

Results

Pairwise preference data were analyzed using binary logistic regression. Binary logistic regression can be used to construct a perceptual scale and provide statistical significance differences between preferences from round-robin paired-comparison data (Lipovetsky & Conklin, 2004; Woods, Satgunam, Bronstad, & Peli, 2010). One advantage of this technique is that it uses the original paired-comparison data that is preferable to an approach that uses the aggregated frequency table data (Blyth, 1972). In brief, the method involved constructing a regression table with the six reverberation times represented in six columns. Separate regression tables were constructed for the YNH and OHI groups. To increase the power of each regression table, results for the three different symphonic excerpts were depicted in the same table and analyzed together. Due to the spectrotemporal similarity of the musical excerpts (Figure 2), it is unlikely there would be an interaction with stimulus excerpt. Each row represented a single trial comparison judgment made by one listener. For the two reverberation times being compared in any one trial, the corresponding column was assigned either a positive 1 for the preferred reverberation time or a negative 1 for the nonpreferred reverberation time; all other columns corresponding to reverberation times that were not part of that trial comparison pair were assigned a 0. A seventh column, known as the identity vector, served as the dependent variable of the analyses. Each row of the identity vector was randomly assigned a value of 0 or 1. If for a given row the value of the identity vector was assigned a 0, then the other values of that row were inverted (i.e., preferred stimulus = –1; nonpreferred stimulus = 1).

Table 2. Pairwise Statistical Significance Results From the Binary Logistic Regression Analyses From the Preference Task.

	1.0	1.5	2.0	2.5	3.0	3.5
1.0	–	**.022***	**.001****	**<.001****	**<.001****	**.075**
1.5	*.859*	–	**.265**	**.131**	**.168**	**.599**
2.0	*.112*	*.077*	–	**.693**	**.792**	**.101**
2.5	*.409*	*.316*	*.443*	–	**.895**	**.042***
3.0	*.316*	*.238*	*.555*	*.860*	–	**.057**
3.5	*.316*	*.238*	*.555*	*.860*	*1.000*	–

Note. Results for the young normal-hearing group are depicted above the diagonal in bold, and results for the old hearing-impaired group are depicted below the diagonal in italics.
$^{*}p < .05$. $^{**}p < .01$.

Five binary logistic regressions were conducted for each of the YNH and OHI regression tables to examine the statistical significance among the six reverberation times for each group. In each of the binary logistic regression analyses, a different reverberation time variable was held constant by being excluded from the model. The results of each model gave the statistical relationship between the excluded reverberation time variable and all the other reverberation time variables that were included in the model. See Table 2 for the statistical significance results of the pairwise comparisons for both the YNH and OHI. For the YNH group, the 1.0 s reverberation time was preferred significantly less than all the other reverberation time conditions (all $p < .05$) except for the 3.5 s reverberation time ($p = .075$), and the 3.5 s reverberation time was preferred significantly less than the 2.5 s reverberation time ($p < .05$). For the OHI group, there were no significant differences between any of the reverberation time conditions (all $p > .05$).

For visualizing the data, a zero-to-one perceptual scale was quantified by normalizing the regression coefficients of the different reverberation times. Because the reverberation time conditions represented an ordinal continuum, the data were plotted as a two-dimensional graph rather than a visual analog scale more typical of preference data (Figure 4). The results of the YNH

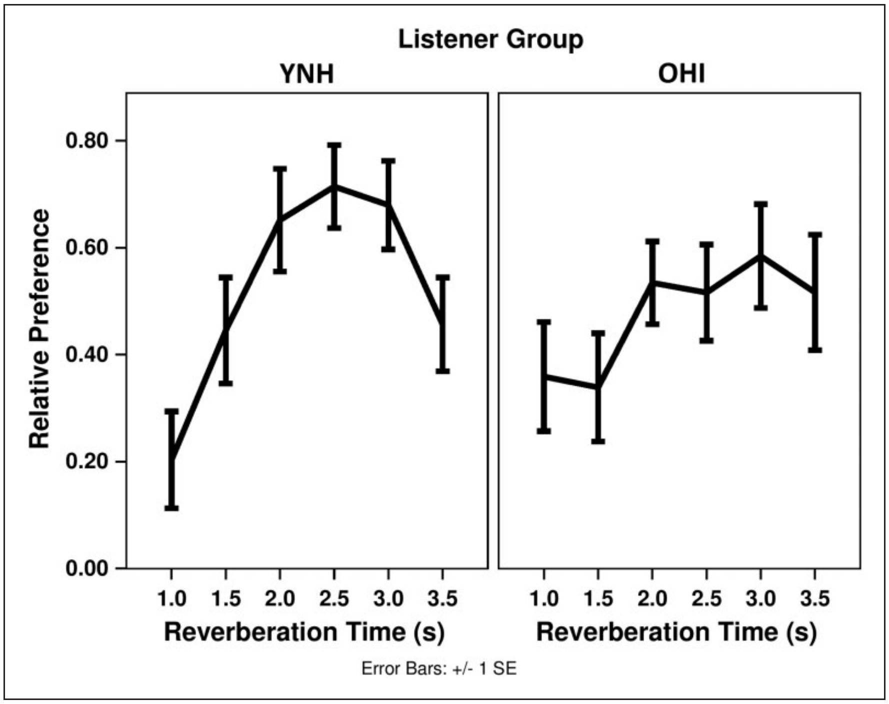

Figure 4. Scaled relative preference across the different reverberation time conditions for both the YNH (left panel) and OHI (right panel) groups. Error bars represent ± 1 standard error.
YNH = young normal-hearing; OHI = old hearing-impaired.

group depict an approximately normal distribution in which listeners tended to prefer higher reverberation times to a point (1.0 s reverberation time significantly less preferred than 1.5 to 3.0 s). The distribution peaked around the 2.5 s reverberation time condition before decreasing (3.5 s reverberation time significantly less preferred than 2.5 s). The results of the OHI group indicated a slight trend for higher reverberation times; however, there were no statistically significant differences between any of the reverberation times.

Experiment 2

The results of Experiment 1 suggest that OHI listeners do not prefer a certain reverberation time when listening to classical music. One possible explanation for this is that they were not sufficiently sensitive to the differences in reverberation. Therefore, even though the samples within a pair had different reverberation times, OHI listeners may not have been able to perceive that difference and therefore had no preference. We conducted a second experiment to address this possibility. The purpose of Experiment 2 was to examine whether OHI listeners are less sensitive to (i.e., less able to discriminate) differences in reverberation time when listening to classical music than listeners with YNH. For the experiment, both YNH listeners and OHI listeners listened to pairs of classical music excerpts that had the same reverberation time, or that differed in reverberation time by varying amounts. Listeners indicated whether excerpts within a pair had the same or different amounts of reverberation. The proportion of the time that listeners correctly identified the pairs with differing reverberation times was compared between the YNH and OHI groups.

Methods

Participants. Eighteen YNH adults and 19 OHI adults enrolled in Experiment 2. One of these YNH listeners and five of these OHI listeners also participated in Experiment 1. Listeners underwent the same audiometric protocol as described in Experiment 1. See Figure 5 for audiometric data and Table 3 for additional listener information. Listener characteristics in Experiment 2 for each group were similar to those of the groups in Experiment 1 (Table 1). Listeners completed an informed consent process and were compensated for their time.

Stimuli and processing. Experiment 2 contained the same processed music excerpts as those used in Experiment 1.

Sensitivity task. Sensitivity to differences in reverberation time was measured using a same–different paradigm. The task consisted of 24 trials. Within each trial, the musical excerpt (i.e., Beethoven, Bruckner, or Mahler) being compared was the same. Each trial had a reference

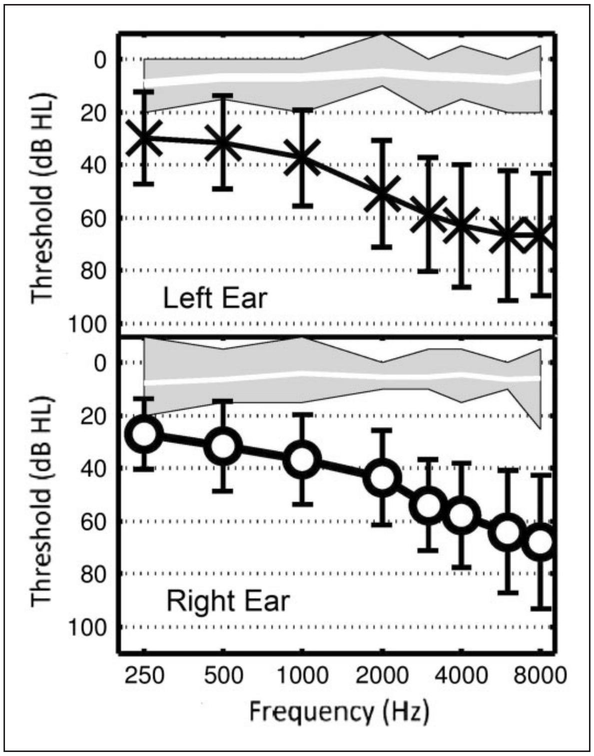

Figure 5. Participant audiograms for Experiment 2 for the left and right ear. The shaded area represents the range for the YNH group, and the white line represents the mean. The symbols represent mean threshold for the OHI group with error bars representing ± 1 standard deviation.
YNH = young normal-hearing; OHI = old hearing-impaired; dB HL = decibels hearing level.

Table 3. Participant Characteristics for Experiment 2 for the YNH and OHI Groups.

	Young normal-hearing group $N = 18$	Old hearing-impaired group $N = 19$
Six-Frequency PTA (dB HL)	$M = 5.5$	$M = 47.7$
	$SD = 4.6$	$SD = 13.4$
	Range: 0.0–9.17	Range: 26.3–73.8
Age (years)	$M = 26.3$	$M = 70.8$
	$SD = 4.1$	$SD = 10.4$
	Range: 20–32	Range: 42–85
No. of Musicians	8	5
Sex	7 Male, 11 Female	13 Male, 6 Female

Note. YNH = young normal-hearing; OHI = old hearing-impaired; PTA = pure-tone average; dB HL = decibels hearing level.

stimulus that had a reverberation time of 1.0 s. The other nonreference stimulus had a reverberation time of 1.5 (Δ0.5 compared with the 1.0 s reference), 2.5 (Δ1.5), or 3.5 (Δ2.5) s for three Δ reverberation time conditions. The presentation order for reference versus nonreference stimuli was counterbalanced for each of the three symphonic compositions (i.e., Beethoven, Bruckner, Mahler) giving 18 comparisons. During the task, listeners indicated whether the excerpts in the trial had the same or different amounts of reverberation using a computer interface. The presentation order of the trials was individually randomized for each listener.

In addition, there were six comparisons in which both excerpts in the pair had the same reverberation time of 1.0 s. There were two such comparisons for each of the three symphonic compositions. These comparisons were included to examine the rate of false positive responses in listeners (i.e., responding that the stimuli were different, when in fact both excerpts had the same reverberation time). The false positive rate for all subjects was 0.329.

Procedure. Stimuli were presented in the same manner and with the same calibration as in Experiment 1. All procedures were approved by the Northwestern University Institutional Review Board.

Results

Sensitivity data were transformed to *d'* for analyses (MacMillan & Creelman, 2004). Figure 6 shows listener performance on the sensitivity task across the different Δ reverberation time conditions (Δ0.5, Δ1.5, Δ2.5) for both the YNH and OHI groups. Results were collapsed across the three symphonic excerpts because of their spectral and temporal similarities. Data were analyzed using a two-way repeated-measures analysis of variance with one within-subjects factor (Δ reverberation time) and one between-subjects factor (listener group). The dependent variable was *d'* sensitivity. The data did not satisfy the assumption of sphericity as indicated by a significant result for Mauchly's Test of Sphericity ($p = .042$). Therefore, a Greenhouse-Geisser correction was applied for all subsequent main effect and interaction tests. There was a significant Δ reverberation time × listener group interaction [$F(1.7, 59.8) = 3.708$, $p = .037$, partial $\eta^2 = .096$], and both main effects were significant: Δ reverberation time [$F(1.7, 59.8$, $p < .001$, partial $\eta^2 = .301$] and listener group [$F(1, 35) = 39.742$, $p < .001$, partial $\eta^2 = .532$].

Given the significant Δ reverberation time × listener group interaction, independent samples *t* tests were conducted between the listening groups at each Δ reverberation time condition to further examine differences in sensitivity between the groups. The groups were significantly different at every level of Δ reverberation time (all $p < .05$). However, after performing a Bonferroni correction, the difference between the listener groups in the Δ0.5 reverberation time condition became nonsignificant ($p = .14$).

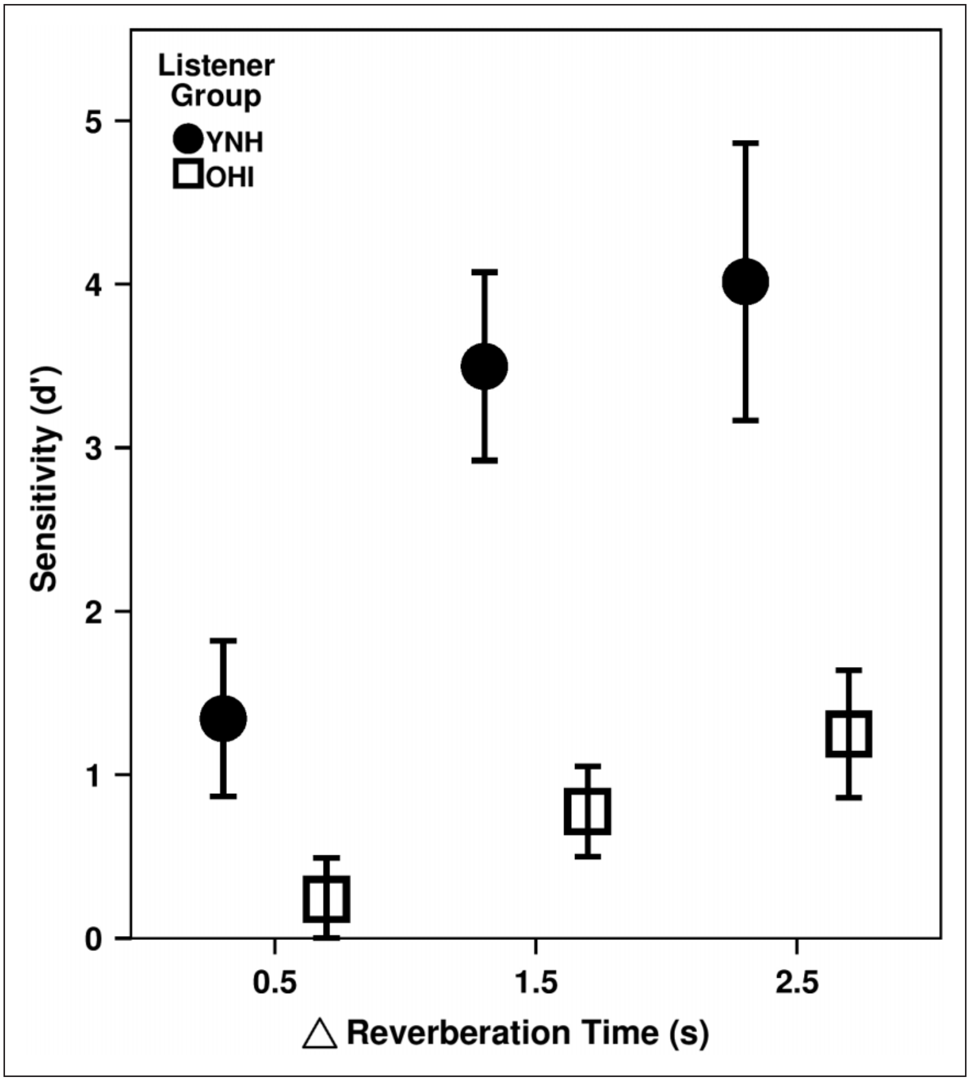

Figure 6. Performance on the sensitivity task as indicated by proportion correct discriminating the samples as a function of their different reverberation times for both the YNH and OHI groups.
YNH = young normal-hearing; OHI = old hearing-impaired.

To further examine how differences in Δ reverberation time affected sensitivity, separate one-way repeated-measures analyses of variance were conducted for each listener group. For both groups, the effect of Δ reverberation time was significant: YNH [$F(1.4, 23.3) = 11.7$, $p = .001$, partial $\eta^2 = .407$] and OHI [$F(2, 34) = 3.449$, $p = .043$, partial $\eta^2 = .161$]. Overall, the effect size was greater for the YNH group suggesting that the sensitivity of the OHI group did not improve as much as the YNH group as the difference between stimuli became larger.

General Discussion

In Experiment 1, the YNH group preferred a moderate reverberation time around 2.5 s. These results are consistent with previous research that was conducted using similar samples of YNH listeners (e.g., Kuhl, 1954). In contrast, the results of the OHI group demonstrated no significant group preference for any of the reverberation times examined. The results of Experiment 2 suggest that this lack of preference may have occurred because the OHI listeners were less sensitive to the differences in reverberation than the YNH listeners. These findings are further discussed in the following.

Knowing the optimally preferred reverberation time for music listening is a critical consideration for constructing and modifying concert venues, as well as for guiding the selection of musical programs to be performed in existing venues (Ando, 2007). This information may even be used to recommend an individual's optimum seat in a given concert hall (Sakurai, Korenaga, & Ando, 1997). While the OHI sample in Experiment 1 is representative of the larger population in age and degree of hearing loss, it is possible that with additional people, there would be a significant preference for music at a certain reverberation time. Nevertheless, it is evident that the OHI listeners were not consistent as a group in their responses. This is in contrast to the YNH listeners who were consistent as a group in this study and prior studies (Kuhl, 1954; Sakai et al., 1998). These results suggest that listeners who are less sensitive to differences in reverberation time (i.e., OHI individuals) as a result of age or hearing impairment may be more tolerant of concert venues that do not meet the exact desired acoustic criteria. In addition, OHI listeners may be more tolerant of venue seats that are considered acoustically suboptimal. Overall, it may be that less concern need be spent regarding optimal reverberation time for music listening for OHI listeners because they may not be sensitive enough to differences in reverberation to express a clear preference.

Understanding how sensitive an individual is to differences in reverberation time may be important for prioritizing seating arrangements in a venue. The current study measured listener sensitivity to differences in reverberation only using classical, symphonic music stimuli. Previous work using a just noticeable difference task has indicated that listener sensitivity to differences in reverberation is independent of whether the stimuli source is instrumental music, choral music, or conversational speech (Bradley, Reich, & Norcross, 1999; Larsen, Iyer, Lansing, & Feng, 2008; Martellotta, 2010). Thus, it is likely that these results are generalizable to other types of stimuli.

While the results indicate that OHI listeners are less sensitive to differences in reverberation in music than YNH listeners, the exact reason for this discrepancy cannot be inferred from the current study. One possibility is that because the acoustic signals were not amplified, the decay of the late energy reflections was likely to fall below the audibility threshold more quickly for the OHI listeners than for the YNH listeners. That is, the OHI listeners were receiving impoverished samples due to decreased audibility with which to compare and judge the relative amounts of reverberation. In addition, decreased audibility may affect sensitivity by limiting the bandwidth of the signal. Larsen et al. (2008) found that sensitivity to differences in direct-to-reverberant energy ratio was poorer for a narrowband signal than a wideband signal. Because the audible bandwidth was reduced for the OHI group due to poorer auditory sensitivity compared with YNH individuals, especially in the high frequencies, that may account for the decreased sensitivity in the current study. It would be interesting to determine if OHI listeners would still be less sensitive to differences in reverberation time even when the signal is amplified to restore audibility.

Another factor potentially contributing to the current findings is that OHI listeners are less sensitive to differences in reverberation due to spatial processing deficits. That is, even if audibility was compensated for OHI listeners, they would still perform differently than YNH listeners because OHI exhibit fundamental deficits. It is well known that OHI listeners encode spectral and temporal characteristics of acoustic signals differently than YNH listeners (e.g., Souza, Wright, Blackburn, Tatman, & Gallun, 2015). As a result, OHI listeners experience spatial processing deficits related to sound localization (Dobreva et al., 2011) and binaural processing (Moore, 2007). These deficits likely affect the way listeners perceive reverberation. In support of this explanation recall that there are declines in perception of reverberant speech even when audibility is compensated (Shi & Doherty, 2008). Thus, it is hypothesized that there are aging and hearing loss-related deficits in the processing mechanisms related to the encoding of reverberation. If this is true, then OHI listeners would likely still be less sensitive (albeit possibly to a lesser extent) to differences in reverberation in music than YNH listeners even when the signal is amplified.

The relative contributions of advanced aging and hearing loss for perception of reverberant music remain unknown. Because both factors commonly present concomitantly in listeners in the real world, we were interesting in examining the combined effects on perception. Previous work has found mixed results as to whether declines in spatial perception are primarily driven by age or hearing impairment-related changes (Dobreva et al., 2011; Kolarik, Moore, Zahorik, Cirstea, & Pardhan, 2016). If performance on the preference and sensitivity tasks were driven primarily by spatial processing deficits, then it is possible that both differences in hearing loss and age contributed to the findings between the listener groups. Further research is necessary to clarify the effects of advanced aging versus hearing impairment on the effects of varying reverberation on music perception.

A limitation of the study is how the simulation was conducted to render the reverberant stimuli. In the current simulation, the combined musical signal was treated as a colocated source rather than individual instruments being spatially distributed as if on a concert stage. Previous work has suggested that music may have different timbre when recorded from different directions (Pätynen & Lokki, 2010). While the results for preferred reverberation times are consistent with previous research, the current simulation does not perfectly emulate concert hall listening. Nevertheless, the primary purpose of the current study was to examine potential differences in music perception between YNH and OHI listeners. Given that the current study has demonstrated clear differences between the groups, further research is warranted to examine differences under more realistic representations of concert hall listening, as well as to consider other acoustic metrics than reverberation time.

Conclusions

The present study comprised two experiments: one investigating the preference of OHI and YNH listeners for music processed with different reverberation times; and another comparing the sensitivity of OHI and YNH listeners to differences in reverberation time. The OHI listeners did not have a significant preference for any of the reverberation time conditions and that they were less sensitive to differences in reverberation time than the YNH listeners. These results suggest that OHI listeners may be more tolerant of concert venues with a wide range of reverberation times. Overall, further research is required to understand the effects of aging and hearing impairment on perception of reverberation in music in concert halls.

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