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Effects of Age on Melody and Timbre Perception in Simulations of Electro-Acoustic and Cochlear-Implant Hearing

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Abstract

Objectives—Recent evidence suggests that age might affect the ability of listeners to process fundamental frequency cues in speech, and that this difficulty might impact the ability of older listeners to use and combine envelope and fine structure cues available in simulations of electro-acoustic and cochlear-implant hearing. The purpose of this paper is to examine whether this difficulty extends to music. Specially, this study focuses on whether older listeners have a decreased ability to utilize and combine different types of cues in the perception of melody and timbre.

Design—A group of older listeners with normal to near-normal hearing and a group of younger listeners with normal hearing participated in the melody and timbre recognition tasks of the University of Washington Clinical Assessment of Music Perception (CAMP) test. The recognition tasks were completed for five different processing conditions: 1) an unprocessed condition; 2) an eight-channel vocoding condition that simulated a traditional cochlear implant and contained temporal envelope cues; 3) a simulation of electro-acoustic stimulation (sEAS) that included a low-pass acoustic component and high-pass vocoded portion, and which provided fine structure and envelope cues; 4) a condition that included only the low-pass acoustic portion of the sEAS and 5) a condition that included only the high-frequency vocoded portion of the sEAS stimulus.

Results—Melody recognition was excellent for both younger and older listeners in the conditions containing the unprocessed stimuli, the full sEAS stimuli, and the low-pass sEAS stimuli. Melody recognition was significantly worse in the cochlear-implant simulation condition, especially for the older group of listeners. Performance on the timbre task was highest for the unprocessed condition, and progressively decreased for the sEAS and cochlear-implant simulation conditions. Compared to younger listeners, older listeners had significantly poorer timbre recognition for all processing conditions. For melody recognition, the unprocessed low-frequency portion of the sEAS stimulus was the primary factor determining improved performance in the sEAS condition compared to the cochlear-implant simulation. For timbre recognition, both the unprocessed low-frequency and high-frequency vocoded portions of the sEAS stimulus contributed to sEAS improvement in the younger group. In contrast, most listeners in the older

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Conflicts of Interest

The authors do not have any conflicts of interest to declare.

group were not able to take advantage of the high-frequency vocoded portion of the sEAS stimulus for timbre recognition.

Conclusions—The results of this simulation study support the idea that older listeners will have diminished timbre and melody perception in traditional cochlear-implant listening due to degraded envelope processing. The findings also suggest that music perception by older listeners with cochlear implants will be improved with the addition of low-frequency residual hearing. However, these improvements might not be comparable for all dimensions of music perception. That is, more improvement might be evident for tasks that rely primarily on the low-frequency portion of the electro-acoustic stimulus (e.g., melody recognition) and less improvement might be evident in situations that require across-frequency integration of cues (e.g., timbre perception).

Keywords

hearing loss; age; melody recognition; timbre perception; cochlear implant; periodicity; fine structure

INTRODUCTION

Older listeners, even those without significant hearing loss, have been shown to have processing deficits that affect auditory perception. A significant body of work has established relationships between advanced age and difficulties in speech perception, especially in complex listening situations, such as speech in background noise. However, other complex auditory signals have received less attention. For example, auditory deficits associated with age may also affect music perception. For older adults with hearing loss, music perception may be further complicated by the degraded signals delivered by hearing devices, including cochlear implants. The present study considers how age influences music perception, with an emphasis on conditions that simulate cochlear-implant listening.

Two important aspects of music perception are melody and timbre. Pitch and melody recognition for individuals with normal hearing are dominated by resolved low-frequency harmonics (e.g., Arehart 1994; Houtsma & Smurzynski 1990; Oxenham 2008). As such, the spectral (place) and temporal (fine structure) cues provided by the resolved low-frequency harmonics produce the most robust pitch percept. Though less salient, temporal envelope cues that result from interactions of higher-frequency unresolved harmonics are sufficient to convey melodic pitch information (Houtsma & Smurzynski 1990). Timbre perception for individuals with normal hearing involves multiple dimensions including temporal envelope, spectral shape (centroid) and fine spectral detail (spectral irregularity) (Grey 1977; McAdams et al. 1995; Kong et al. 2011; Caclin et al. 2005). Listeners can use these temporal and spectral cues both independently and in combination (Samson et al. 1997; Caclin et al. 2005).

Older listeners might be at a disadvantage in melody recognition and timbre perception due to age-related deficits in the processing of temporal envelope and fine structure cues. Several studies have shown that older listeners have decreased ability to utilize temporal envelope cues (e.g., Souza & Boike 2006; Grose et al. 2009; Souza et al. 2011). Recent work has also shown that older listeners often have reduced ability to process temporal fine structure (e.g., Vongpaisal & Pichora-Fuller 2007; Hopkins & Moore 2011; Smith et al. 2012). For example, Hopkins and Moore (2011) reported that older listeners without significant hearing loss and with normal frequency resolution had significantly worse performance on tasks of temporal fine structure sensitivity. Russo et al. (2012) recently reported that older adults with normal hearing showed poorer performance than younger adults with normal hearing on a melodic perception task requiring identification of a shifted

pitch. This finding was attributed by Russo et al. to an age-related decrement in auditory temporal processing (phase locking) abilities.

Insights into the potential impact of age-related deficits in envelope and fine structure processing on music perception can be gleaned from studies that consider real and simulated cochlear-implant listening. Processing schemes for cochlear implants begin by bandpass filtering the incoming music signal. The envelopes within each band are then extracted, low-pass filtered, compressed to fit the electrical dynamic range, and finally used to modulate trains of electrical pulses. While providing listeners with access to temporal envelope cues, cochlear-implant processing strategies provide only sparse spectral detail and as such, do not convey information about fine structure and the frequencies of individual harmonics (Moore, 2003; Wilson & Dorman 2008; Drennan & Rubinstein 2008). Similarly, simulations of cochlear-implant processing are generated by reducing the number of frequency channels in a signal and using envelope extraction that removes temporal fine structure.

Melody recognition with real and with simulated cochlear-implant hearing (where spectral and temporal fine structure cues are lacking) is significantly worse than with normal hearing (Kong et al. 2004; Gfeller et al. 2005; Cooper et al. 2008; Nimmons et al. 2008; Kang et al. 2009; Singh et al. 2009; Golub et al. 2012; Wright & Uchanski 2012). Furthermore, melody recognition improves when cochlear-implant listeners have access to residual acoustic hearing (Kong et al. 2005; Dorman et al. 2008; Gfeller et al. 2005; El Fata et al. 2009), with the majority of the improvement due to cues provided by low-frequency hearing alone rather than the combination of cues provided by both acoustic and electrical hearing (Kong et al. 2005; Dorman et al. 2008).

Similar to melody recognition, identification of musical instruments (a common task of timbre perception) is reduced in real and simulated cochlear-implant hearing (Fujita & Ito 1999; Gfeller et al. 2002; McDermott, 2004; Nimmons et al. 2008; Driscoll et al. 2009; Kang et al. 2009; Golub et al. 2012; Wright & Uchanski 2012). Kong et al. (2011) showed that the number and strength of timbre cues is reduced in cochlear-implant listening. The authors reported that timbre perception was characterized by three dimensions (temporal envelope, spectral envelope and spectral fine structure) for listeners with normal hearing. In contrast, timbre perception for listeners with cochlear implants was best described with two dimensions, with one dimension strongly correlated with temporal envelope and a second dimension less strongly correlated with spectral shape. For timbre perception, the addition of low-frequency acoustic hearing to electrical hearing has led to mixed results. Some studies have shown that instrument identification is not improved with access to low-frequency acoustic information (Golub et al. 2012; Brockmeier et al. 2010). In contrast, Gfeller et al. (2006) showed that subjects with electro-acoustic stimulation (residual hearing and a short-electrode cochlear implant in the same ear) showed significantly better musical instrument identification compared to listeners with traditional long-electrode implants. Kong et al. (2012) reported that the strength of timbre cues – especially for spectral shape – was much stronger for some, but not all, listeners who combine acoustic with electrical hearing.

The degraded information provided by cochlear-implant hearing, compounded with a reduced ability to use temporal cues, might lead to especially poor music perception for older cochlear-implant recipients. Previous studies have suggested this to be the case. For example, using multivariate regression techniques in the analysis of data from 209 adults with cochlear implants, Gfeller et al. (2008) reported that age was a significant predictor for reduced melody recognition. Gfeller et al. (2012) also recently showed that age was a strong negative predictor for melody recognition for adults with cochlear implants both with and without access to low-frequency hearing. While there is paucity of studies examining timbre

and age, Golub et al. (2012) speculated that age was a potential factor in the lack of improvement in timbre perception when electro-acoustic hearing was compared to cochlear-implant hearing. Although not a direct examination of music perception, Souza et al. (2011) showed that older adults were significantly worse at using high-rate envelope fluctuations in the perception of voice pitch conveyed by changes in fundamental frequency, using simulations of cochlear-implant and electro-acoustic hearing.

The present study explores the hypothesis that older adults will not be able to use and integrate different types of cues as well as younger adults in melody recognition and in timbre perception. The experimental design uses noise-vocoder simulations of cochlear-implant and electro-acoustic hearing to vary the types of cues available to the older and younger listeners. The cochlear-implant simulation allows for the assessment of how well listeners can use envelope-only cues; the electro-acoustic simulation allows for the assessment of how well listeners can use and integrate fine structure and envelope cues. Older adults are predicted to have decreased melody recognition due to possible age-related deficits in the ability to temporally encode information about resolved low-frequency harmonics (available in the electro-acoustic simulation). In addition, both melody and timbre perception are expected to be worse in older listeners due to potential age-related degradation in the ability to utilize the (already less salient) envelope cues in the simulated cochlear-implant condition. Finally, older adults are also predicted to have increased difficulty integrating across-frequency cues in the electro-acoustic simulations.

METHODS

Listeners

Participants included a group of 12 younger adults with normal hearing (ages 19 to 35; mean age 26.3) and a group of 10 older adults with (near) normal hearing (ages 65 to 81; mean age 69.9). Normal hearing for the younger group was defined as thresholds of 20 dB HL (ANSI 2004) or better across audiometric frequencies from 250 to 8000 Hz, bilaterally. (Near) normal hearing for the older group was defined as thresholds of 25 dB HL or better across audiometric frequencies from 250 to 4000 Hz, bilaterally (with the exception of two subjects who had one or two thresholds of 30 dB HL in one ear only). Due to the limited availability of older subjects showing no signs of hearing loss, thresholds at 6000 Hz and 8000 Hz were variable in the older group. At 6000 Hz, thresholds ranged from 10 dB HL to 50 dB HL across the two ears for all older subjects (mean threshold 26 dB HL). At 8000 Hz, thresholds ranged from 10 dB HL to 65 dB HL across the two ears for all older subjects (mean threshold 34 dB HL). Figure 1 shows the age distribution and the thresholds (averaged across left and right ears) as a function of frequency for the individual older subjects. All participants had normal tympanometry, were recruited from the Denver/Boulder metropolitan area, and passed a cognitive screening test, the Mini-Mental State Exam (Folstein et al. 1975). Listeners were paid \$10/hour for their participation. The experimental protocol was implemented in compliance with the Institutional Review Board at the University of Colorado Boulder.

To consider possible effects of musical training (c.f., Gfeller et al. 2012), participants completed a survey that asked about their musical backgrounds. The survey gathered rank-ordered responses for the amount of formal and informal musical training participants had received as well as their listening habits. Responses were provided as follows: number of total years of participation in musical activities, including self-teaching of music and community ensembles (0=0 years; 1=1–5 years; 2=6–10 years; 3=11–15 years; 4=16–20 years; 5=21+ years); highest level of formal music education including academic courses, private lessons, and school ensembles (0=no music education; 1=elementary school, 2=junior high, 3=high school; 4=college; 5=graduate school); and hours/week spent

listening to music (1=0–4 hours/week; 2=4–8 hours/week; 3=8–12 hours/week; 4=12–16 hours/week; 5=>16 hours/week).

Test Materials

Test materials were taken from the UW-CAMP (Kang et al. 2009; Nimmons et al. 2008). The UW-CAMP test is a validated computerized assessment that is designed to measure the ability of cochlear-implant recipients to accurately perceive several aspects of music. The UW-CAMP includes three subtests: pitch direction discrimination, melody recognition, and timbre recognition. The current study used two of the three subtests: melody recognition and timbre recognition.

Stimuli

Twelve common melodies were included in the melody recognition subtest: “Frère Jacques,” “Happy Birthday,” “Here Comes the Bride,” “Jingle Bells,” “London Bridge,” “Mary Had a Little Lamb,” “Old MacDonald,” “Rock-a-Bye Baby,” “Row Row Row Your Boat,” “Silent Night,” “Three Blind Mice,” and “Twinkle Twinkle Little Star” (Nimmons et al. 2008). Melodies were comprised of digitally synthesized tones of 500-ms duration. Rhythmic cues were eliminated by presenting 16 tones that were equal length in an eight-second period, at a tempo of 60 beats per minute, resulting in isochronous melodies. Melodies were played in the octave surrounding and above middle C, with the amplitude of individual notes roved by 4 dB. The CAMP subtest for melody included five prerecorded tokens of each melody, with one of the five tokens randomly selected for each stimulus presentation (Nimmons et al. 2008). See Nimmons et al. (2008) and Kang et al. (2009) for further details on stimulus generation for the UW-CAMP test melodies. The melodies included in the UW-CAMP software represented the unprocessed condition for the current study.

Eight common musical instruments were included in the timbre recognition subtest: cello, clarinet, flute, guitar, piano, saxophone, trumpet, and violin (Nimmons et al. 2008). The eight instruments represented the four major instrumental families: brass, strings, percussion, and woodwinds. The recordings were made by experienced musicians playing a melodic series of five notes on real musical instruments: C4-A4-F4-G4-C5. The notes were played at mezzo forte at 82 beats per minute. See Nimmons et al. (2008) and Kang et al. (2009) for further details on stimulus generation for the UW-CAMP test musical instrument stimuli. The musical instrument recordings included in the UW-CAMP software represented the unprocessed condition for the current study.

Stimulus Processing and Presentation

Both the melody and timbre stimuli were modified to create five different conditions. The first condition represents normal hearing and is referred to as the unprocessed (UNP) condition. The second condition simulates a traditional long-electrode cochlear implant using vocoding (VOC). The third condition simulates a shorter insertion electrode with some residual low frequency hearing and is called the simulated electro-acoustic stimulation condition (sEAS). For the final two conditions, the sEAS stimuli were partitioned into a high pass portion (sEAS[HP]) and low pass portion (sEAS[LP]).

In the UNP condition, the stimuli were bandpass filtered from 80–6000 Hz using a 12th order elliptical filter. In the VOC condition, the stimuli were processed with a noise-excited 8-channel vocoder. Vocoder simulations can be effectively implemented with either sine-wave carriers or noise carriers. In this study, we chose to use a noise carrier for two reasons. First, the use of a noise vocoder facilitates comparisons of the present work to other recent studies in our laboratory looking at age effects on electro-acoustic benefit for perception of

fundamental frequency of vowels (e.g., Souza et al. 2011; Arehart et al. 2011). Second, several studies have shown that simulations with noise carriers correspond more closely to performance by individuals wearing real cochlear implants than do simulations with sine-wave carriers (e.g., Stone, Fullgrabe, & Moore 2008; Souza & Rosen 2009). The VOC stimuli were first bandpass filtered into eight contiguous channels, based on the Greenwood frequency place map (Greenwood 1990), between 80 Hz and 6000 Hz, using a third-order Butterworth filter. Within each channel, the envelopes were obtained by half-wave rectification followed by low-pass filtering (using a fourth-order Butterworth filter with a 300-Hz cutoff). Each of the envelopes was modulated using an independent noise carrier. The individual channels were then added together, with the RMS level of each channel equalized to the level obtained from the initial eight-channel filtering. The resulting signals were band-limited by low-pass filtering at 6000 Hz using the same filter that was used for the UNP condition.

The sEAS stimuli were constructed by combining a low-pass unprocessed (acoustic) portion (sEAS[LP]) with a high-pass vocoded portion (sEAS[HP]). The low-pass filter for sEAS[LP] was implemented using a 512-point Hamming-windowed linear-phase finite impulse response [FIR] filter with a cutoff of 656 Hz, which corresponded to the frequency range of channels 1–3 of the vocoded stimulus (Souza et al. 2011). The high-pass portion extended above 656 Hz, and included channels 4–8 of the vocoded stimulus described above.

For the processed melody stimuli, each of the five original versions of the twelve melodies included in the UW-CAMP software was used to create five different vocoded versions of each melody. Because the UW-CAMP software included only one version of each of the instruments in the timbre subtest, it was important to eliminate concerns surrounding stationary noise artifacts for the simulated timbre stimuli. Therefore, five different versions of simulations (for both VOC and sEAS conditions) for each of the instruments were created, with each of the five versions based on a different noise sample.

Because it is important to consider the potential confounding effects of age-related changes in high-frequency auditory thresholds in older listeners, the presentation level of the stimuli was verified to be clearly audible to the older listeners. An analysis of excitation patterns of the musical stimuli (Moore et al. 1997; Moore & Glasberg, 1997) showed that the stimuli for all individual older subjects were at least a 10-dB sensation level at 4200 Hz, with the average sensation levels across 240–4200 Hz ranging from 20.4 dB to 36.0 dB for individual older listeners.

Stimuli were delivered in the sound field at 0° azimuth, at 65 dBA from the level of the listener's head, and in a double-walled sound treated booth. The UW-CAMP software was run on a Dell Vostro 1500 laptop. Due to the use of the additional noise tokens for the timbre subtest, MATLAB® (Mathworks, 2008) software was used to play out the stimuli and the graphical user interface for the timbre task, while the UW-CAMP software was used for the melody task. Stimuli were fed through an E-MU 0404 USB 2.0 Audio/MIDI Interface and then delivered through a Crown D-75A Amplifier and KEF iQ1 loudspeaker.

Procedure

Listeners participated in approximately four hours of testing divided over three visits: one initial visit (1 hour in duration) and two test visits (1.5 hours each). In the initial visit, familiarization was performed using commercial recordings of the 12 melodies in iTunes, over earphones, and including rhythmic cues. This step was taken to ensure that all subjects were familiar with the melodies when rhythmic characteristics were intact. All subjects indicated that they were familiar with all 12 melodies before further testing was performed. Following the melodic familiarization, subjects completed two practice blocks of

unprocessed melody recognition and unprocessed timbre recognition, to complete the initial visit. Each block included the following four components. The first component was melody practice in which subjects listened to each melody twice. The second component was the melody test in which subjects listened to a melody and then indicated which melody they heard, in a closed set. Each melody was tested three times in randomized order. The third component was timbre practice, in which subjects listened to each music instrument twice. The fourth component was the timbre test, in which subjects listened to a musical instrument and then indicated which instrument they heard, in a closed set. Each instrument was tested three times in randomized order. No feedback was provided on any trials. The results from the initial visit were not included in the final data set.

During each of the two test visits, subjects completed one test block in each processing condition, in randomized order, for a total of five test blocks. Each test block consisted of the same four tasks that were included in the initial visit: melody practice, melody test, timbre practice, and timbre test. As during the initial visit, the practice consisted of listening to each melody or musical instrument twice. The practice provided acclimatization to each stimulus condition prior to testing in that condition. The test sessions also followed the same procedure as during the initial visit, including three presentations of each melody or musical instrument in randomized order, with closed-set identification.

RESULTS

Figure 2 shows the proportion of trials in which younger and older listeners correctly identified melodies (top left panel) and musical instruments (bottom left panel) in the UNP, sEAS and VOC conditions. The melody and timbre data were arcsine transformed (Studebaker, 1985) and separately subjected to mixed-model analysis of variance (ANOVA) with a between-subject factor of group and a within-subject factor of processing condition. Greenhouse-Geisser corrections were used when Mauchley's test of sphericity was significant.

Mean scores for melody recognition were high (>93%) in both groups in the UNP and sEAS conditions. In the VOC condition, performance was lower (younger group - 37.5%; older group - 18.5%), but still well above chance (8.3%). Summarized in Table 1, the statistical analysis shows a significant main effect of processing and a significant interaction of processing by group. The between-subject factor of group was not significant. Pairwise comparisons with Bonferroni adjustments revealed that UNP was not significantly different from sEAS in either group ($p=1.0$), but both UNP and sEAS were significantly different from VOC in both groups ($p<0.001$). The significant interaction was driven by the poorer performance of older adults compared to younger adults in the VOC condition ($p=0.009$), with no significant between-group differences in the other two conditions (UNP: $p=0.765$; sEAS: $p=0.307$). In summary, both groups improved significantly in the sEAS condition compared to the VOC configuration.

In the timbre task, average instrument recognition scores were highest in the UNP condition (younger group - 96.5%; older group - 85.0%). Scores decreased both in the sEAS condition (younger group - 81.1%; older group - 64.2%) and in the VOC condition (younger group - 64.2%; older group - 37.1%). Mean performance in all conditions was well above chance (12.5%). Summarized in Table 2, the statistical analysis showed a significant main effect of processing and of age (based on the significant group difference), but the interaction between processing by age (group) was not significant. Pairwise comparisons with Bonferroni adjustments revealed that all conditions were significantly different from each other, across groups and analyzed separately in each group ($p<0.01$ for all comparisons). In addition, older adults performed significantly poorer than younger

adults in all conditions ($p < 0.01$). Thus, both groups showed significant and comparable improvement when comparing performance in the sEAS condition to that of the VOC condition (younger group – 16.9 percentage points; older group – 18.5 percentage points). In contrast to melody recognition, both groups of listeners also showed better performance in the UNP condition compared to the sEAS condition (younger group – 15.4 percentage points; older group – 29.4 percentage points).

To fully explore age effects related to the sEAS condition, performance was measured for the low-pass unprocessed portion (sEAS[LP]) and the high-frequency vocoded portion (sEAS[HP]) of the full sEAS stimulus. Figure 2 (right column) shows the proportion of trials in which younger and older listeners correctly identified melodies (top right panel) and musical instruments (bottom right panel) in the full sEAS, sEAS[LP] and sEAS[HP] conditions. Older and younger adults demonstrated the same patterns of performance in melody recognition. Melody recognition scores were very high ($> 93\%$) for both the full sEAS stimuli and the sEAS[LP] stimuli, and fell substantially for the sEAS[HP] stimuli (younger listeners – 37.5%; older listeners – 18.5%). Pairwise comparisons with Bonferroni adjustments showed that in both groups, scores for the full sEAS stimuli were not significantly different from scores for the sEAS[LP] stimuli ($p = 1.0$), but scores for both the full sEAS and sEAS[LP] stimuli were significantly different from scores for the sEAS[HP] stimuli ($p < 0.001$).

For timbre perception, older and younger adults differed in their patterns of performance for the full sEAS, sEAS[LP] and sEAS[HP] stimuli. For younger adults, the full sEAS scores (average 81.1%) were significantly better than the sEAS[LP] scores (average 67.4%) ($p = 0.004$) and the sEAS[HP] scores (average 56.6%) ($p < 0.001$). Thus, younger listeners benefited when they had access to both portions of the sEAS stimulus compared to either portion by itself. In contrast, older listeners did not show this benefit. For older adults, full sEAS scores (average 55.6%) were significantly better than the sEAS[HP] scores (average 39%) ($p < 0.001$) but were not significantly better than the sEAS[LP] scores (average 51.2%) ($p = 0.539$).

Finally, an analysis of the musical training survey showed that older and younger subjects did not differ significantly in terms of musical training (total score for all types of training and activities) [$F(1,19) = 0.23$; $p = 0.880$] or listening habits [$F(1,19) = 3.24$; $p = 0.088$]. Performance on melody and timbre tasks was not significantly correlated with musical training or listening habits for any condition ($p > 0.05$ for all comparisons).

DISCUSSION

Age Effects in the Use of Cues

The main goal of this study was to compare how older and younger listeners perceive melody and timbre in several hearing conditions: UNP, sEAS and VOC. Of primary interest was how age affects music perception when listeners have access to low-frequency cues (as in the sEAS condition) compared to when listeners are restricted only to envelope cues (as in the VOC condition). Older adults were predicted to have decreased melody recognition due to possible age-related deficits in the ability to make use of information from resolved low-frequency harmonics (available in the sEAS condition). This prediction did not hold true as reflected by the high melody recognition scores of the older subjects in the sEAS and sEAS[LP] conditions. However, the significantly lower melody and timbre recognition scores in the VOC condition support the original prediction that older listeners have a diminished ability to utilize envelope-only cues for music perception. The age effect found here for simulated cochlear-implant hearing is consistent with the Gfeller and colleagues (2008, 2012) who reported advanced age to be a negative predictor for melody recognition

in a large group of adults with traditional long-electrode cochlear implants. However, in contrast to Gfeller et al (2012), performance on the recognition tasks by our subjects was not significantly related to musical training.

Use and Integration of Cues in the sEAS Stimulus

The results of our study also provide insight into how younger and older listeners differ in the ability to use and combine the different types of cues in the sEAS stimulus. For melody recognition, performance in the full sEAS condition and in the sEAS[LP] condition were both comparable and at ceiling (>93%) for both groups of listeners. This result suggests that sEAS performance for melody recognition is driven by place or temporal fine structure information provided by low-frequency resolved harmonics (Smith et al. 2002; Oxenham 2008). High-frequency envelope cues did not confer any additional benefit to melody recognition. This finding is consistent with the studies of Kong et al. (2005) and Dorman et al (2008) who showed that improvement in melody recognition in electro-acoustic stimulation is primarily due to low-frequency hearing alone rather than the combination of cues provided by both acoustic and electrical hearing.

For timbre recognition, the groups of younger and older listeners differed in their abilities to use and combine the sEAS[LP] and sEAS[HP] components. As a group, younger adults benefited from use of the full sEAS stimulus, indicating that the combination of the low-pass acoustic component plus the high-pass vocoded component was superior to performance with either component alone. Hossain and Assmann (2012) also reported that younger listeners (ranging in age from 19 to 44 years) achieved higher scores on musical instrument identification for simulations of electro-acoustic hearing compared to simulations of cochlear-implant hearing. In contrast to the younger group, the older group was not able to leverage the additional high-frequency vocoded information that was available in the full sEAS condition. As has been suggested by Arehart et al. (2011) and Golub et al. (2012), the integration of multiple types of signals might add a level of complexity that is more difficult due to cognitive changes associated with aging.

It is also interesting to consider individual variability in the use and integration of cues in the sEAS stimulus. Figure 3 shows sEAS benefit (defined as performance for the full sEAS stimulus minus the performance for the sEAS[LP] stimulus) as a function of age for both melody recognition and musical instrument identification. Little intersubject variability is evident in benefit for melody recognition for either the younger or older listeners. In contrast, more variability across subjects is evident for timbre perception. While - as a group - older subjects did not show significant benefit from the integration of low and high frequency cues, four of the ten older listeners demonstrated modest benefit (10 to 15 percentage points). In addition, the benefit in the younger listeners varied from minimal (2 percentage points) to substantial (31 percentage points). The variability is consistent with other timbre studies that show that both normal-hearing younger listeners (McAdams et al. 1995; Samson et al. 2002) and listeners with cochlear-implants (Kong et al. 2012) vary in their weighting and use of the multiple cues (e.g., envelope, spectral shape, spectral detail) available for timbre perception. For example, Kong et al. (2012) reported that three out of seven listeners with cochlear implants in one ear and residual hearing in the other ear benefited in timbre perception from the combination of electric and acoustic cues. While not specifically related to timbre, Arehart et al. (2011) also reported substantial variability among the ability of both older and younger listeners to integrate low-pass acoustic information with high-pass vocoded information in a competing speech task.

The exact source(s) of the intersubject variability in sEAS benefit for timbre perception is unclear. However, it is possible that age - to some extent - serves as a mediating factor in the ability of listeners to access several types of cues important for timbre recognition. Timbre

perception relies on several sound attributes including spectral shape and temporal onsets and offsets (Heng et al. 2011; Kong et al. 2011; Moore, 2012). Older listeners might be less able to utilize these cues either due to auditory processing deficits associated with aging (e.g., Macdonald et al. 2010) and/or due to higher level (cognitive) deficits.

Clinical Implications

Because this study was based on simulations, the current results are limited in their direct application to clinical populations. While acknowledging this important caveat, the present results – together with studies of melody and timbre perception in listeners with real cochlear implant and electro-acoustic stimulation hearing systems – provide insights that will be helpful to consider in clinical contexts. A primary conclusion is that performance on a music perception task involves a complex interplay between the cues important for that task, the cues effectively conveyed by a particular hearing condition (or device) and the ability of the listener to make use of those cues. The current simulation study suggests that age plays an important role in this complex interplay. The findings suggest that older listeners will have degraded timbre and melody perception in traditional cochlear implant listening due to an age-related deficit in processing temporal cues (see also Souza & Boike 2006; Souza et al. 2011). The results also suggest that music perception by older listeners with cochlear implants will be improved with the addition of low-frequency residual hearing. The amount of improvement will depend on the extent to which low-frequency acoustic information can effectively deliver spectral and/or temporal cues to a compromised cochlea. In addition, these improvements might not be comparable for all dimensions of music perception. That is, more improvement might be evident for tasks that rely primarily on the low-frequency portion of the electro-acoustic stimulus (e.g., melody recognition) and less improvement might be evident in situations that require across-frequency integration of cues (e.g., timbre perception).

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This study considers how age affects how listeners with (near) normal hearing utilize envelope and fine structure cues in music perception. Older listeners showed decreased ability to process envelope cues in both melody and timbre recognition. Older listeners benefited from low-frequency fine structure information, though improvement was greater for melody compared to timbre. Advanced age affects the ability of listeners to utilize and integrate across-frequency cues required for optimal timbre perception. Though based on perception by normal-hearing listeners, this study suggests that music perception in older listeners will improve in electro-acoustic hearing configurations compared to traditional cochlear-implant hearing configurations.

Figure 1.

Characteristics of listeners in the older group are shown, including the audiograms averaged over the right and left ears (top panel) and the distribution of ages (bottom panel).

Figure 2.

Results for both younger and older listeners are shown for melody recognition (top left panel) and timbre recognition (bottom left panel) shown for the unprocessed (UNP), simulated electroacoustic (sEAS) and vocoded (VOC) conditions. Melody recognition (top right panel) and timbre recognition (bottom right panel) are shown for the following conditions: the full sEAS condition, the low-pass filtered portion of the sEAS (denoted here as [LP]) and the high-pass vocoded portion of the sEAS (denoted here as [HP]).

Figure 3.

Benefit for sEAS (defined as performance in the full sEAS condition minus the performance for the sEAS[LP] condition) is plotted as a function of age for both melody recognition and timbre perception.

Table 1

Summary of mixed-model analysis of variance (ANOVA) for arcsine-transformed percent correct scores for melody recognition. *Note.* Proc = processing

Effect	<i>df</i>	F	<i>p</i>	Partial η^2
Proc	1.56, 31.1	318.2	<0.001	0.941
Proc x Group	1.56, 31.1	5.7	0.013	0.220
Group	1, 20	0.1	0.730	0.006

Note. Proc = processing

Table 2

Summary of mixed-model analysis of variance (ANOVA) for arcsine-transformed percent correct scores for timbre recognition.

Effect	<i>df</i>	F	<i>p</i>	Partial η^2
Proc	2, 40	111.8	<0.001	0.848
Proc x Group	2, 40	0.4	0.649	0.021
Group	1, 20	75.3	<0.001	0.790

Note. Proc = processing