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4aAAb5. The sensitivity of hearing-impaired adults to acoustic attributes in simulated rooms

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In previous studies we have shown that older hearing-impaired individuals are relatively insensitive to changes in the apparent width of broadband noises when those width changes were based on differences in interaural coherence [W. Whitmer, B. Seeber and M. Akeroyd, J. Acoust. Soc. Am. 132, 369-379 (2012)]. This insensitivity has been linked to senescent difficulties in resolving binaural fine-structure differences. It is therefore possible that interaural coherence, despite its widespread use, may not be the best acoustic surrogate of spatial perception for the aged and impaired. To test this, we simulated the room impulse responses for an enclosure with varying surface absorption using room modelling software (ODEON). Bilaterally impaired adult participants were asked to sketch the perceived size of broadband noise, speech tokens and a musical instrument excerpt that were convolved with these impulse responses and presented to them in a sound-dampened enclosure through a 24-loudspeaker array. Participants' binaural acuity was also measured using an interaural phase discrimination task. Corroborating our previous findings, the results showed less sensitivity to interaural coherence in the auditory source width judgments of older hearing-impaired individuals, indicating that alternate acoustic measurements in the design of spaces for the elderly may be necessary.

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INTRODUCTION

Given the evidence of senescent changes to the auditory system (cf. Gordon-Salant et al., 2010), it is possible that there are related changes to our perception of auditory space. One potential change may occur along the dimension of width – the space that an auditory signal is perceived to occupy. Auditory source width has mostly been studied from the perspective of acoustic quality (i.e., its role in the overall subjective evaluation of spaces). From the perspective of grading auditoria, the acoustic similarity of the early reflections arriving at the two ears – the interaural coherence (IC) – has been repeatedly shown to be inversely proportional to the perceived width of that source (e.g., de villiers Keet, 1968; Barron, 1971).

In previous experiments, we used broadband noises of varying IC to examine the perception of source width in hearing-impaired (HI) individuals. Mixing two independent noises to control coherence over headphones (Plenge, 1972), we found that younger normal-hearing (NH) participants sketched increasingly larger sources with decreasing IC. Older HI participants, however, sketched sources that did not vary in width with IC (Whitmer et al., 2012). In a follow-up experiment, we presented two independent, ±45° low-pass, high-pass or speech-spectrum noises that were attenuated re a center noise to vary IC in a room. Some HI participants (those who exhibited an ability to detect interaural phase differences) sketched wider images to more incoherent stimuli, but not to the same extent as NH participants. HI participants who could not detect interaural phase differences sketched source widths that did not vary with IC (similar to the previous headphone results). Those participants appeared to not base their judgments of width on interaural coherence, nor on sensation level, but on the envelopment caused by varying the signal level to achieve the same sensation level. Merimaa and Hess (2004) found that sounds convolved with impulse responses taken from a large fan-shaped hall produced broad images for NH listeners despite those impulse responses having a high IC. Other factors, such as the (monaural) reverberation time – the time for the sound to decay 60 dB SPL from onset – or the lateral-energy fraction – the power from the left and right lobes relative to total power – can also affect the percept of auditory source width. It is therefore possible that interaural coherence, despite being a prominent measure for all auditoria (cf. Beranek, 2008), may not be the best acoustic surrogate of spatial perception for the aged and impaired. If so, this change in the importance of acoustic attributes could be relevant to the design of spaces for the aged and impaired as well as to spatial processing by hearing aids.

To examine how HI participants may use different cues to perceive the spatial extent of sound sources, the current study used modeled room impulse responses to present stimuli that varied along multiple measures of auditoria: interaural coherence (IC), lateral-energy fraction (LF) and reverberation time (RT). Impulse responses were based on fixed source and receiver positions in a room with varying absorption coefficients (α), which dictate the proportion of sound that is absorbed. Four sound sources were chosen to vary in spectral content and envelope while all being broadband: (1) speech-spectrum noise, (2) a word with sudden, labial plosive onset ("boast"), (3) a word with a slow coronal fricative onset ("zeal"), and (4) a bowed string instrument with amplitude modulation (vibrato). A correlation between the sketched widths of incoherent stimuli and interaural phase discrimination was found in our previous study, so the same procedure, based on Hopkins and Moore (2010) was used again to distinguish participants into those with and without low-frequency binaural temporal fine-structure (TFS) resolution.

METHODS

Participants

Fourteen HI adults (8 female) aged 42-73 years were recruited from a pool of available attendees at clinics of the local hospitals. Five NH adults (1 female) aged 23-40 years were recruited from the employees of the Institute. Pure-tone airborne and bone-conduction thresholds were assessed in a sound-dampened booth (1.5 × 1.3 × 2 m) using the modified Hughson-Westlake method (British Society of Audiology, 1981).

Participants' binaural temporal fine-structure thresholds were also measured in the same booth through circumaural headphones using the Hopkins and Moore method (2010). The binaural TFS task stimuli were sequences of four 500-Hz sinusoids of 400 ms duration, onset/offset gates of 50 ms and gaps of 20 ms. For the probe stimulus, all tones were diotic. For the target stimulus, the second and fourth tones had an interaural phase difference (IPD) that was geometrically adjusted – multiplied/divided by 1.25^3, 1.25^2 and 1.25 for the first, second and third-eighth reversals, respectively – using a three-up/one-down rule in two-alternative adaptive procedure. The probe and target were presented in random order on each trial at 55 dB A. The interstimulus interval was 200 ms. Participants were first presented with examples of the probe stimulus and the target stimulus with a 180° IPD then ran 5-10 practice trials with the same 180°-IPD target stimulus. Thresholds – if obtainable – were computed from the average of the IPD at the last six reversals.

TABLE 1. Participant list, showing group, age (years), left and right ear four-frequency average thresholds (4FA; dB HL), air-bone conduction gap (dB HL) and binaural TFS threshold (°).

Subject	Group	Age	L 4FA	R 4FA	A-B gap	TFS threshold
1	NH	39	6.25	3.75	5	7.7
2		40	8.75	1.25	7.5	9.3
3		26	7.5	2.5	2.5	10.4
4		28	1.25	3.75	6.25	11.2
5		23	2.5	3.75	7.5	14.0
6	HI+TFS	42	26.25	45	11.25	25.4
7		66	38.75	37.5	13.75	26.4
8		63	35	45	10	30.6
9		73	40	41.25	6.25	33.0
10		60	32.5	32.5	6.25	36.9
11		63	38.75	61.25	2.5	62.0
12		69	43.75	42.5	10	64.4
13	HI-TFS	65	81.25	45	5	--
14		70	37.5	40	2.5	--
15		70	42.5	65	10	--
16		71	46.25	37.5	0	--
17		72	38.75	36.25	6.25	--
18		56	28.75	32.5	11.25	--
19		70	62.5	68.75	5	--

Apparatus

For the sketching task, participants were seated in a sound-dampened room (2.5 × 4.4 × 2.5 m) in the middle of a circular array of 24 loudspeakers spaced at 15° with a 0.9-m radius. The stimuli were presented from an outboard signal processor (MOTU 24), digital-to-analog convertor (Fostex VC-8), attenuator (Behringer Ultralink) and powered loudspeakers (Phonic 207). Responses were given with a touch screen monitor directly in front of the participant and just below the level of the loudspeakers.

Stimuli

Participants were presented with four different source signals: (1) long-term average speech-spectrum noise (LTASS), (2) the single-syllable word token "zeal" taken from the FAAF corpus (Foster & Haggard, 1987), (3) the word token "boast" from the same corpus, and (4) a violin playing C4 with vibrato. All stimuli were originally recorded at 16 bits, 44.1 kHz in anechoic conditions. All stimuli were 500 ms in duration with 20-ms onset/offset gates and were presented at a long-term average A-weighted level of 65 dB SPL. The level was increased to 85 dB A for participant 19.

Using room modeling software (ODEON), a rectangular 5 × 8 × 3 m enclosure was simulated with a point source at 2.5 × 1 × 1.5 m and a receiver at 2.5 × 5 × 1.2 m (i.e., a source-receiver distance of 4 m). All surfaces were assigned the recommended scattering coefficient of 0.05 and absorption coefficient (α) values of 0.1-0.9 across all frequencies. Using a maximum of 5000 reflections, one-second room impulse responses were generated at each α value. Three common measures of acoustic quality were calculated from these impulse responses: the interaural coherence of the early (0-80 ms) arriving sound [IC(E)], the lateral-energy fraction (LF) and the reverberation time (RT60). The LF was calculated by taking the sum of the loudspeaker output multiplied by the appropriate normalized values from a bi-cardioid response and dividing by the total output. These calculations are shown in Table 2.

TABLE 2. The interaural coherence of the early reflections [IC(E)], lateral-energy fraction (LF) and reverberation time (RT60) for all simulated rooms with absorption coefficient α on all surfaces.

					α				
Measure	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
IC(E)	0.18	0.30	0.29	0.41	0.43	0.54	0.60	0.77	0.89
LF	0.57	0.53	0.47	0.38	0.28	0.19	0.10	0.04	0.01
RT60 (s)	1.17	0.60	0.40	0.30	0.24	0.20	0.17	0.15	0.14

A 24-channel impulse response based on the location of each loudspeaker in the circular array was generated using the auralization system developed by Favrot and Buchholz (2010). Examples of the first 100 ms of these responses for rooms with α values of 0.2, 0.5 and 0.8 are shown in Figure 1. These responses were then convolved with the four signals for presentation. The IC(E) and LF for each particular convolution (i.e., room ∗ signal) were used in the correlation analysis of the results.

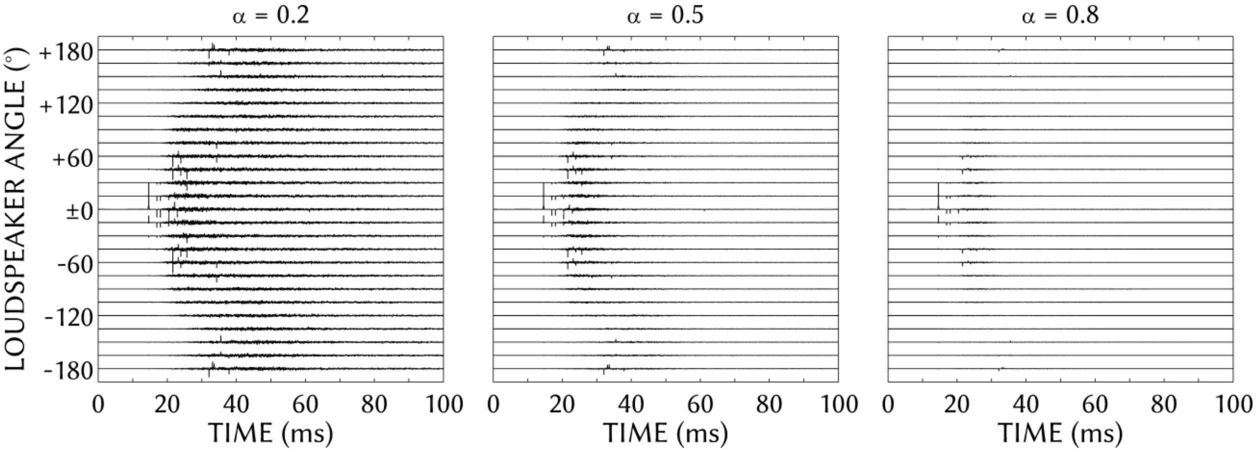

FIGURE 1. First 100 ms of the 24-channel impulse responses (for presentation from a circular loudspeaker array with loudspeakers at 15° intervals) for simulated rooms with absorption coefficients (α) on all surfaces of 0.2 (left), 0.5 (middle) and 0.8 (right panel). The loudspeaker angles are given from left at the bottom to right at the top. The modelled room dimensions were 5 × 8 × 3 m with the source at an [*x*, *y*, *z*] position of [2.5, 1, 1.5] and receiver at [2.5, 5, 1.2] (i.e., both source and receiver equidistant from the long wall and 4 m apart).

Procedure

For each trial of the sketching task, participants were asked to sketch the width of the stimulus heard onto a touch screen displaying a 912 × 558 pixel image (see Figure 2). The image showed a room with the same relative dimensions as the simulated room used for the stimuli from the perspective of the midpoint of the shorter wall. Participants were asked to consider that they were sitting in this arbitrary room. When the participant touched the screen, a red 8 × 8 pixel square appeared centered at the contact point. Prior to testing, participants were given a demonstration of how to use the touch screen for sketching, then given an example of each signal type convolved with the α = 0.1 and 0.9 room impulse responses (i.e., eight trials consisting of the extreme cases of low and high reverberation). After this familiarization step, participants sketched the apparent source widths of four presentations of each stimulus and room type for a total of 144 trials. The stimuli were presented in randomized order. The perceived width was measured as the difference between the left and rightmost extent of each sketch.

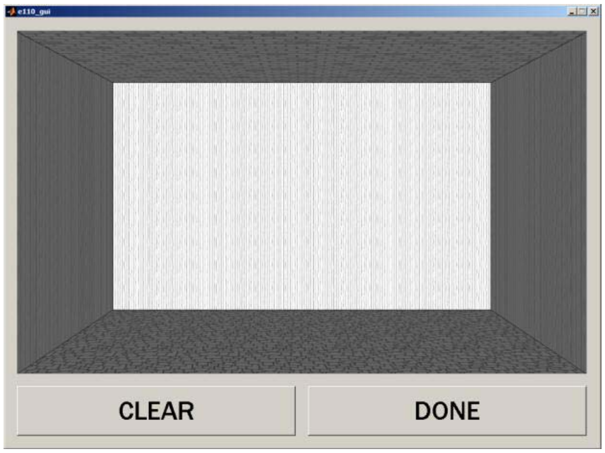

FIGURE 2. Example of experimental interface for sketching task.

RESULTS

For each signal type and room α, sketched widths were calculated from the average of the four repeats of each stimulus presented to each participant. Figure 3 shows the mean widths (different symbols), 95% repeated-measures confidence intervals (error bars) and exponential fits to the data (same colors as symbols) across NH participants, HI participants with TFS data (HI+TFS) and HI participants without TFS (HI-TFS) data in separate panels. The NH data showed a clear, significant decrease in width with increasing α for all signal types, from an average of 592 pixels (i.e., approximately the entire extent of the back wall of the image shown to participants) for an α of 0.1 to an average of 68 pixels for an α of 0.9. Post hoc analysis reveals that the widths of the violin signal (green triangles in Fig. 3) were sketched significantly smaller ($p < 0.05$) overall than the other signals. Both the HI+TFS and HI-TFS data also exhibited a significant decrease in width with increasing α, but not to the same extent, ranging on average from 471 to 258 and 341 to 243 pixels, respectively. For the HI-TFS group, widths did not significantly vary for the LTASS noise.

To examine the role of different acoustic measures, the Pearson product-moment correlation coefficients were computed for the logarithm of individual widths for each signal type as a function of the IC, LF and RT separately for the respective signal convolved with each room α. The correlation coefficients, averaged across participants and stimuli are shown in the bottom left of each panel in Figure 3. To determine which of the given room measures might be a better predictor of perceived width, the Williams' T2 test (a modified t test for comparing correlations within samples; Steiger, 1980) was used. For the NH group, LF was significantly more correlated with width than either IC [$t(34) = 3.20$; $p < 0.01$] or RT [$t(34) = 3.74$; $p < 0.001$]. For either of the HI groups, none of the measures were significantly more correlated to width than the others.

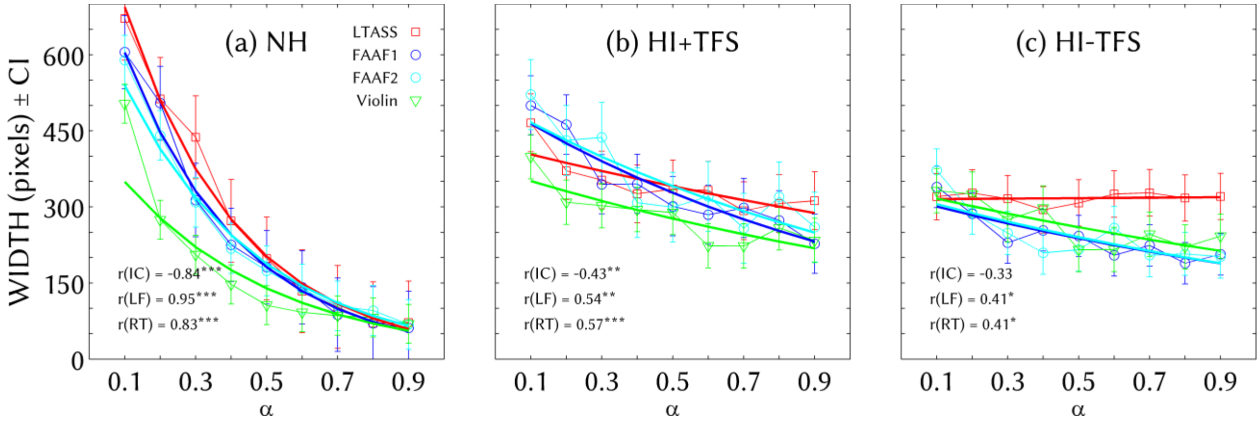

FIGURE 3. Mean sketched widths as function of absorption coefficient (α) and signal type: long-term average speech spectrum (LTASS) noise (red squares), the word "zeal" (FAAF1; blue circles), the word "boast" (FAAF2; cyan circles) and violin vibrato C4 (green triangles). Solid lines in respective colors show exponential fits to the data. Error bars show 95% repeated-measures confidence intervals. Correlation coefficients (*r*) for mean widths as a function of interaural coherence (IC), lateral fraction (LF) and reverberation time (RT) are given in the bottom left corner of each panel (asterisks refer to $p < 0.05$, 0.01 and 0.001 significance, respectively). The left panel (a) shows results from NH participants, the middle panel (b) shows results from HI participants with TFS data, and the right panel (c) shows results from the HI participants without TFS data.

Since the acoustic measures were correlated with one another (see Table 2), partial linear correlations between width and these measures, accounting for variance due to the other measures, were also computed for each signal type as well as participant group (with conservative Bonferroni corrections for multiple comparisons). For the NH group, IC was not significantly correlated with width when accounting for the variance in width due to either LF or RT. Both LF and RT were significantly correlated with width when accounting for IC (r = 0.81-0.99; all $p < 0.05$). For the HI+TFS group, there was the same pattern in findings: both LF and RT were significantly correlated with width when accounting for IC (r = 0.82-0.96; all $p < 0.05$), but IC was not significantly correlated with width when accounting for either LF or RT. The only exception was for LTASS noise, for which LF was not significantly correlated to width when accounting for IC. For the HI-TFS group, RT was significantly correlated with width when accounting for either IC or LF, but only for the two word signals ("zeal" & "boast"). There were no other significant partial correlations for the HI-TFS group.

TABLE 3. Multiple un-normalized linear-regression coefficients (β) for source width as a function of interaural coherence (IC), lateral-energy fraction (LF) and reverberation time (RT) for each signal type and participant group. R^2 approximates goodness-of-fit. Coefficients in boldface are significantly non-zero.

Signal	Group	β(IC)	β(LF)	β(RT)	β_0	R^2	F
LTASS noise	NH	**-0.63**	**1.38**	**0.08**	**2.36**	0.99	201.6***
	HI+TFS	**-0.01**	**0.03**	**0.16**	**2.48**	0.94	26.1**
	HI-TFS	0.03	-0.01	0.02	2.48	0.13	0.3
FAAF1 "zeal"	NH	**-0.04**	**1.69**	**0.15**	**1.78**	0.99	205.7***
	HI+TFS	**0.02**	**0.38**	**0.13**	**2.36**	0.92	19.4**
	HI-TFS	0.03	0.13	0.16	2.26	0.75	5.1
FAAF2 "boast"	NH	**-0.67**	**1.23**	**0.07**	**2.46**	0.97	51.5***
	HI+TFS	**-0.09**	**0.33**	**0.10**	**2.49**	0.83	8.1*
	HI-TFS	**-0.18**	**-0.25**	**0.31**	**2.43**	0.91	16.0**
Violin	NH	**-0.56**	**0.68**	**0.37**	**2.30**	0.98	74.0***
	HI+TFS	**-0.22**	**0.18**	**0.09**	**2.54**	0.88	12.2**
	HI-TFS	-0.20	0.003	0.13	2.52	0.57	2.2

To further examine potential patterns and changes in the contributions of the given acoustic features to the different participant groups' width judgments, un-normalized multiple linear regressions with mean width as an exponential variable [i.e., $\log_{10}$(width)] were performed. The coefficients are shown in Table 3. Regression coefficients were significantly non-zero across signal types for both the NH and HI+TFS groups; coefficients for HI-TFS data were only significant for the the word token "boast" (FAAF2). For the NH group, unique weightings were given to both the word token "zeal" (FAAF1) and Violin stimuli, whereas weightings for LTASS noise and the token "boast" were quite similar. For the HI+TFS group, the weighting of LF was greater for the two word tokens than the two non-speech stimuli. The weighting of RT for the HI+TFS group was similar across signals, and proportionally much greater than for the NH group.

DISCUSSION

The data here show a reduced range in perceived widths by older HI individuals compared to younger NH individuals when listening to stimuli presented in simulated rooms. This accords with our previous published study (Whitmer et al., 2012). Unlike that study, where the sounds had the same interaural coherence from onset to offset, the stimuli here had the natural acoustic decay of the sounds in the prescribed space. This aspect may have affected the general width of judgments. In our previous free-field study, the HI individuals that were able to discern interaural phase differences sketched narrow widths on average for noises varying in interaural coherence (IC). In the current study, the HI individuals able to discern interaural phase differences (the HI+TFS group) sketched, on average, images that while not as wide as the NH images for the lowest α, were wider than the NH images for the highest α.

For this particular testing scheme, it appears that both lateral-energy fraction LF and RT contribute more than IC to both NH and HI participants' perception of auditory source width. While this seems to be contrary to previous studies in auditoria (cf. Beranek, 2008), there are several key differences in method. First, the current study was directly interested in the study of *width*, not the *quality* of it per se. Second, the rectangular room as opposed to the complex performance enclosures normally used most likely had an influence on how width was perceived. Unlike large halls with long reverberation times that can produce long RT *and* high IC (e.g., Merimaa & Hess, 2004), the simulated smaller 5 × 8 × 3 m room of the current study had highly correlated acoustic factors, making subsequent weighting analysis difficult.

While three imperfect correlational comparisons do not constitute a complete analysis, the results above do indicate that when sketching width, non-coherence factors play a larger role. Several of the HI participants had asymmetries greater than 15 dB HL, yet showed similar sketching results to other, symmetrically impaired participants. We interpret this to be further signs of these HI participants relying more on monaural characteristics – reverberation time, and to a lesser degree, lateral-energy fraction (which monaurally would be a frequency-dependent level change) – for the perception of width than NH participants. The current study demonstrates changes in the importance of particular measures to spatial impression with age and impairment that should be considered in the design and evaluation of spaces targeted to these populations.

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REFERENCES

Barron, M. (**1971**). "The subjective effects of first reflections in concert halls: The need for lateral reflections," J. Sound Vib. **55**, 475-494.

Beranek, L. (**2008**). "Concert hall acoustics – 2008," J. Audio Eng. Soc. **56**, 532-544.

British Society of Audiology. (**1981**). "Recommended procedures for pure tone audiometry using a manually operated instrument," Br. J. Audiol. **15**, 213-216.

Favrot, S., Buchholz, J. (**2010**). "LoRA: A loudspeaker room auralization system," Acta Acustica **96**, 364-375.

Foster, J., and Haggard, M. (**1987**). "The four alternative auditory feature test (FAAF): Linguistic and psychometric properties of the material with normative data in noise," Br. J. Audiol. **21**, 165-174.

Gordon-Salant, S., Frisina, R., Fay, R., Popper, A. (eds.) (**2010**). *The aging auditory system*, Springer, New York.

Hopkins, K., and Moore, B. (**2010**). "Development of a fast method for measuring sensitivity to temporal fine structure information at low frequencies," Int. J. Audiol. **49**, 940-946.

de villiers Keet, W. (**1968**). "The influence of early lateral reflections on the spatial impression," Proceedings of the Sixth International Congress on Acoustics, Tokyo, Japan, pp. E2-E4.

Merimaa, J., Hess, W. (**2004**). "Training of listeners for evaluation of spatial attributes of sound," Proceedings of the 117th Convention of Audio Engineering Society, San Francisco, California, Preprint 6237.

Plenge, G. (**1972**). "Über das problem der im-kopf-lokalisation (On the problem of in-head localization)," Acustica **26**, 241-252.

Whitmer, W., Seeber, B., and Akeroyd, M. (**2012**). "Apparent auditory source width insensitivity in older hearing-impaired individuals," J. Acoust. Soc. Am. **132**, 369-379.

Whitmer, W., Seeber, B., and Akeroyd, M. (**2013**). "Measuring the apparent width of sound sources in normal and impaired hearing," in B. Moore, R. Patterson, I. Winter, R. Carlyon and H. Gockel, eds., *Basic aspects of hearing*: *Advances in experimental medicine and biology 966*, Springer-Verlag.

Whitmer, W., Seeber, B., and Akeroyd, M. (in preparation). "The perception of auditory source width using interaural coherence for hearing-impaired individuals," J. Acoust. Soc. Am.