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The effect of hearing-aid compression on judgments of relative distance

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Abstract

The overall level of a sound is an important auditory cue to distance in rooms, but this cue might be affected adversely by the amplitude compression found in most modern hearing aids because this explicitly changes levels. This prediction was tested using a synthetic-distance design to measure the just-noticeable difference (JND) in distance from distances of 2 m or 5 m. Twenty six aided listeners participated. The results did not show any effect of compression ratio upon JNDs. A possible interpretation is that the listeners had acclimatized to the effect their aids have on level.

I. INTRODUCTION

The auditory perception of the distance of sound sources in rooms is based mainly on level (for reviews, see Coleman, 1963; Blauert, 1997; Zahorik *et al.*, 2005). One cue is the overall level of a sound: the farther away a source is, the less intense is the sound that arrives at a listener. In an anechoic environment, the rate of reduction of level is 6 dB per doubling in distance (i.e., an inverse-square law), but for other environments the rate is somewhat less. A second cue, but one which can only be used when there is a substantial amount of reflections or reverberation (i.e., echoic environments), is the ratio of the level of the first-arriving sound to the level of the remainder; the larger this is, the closer is the sound source (see Zahorik, 2002b, for a discussion of how this ratio could be measured). There are two other acoustic cues to distance, though of less relevance to sources in most rooms as they only affect particularly distant or close sources. If a source is farther than about 15 meters then absorption by the air affects high frequencies more than low frequencies (Blauert, 1997), while if the source is closer than about 1 meter then the interaural time and level differences that indicate direction can be affected (Brungart *et al.*, 1999).

As self-report data have shown links between difficulties in distance perception and auditory disability (Gatehouse and Noble, 2004), Akeroyd *et al.* (2007) developed an experimental paradigm to study judgments of relative distance by hearing-impaired listeners. The paradigm used the “room-image” method (Allen and Berkeley, 1979) to calculate the angle of arrival, time of arrival, and level at arrival of the direct sound and the first 74 reflections at a listener placed in a virtual 7×9 m room. Each of these 75 sounds was then presented using a circular array of loudspeakers, at the required level, required time, and from the loudspeaker closest to the required angle (c.f. Hafter and Seeber, 2004). The result is a recreation of what would have been heard in the room. The system gives a vivid percept of distance, with the sound appearing to come from farther away than the actual loudspeakers.¹

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Akeroyd *et al.* (2007) measured just-noticeable differences (JND) in distance in four tasks, using two reference distances (2 and 5 m) crossed with two comparison directions (either closer-than or farther-than the reference). These JNDs were measured under conditions termed “normal level”, in which the overall level variation due to the inverse-square law was included, and “equalized level”, in which this variation was removed. The stimuli were single sentences. For the “normal-level” conditions it was found that the JNDs were largest for the farther-than-5-m task and smallest for the closer-than-2-m task, consistent with the typical result that thresholds for distance discrimination generally increase with farther reference distances (Zahorik *et al.*, 2005). In general, the results for the hearing-impaired listeners did not differ from those of the normal-hearing listeners, excepting (1) in the farther-than-5-m task the group of hearing-impaired listeners performed more poorly than an age-matched normal-hearing group, and (2) everyone with a hearing-loss of more than about 25 dB performed at chance in the “equalized-level” conditions.

Level is crucial to distance perception, but the deliberate purpose of a hearing-aid compressor is to control level (for a review, see Moore, 2008). An ideal fast-acting compressor will reduce the instantaneous fluctuations in level inherent to speech or dynamically-changing backgrounds, and so can improve the audibility of the weaker parts of a speech signal (e.g., Dillon, 2001). An ideal slow-acting compressor will instead act as an automatic volume control, adjusting the gain when the listener moves from one environment to another. Compression creates a nonlinear relationship between the actual level of a sound and that received by the listener via the hearing aid, thus alleviating some of the effects of loudness recruitment that would be not compensated by a linear (i.e., non-compressive) hearing aid. But compression should therefore adversely affect distance perception, as it should interfere with the levels of sounds upon which distance perception is based. Thus, it was felt valuable to study experimentally the effects of hearing-aid compression on judgments of relative distance. The experiment reported here repeated the “normal-level” conditions of Akeroyd *et al.* (2007), using a sample of 26 aided listeners from our research panel. Each listener wore their own aids: the sample included listeners with two linear aids, or two compressive aids, or one of each, and with a variety of gains and compression settings.

II. EXPERIMENTAL METHOD

The method was the same as that used by Akeroyd *et al.* (2007). Briefly, the room-image method (Allen and Berkeley, 1979) was used to calculate the azimuths, time delays, and level differences of the direct path and the first 74 echoes in a virtual 7×9 m room. The virtual listener was placed near one corner and the sources were set to be at distances from it of 1 to 8 m, along a diagonal of the room. These calculations were then used to determine the choice of actual loudspeaker, time delay, and attenuation used to present a stimulus and 74 copies of it. The loudspeakers were arranged in a circle, at 15° intervals, with the listener at the center, and were placed in a room that was 2.5 m wide by 4.4 m long by 2.5 m tall. The room was not anechoic, but its walls were acoustically treated with sound-absorbing foam to reduce its reverberation time to an average across frequency (250-8000 Hz) of about 80 ms. The average A-weighted background level was about 20 dB (for further details see Akeroyd *et al.*, 2007, especially Figures 1 and 2).

A two-interval, two-alternative forced-choice method was used to determine psychometric functions for judgments of relative distance. Forty eight trials per point were run for each

¹For a full discussion of the system see Akeroyd *et al.* (2007). It is worth noting here (1) that the system uses loudspeakers, not headphones, and therefore avoids the problems due to individualization of HRTFs that can affect virtual acoustics; but (2) the system is limited to presenting sounds in the horizontal plane; and (3) coloration of reflections is not (yet) implemented.

psychometric function. In the reference interval the simulated distance was either 2 m or 5 m. In the comparison interval the simulated distance was either 1.00, 1.33, 1.67, 2.00, 2.33, 2.67, or 3.00 m (for the 2-m reference), or 2, 3, 4, 5, 6, 7, or 8 m (for the 5-m reference). The order of the intervals was randomized across trials, and they were separated by an inter-stimulus interval of 1200 ms (Akeroyd *et al.* used 500 ms; the change was made here in order to give the hearing aid compressors longer to stabilize between stimuli). Just-noticeable differences (JNDs) were measured for four conditions, corresponding to changes in distance closer than a reference of 2 m (“2-closer”), farther than 2 m (“2-farther”), closer than 5 m (“5-closer”), and farther than 5 m (“5-farther”) (unless otherwise stated, all the statistics for the data reported below are listed as quadruplets, in the order 2-closer / 2-farther / 5-closer / 5-farther). The JNDs were found from fitting psychometric functions to the data and then finding the change in distance corresponding to a d' of 1.0. The psychometric function was based on the assumption that the detectability of a change in distance (d') was proportional to the value of the change. The stimuli in the two intervals were short spoken sentences, one spoken by a female and the other by a male; the gender of the sentences used for the reference and comparison distances was randomized across trials (the sentences were chosen randomly from the “BKB” and “ASL” corpora; Bench and Bamford, 1979; Macleod and Summerfield, 1990). Listeners were required to decide which of the sentences was farther away. No feedback was given. The level of the stimuli was set so that a very long sequence of “ASL” sentences set to a synthesized distance of 2 m gave an long-term average level of 65 dB(A) at a microphone at the center of the loudspeaker ring.

Twenty six listeners participated, aged 45 – 78 years (mean = 65 years), with better-ear average hearing losses (average of pure-tone thresholds at 500, 1000, 2000, and 4000 Hz, termed “BEA”) of 28 – 84 dB (mean = 57 dB) and worse-ear losses of 33 – 98 dB (mean = 66 dB). They were chosen from the pool available to the Institute of Hearing Research, sourced from postal surveys, attendees at local clinics, and occasional other sources.

All the listeners were experienced hearing-aid users, and wore their own aids that had been fitted by the local audiological services. The aids came from a variety of manufacturers: Unitron, Siemens, Oticon, Phonak, Puretone, and Microtech. The compression parameters of the hearing aids were derived from measurements of their output levels for input levels from 55 to 75 dB SPL at frequencies of 500, 1000, 2000, and 4000 Hz, which were collected using a hearing-aid analyzer (Siemens Unity 2).² It was convenient to have a simple overall classification of whether an aid was linear or compressive: if the measured compression ratio between 60 and 65 dB SPL, at 1000 Hz, was greater than 1.25, then the aid was considered as compressive. Twenty eight of the aids were so classified: for these, the median compression ratios at 250, 500, 1000, 2000, and 4000 Hz were 1.02, 1.3, 1.8, 1.8, and 1.6. Nine listeners wore two linear aids (termed “linear/linear”), six listeners wore one linear aid and one compressive aid (“linear/comp”), and eleven listeners wore two compressive aids (“comp/comp”).

III. RESULTS

Figure 1 shows the JNDs, in meters, for the judgments of distance. The open circles plot the data from the linear/linear listeners, the diamonds the data from the linear/comp listeners, and the hourglasses the data from the comp/comp listeners. The dots re-plot the JNDs measured using 77 *unaided* listeners from Akeroyd *et al.* (2007). Each line shows an exponential curve fitted to the data for the *unaided* listeners (i.e., $\text{JND} \propto e^{cH}$, where H is the

²Three other listeners also participated, but for them either no or unreliable compression data were obtained, and so their results are excluded.

hearing loss and c is a constant): the lines were calculated over BEAs from 20 to 59 dB — the largest hearing loss included in Akeroyd *et al.* (2007) — and then extrapolated to the larger hearing losses of the present aided listeners. The scatter in the data points for the aided listeners is comparable to that found for unaided listeners, and there was no obvious effect of hearing-aid compression: none of the aided groups yielded thresholds substantially above the extrapolation from the unaided listeners. This was demonstrated by calculating the difference between the measured JND for each aided listener and the predicted JND given the curve-fit to the data for the unaided listeners, and then comparing, by one-sample t -test, the across-listener means of the differences from zero; all four were non-significant ($t(25) = 1.3, 0.79, -0.71, -0.94$; $df = 25$; $p > 0.05$).

A set of four one-way ANOVAs showed no significant effect of compression, in that the differences between the three groups of data for aided listeners — i.e., linear/linear *vs.* linear/comp *vs.* comp/comp — were not statistically significant for any of the JNDs ($F(2, 23) = 0.83, 1.91, 1.32, 0.46$, all $p > 0.05$). A correlation analysis confirmed this: a large number of correlations were calculated between each of the four JNDs and some measure of compression ratio, but all were found to be non-significant.³ Figure 2 illustrates one of these analyses: the four panels show the four JNDs as a function of the 60-65 dB compression ratio, averaged across 250, 500, 1000, 2000, and 4000 Hz and then across ears. The lack of any effect of compression ratio is clear.

IV DISCUSSION

This experiment did not demonstrate any substantial or reliable effect of hearing-aid compression on judgments of relative distance. This was somewhat unexpected, as the cues to auditory distance are based on the levels of sounds and the purpose of hearing-aid compression is to modify level.

The expectation is particularly clear where the inverse-square law dominates, and the overall level reduces at a rate of 6 dB per doubling of distance. The formal relationship for the level difference ΔL between distances d_1 and d_2 is thus $\Delta L = 6\log_2 d_2 - 6\log_2 d_1$. But, by the definition of compression ratio, a change in the output of a hearing aid of 1 dB requires a C dB change in its input, where C is the value of the compression ratio. If the JND for distance is determined by the value of ΔL received by the listener — i.e., *after* compression — then it depends on ΔL before compression and the reference distance d_1 thus:

$$JND_C = (2^{C\Delta L/6} - 1) d_1, \quad (1)$$

where the JND is taken as the difference, in meters, between d_1 and d_2 . The ratio of the JND with compression (JND_C) to the “normal” JND without compression (JND_N) is therefore

$$\frac{JND_C}{JND_N} = \frac{2^{C\Delta L/6} - 1}{2^{\Delta L/6} - 1}. \quad (2)$$

³For these analyses any compression ratio found to be larger than 10 was reset to 10. This was done as any larger than 10 were felt to be adversely affected by experimental error — recall that they were derived from input/output functions over a 5-dB range — and therefore unreliably large. Almost 150 separate measures of compression were obtained, using compression ratios calculated from the hearing-aid input/output functions at 55-60, 60-65, or 70-75 dB SPL, taken either at individual octave frequencies from 250 to 4000 Hz or various averages of, and either the least compressive across ears, the most compressive, or the average across ears. As a large number of correlations were conducted, a Bonferroni correction was applied to the α level for statistical significance. Even without this correction, however, only three of the correlations had a probability less than the conventional α of 0.05. Given such a small number — each of which involved a compression ratio measured at 3000 Hz but no other frequency — it is not clear that these occasional correlations offer any predictive insight or reliability.

For example, if the limiting value of ΔL is 2 dB and the compression ratio is 3, then the JND will be 3.8x its non-compressive value. For small values of ΔL and compression ratio, Equation 2 can be approximated by the power function, $\text{JND}_C/\text{JND}_N \approx C^p$, where the exponent p equals 1.25 for a ΔL of 2 dB and a range of C of 1-4.⁴ Thus, the JND with compression should depend strongly on the value of the compression ratio.

At least three reasons can be offered as to why this effect was not observed. It may be the case that hearing aids have their effects in the overall scale of the perceived auditory world rather than in relative judgments within that world. Given that in normal hearing the perceptual scale of auditory distance is a compressive function of physical distance, with listeners generally underestimating how far away a sound actually is (summarized by Zahorik, 2002a, & Zahorik et al., 2005), it is possible that a compressive hearing aid may exacerbate this by further reducing the scale of the auditory world. This could be tested experimentally by including judgments of absolute distance in the design; it would be expected that the absolute distance of sounds would be judged to be closer with hearing aids than without. A second possible reason is that the listeners — who were all experienced hearing-aid users — were acclimatized to the effects of their own hearing aids on intensity, and so had learned to overcome the effect of compression (e.g. Robinson and Gatehouse, 1996; for a review, see Munro, 2008). If so, it would be of value to study first-time, un-acclimatized, users, especially as any immediate adverse effects on judgments of distance may be influential in the self-reports used by the audiologist to fine tune the hearing-aid. A third reason is that speech has rapid, large dynamic fluctuations in level that may interfere with any judgments based on overall level. But a fast compressor will reduce these fluctuations — though they would only disappear to zero if the compression was instantaneous and the compression ratio was infinite — and so might lead to an improvement in performance via a reduction in interference (and always assuming that the effect was large enough to dominate the overall level change due to the compression). This was examined informally using measurements of the attack and release time that were taken at the same time as the input/output measurements (see Method), but none of the correlations between either time constant and either the four JNDs or their means were statistically significant. Nevertheless, the question of the effect of speed of compression on intensity resolution is somewhat neglected and deserves future study.⁵

The wider issue underlying these analyses is the assumption that the ability to detect changes in relative distance was due to the ability to detect changes in level: i.e., that performance is founded on intensity resolution. The effects of hearing impairment on intensity resolution are complex, and different experiments have found performance to be worse, better, or about the same as for normal-hearing controls (for a review, see Moore, 2007). Most studies of intensity discrimination with hearing aids have used linear amplification, however (e.g., Robinson and Gatehouse, 1996), and none have used speech stimuli with hearing-impaired listeners. In principle, if the JND for intensity is x dB unaided, then it should be Cx dB with very fast compression. One might therefore expect adverse effects on intensity discrimination, which may, for an un-acclimatized listener, be of consequence during fitting. It would be of interest to measure the effects of compression on the ability to discriminate changes in the level of free-field presented speech.

⁴The exponent p depends slightly on both the level difference at threshold (ΔL) and how much the level changes per doubling in distance: e.g., for a ΔL of 1 dB and 6 dB per doubling, then p is 1.12, but for a ΔL of 1 dB and 4 dB per doubling then p is 1.18.

⁵The attack/release times used here were taken at 1000 Hz. The analyses used the data from 16 of the 17 people with either one or two hearing aids; if they had two, the left and right values were averaged; one listener was excluded as an outlier in both JND and release time.

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FIG. 1.

The just-noticeable differences (JNDs), in meters, plotted as a function of the better-ear hearing loss for listeners fitted with two linear aids (open circles), one linear and one compressive aid (diamonds), and two compressive aids (hourglasses). The dots plot the JNDs measured using 77 unaided listeners from Akeroyd *et al.* (2007), and the lines show exponential curves fitted to these data. The largest hearing loss for the unaided listeners was 59 dB, and so the lines have been extrapolated above that value to the higher hearing losses of the aided listeners. The four panels are for the four tasks (see text).

FIG. 2.

The JNDs plotted as a function of the average compression ratio. The four panels are for the four tasks.