THE Hearing Review®

musicians and hearing aid design

What Special Hearing Aid Properties Do Performing Musicians Require?

Performing musicians need a dispensing professional who will listen to both them and their hearing aids

By Mead C. Killion, PhD, ScD(hon)

Although for a while the emphasis in hearing aid design appeared to have been in favor of speech at the expense of music fidelity, there seems to be no evidence to support the need for a trade-off between high fidelity for music and high intelligibility for speech in noise.

This paper summarizes information on what is required of a high-fidelity system. Much of the information was already contained in Snow's 1931 paper[1] on the audible frequency ranges of music and speech. Research since that time has done little to modify those conclusions.

Even with the introduction of digital audio, the basic answers still held, although new questions arose, regarding the sampling rate and number of bits required for full-fidelity digital encoding. After extensive experiments, a sampling rate of 44.1 kHz (theoretical 22 kHz bandwidth) with 16 bits of precision (96 dB dynamic range) was chosen for CDs. Similarly, experiments with data compression led to mp3 (MPEG-3 Fraunhofer IIS) compression, where a 600 MB CD wave file can be compressed to 60 MB (128 kbs) with little loss in quality, or to 90 MB (192 kbs) with no detectable difference from the original in careful A-B comparisons except, on occasion, with carefully contrived wave files.

In this paper, a summary of the requirements for high-fidelity reproduction of live music is followed by a review of some recent verifications of these guidelines as applied to hearing aids, using listening tests, Accuracy Scores, and intelligibility-in-noise tests. None of these measures support a digital advantage for music, although digital processing can be used to improve the accuracy and smoothness of the real-ear hearing aid insertion response.

In the author's informal listening tests (piano, violin, trumpet, voice, and listening to music in automobiles), most digital hearing aids appear to have been designed with speech in mind. In addition to different delays between adjacent compression bands (which can make a single piano note sound like two notes in quick succession), compression recovery time constants that are too fast, and inadequate headroom for live music before distortion sets in, some digital hearing aids appear to have included a search-and-destroy noise reduction that, like its more aggressive relative that is ensconced in every cell phone, attempts to eliminate anything that is not speech.

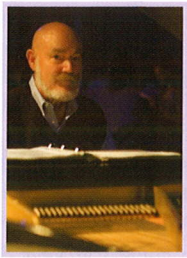
Fortunately, digital and analog hearing aids that perform well on live music exist, and they can be identified in several ways as described below. The easiest is probably to do a listening comparison between the unaided and aided sound of the hearing aid with music played on a high-fidelity system whose peak SPL output (as measured on a sound level meter set to C, fast) equals that experienced for live music (see discussion in sidebar). Such a system can be easily set up in the dispensing office for a few hundred dollars.

At one time, cochlear implant processors allowed their wearers to hear four-part barbershop-quartet harmony. Later, music was sacrificed in an attempt to improve processing of speech. The pendulum has recently swung back, and the processing of music appears to have been reinstated as an important goal. It is heartening that a move in this direction also seems apparent in recent digital hearing aid designs.

What Do We Know? Requirements for Reproduction of Live Music

In this section, available data on the high-level requirements for high fidelity in hearing aids are summarized. Only an abbreviated literature review is included here; an expanded summary with the requirements for static and dynamic hearing aid compression and an extensive list of references can be downloaded.[2]

Dynamic range (the difference between peak SPLs and noise levels) and the peak SPLs of music. The writer has often measured the Chicago Symphony



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Orchestra (CSO) at 104 to 106 dB(C) in the last few bars of a selection (at the end of Stravinski's *Rite of Spring*, for example), corresponding to instantaneous (oscilloscope) peaks of 114-116 dB. Since those levels last for only 10 or 15 seconds, they add excitement without risk of hearing damage: a level of 106 dB(A) is safe for 6 minutes by the NIOSH-1997 "85/Trade 3" recommendations. Musicians can produce similar peak levels at their own ears even when playing solo, unamplified. A typical hearing aid microphone can operate linearly to nearly 120 dBSPL peaks, providing more than adequate headroom.

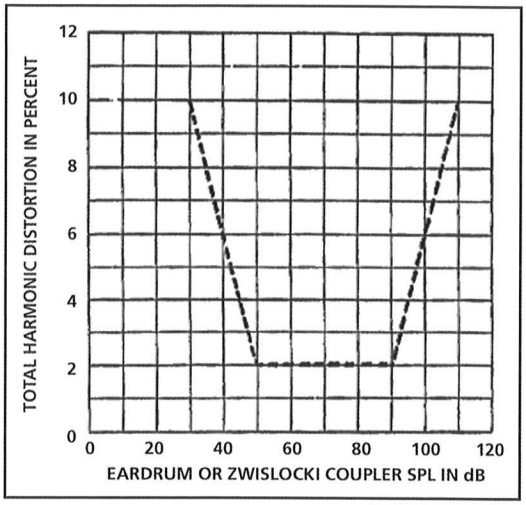

FIGURE 1. Estimated maximum hearing aid distortion, measured at the eardrum, which will be inaudible on speech or music. From Killion 1979.[2]

Perhaps in order to conserve battery drain, the input A/D converter of some digital circuits fails to handle instantaneous peak levels of 116 dB or even 110 dB without distortion, providing a noticeable distortion on live symphony and jazz concerts as well as for the musicians themselves. However, this lack of headroom is not an inherent limitation in hearing aids. A few years ago, several Chicago Symphony Orchestra musicians wore (non-digital) hearing aids with adequate headroom during practice and performance. These musicians included a former Concertmaster and the Principal of the second violin section. *Author's Note: Even the 120 dB capability of hearing aid microphones may be exceeded by high-intensity music associated with some heavy-metal, rock, country-western, and blues bands. Amplified music was not covered by Snow,[1] Olson,[3] or Fletcher[4] and will not be considered here (Larry Revit provides his observations about this topic in the preceding article).*

Dynamic range and concert hall noise levels. Concert hall noise levels are reported as 32 dB A-weighted (the writer has measured 33 dB(A) in Chicago's Orchestra Hall). The typical living room noise level is 45 dB(A) when the furnace or air conditioner is running, and may drop to concert-hall levels in their absence. A typical hearing aid microphone has a noise level of 26 dB(A) or less, significantly lower than even a quiet concert hall.

Allowable distortion. Normal ears start distorting noticeably at high levels. We ignore the intermodulation distortion that produces distortion-product otoacoustic emissions, since those are considered a normal part of the auditory system and are even used by violinists to aid tuning. Based on several studies, the graph in Figure 1 shows a conservative estimate of the allowable total harmonic distortion (as from hard or soft clipping, for example) before it becomes audible for music.

Above the levels shown in Figure 1, distortion becomes first audible and then quite annoying. At levels above 110 dBSPL, the typical normal ear is distorting so badly that music and speech take on a harsh quality. A fiddler friend who plays regularly in country-western bands said that without high-fidelity earplugs, it is almost impossible to distinguish the sound of other musicians; she is essentially playing in front of a wall of sound.

Orchestral peaks of 104-106 dB do not typically introduce objectionable aural distortion, although a slight harshness can sometimes be noticed by comparison to the cleaner sound with high-fidelity earplugs inserted. At the 110+ dB levels of a blues bar or country-western band, the harshness is often quite pronounced.

Fortunately, many hearing aid receivers can produce levels in excess of 116 dBSPL instantaneous peaks (104-106 dBSPL sound level meter readings) without noticeable distortion. Most distortion in digital hearing aids is probably a result of input overload, although output clipping can occur at high levels if the electrical impedance of the receiver is too high or the gain for loud sounds is too high. The solutions to output clipping are to use a lower impedance (or larger) receiver, and/or to readjust the hearing aid.

Frequency response and bandwidth. Harry Olson,[3] the dean of acoustical engineers, concluded that "the reproduction of

continued on page 26

But how can I tell if a hearing aid will be acceptable for live music?

(Answer: You need to listen to the hearing aid!)

After reading the "final draft" of this paper, audiologist Gail Gudmundsen said, "That's fine, but you haven't told me anything useful. You didn't tell me how to find a hearing aid that would be good for music or the musician."

My first reaction was to point out that, if there was an easy answer, we wouldn't be writing on this topic. For years, starting well before the temporary enthusiasm for coherence measurements in the 1960s, engineers on the hearing aid ANSI standards committee have sought measurements that would separate the good from the bad. The problem with hearing aid design is similar to the one expressed in the wry saying: "It is hard to make something foolproof because fools are so ingenious." I was reminded of this recently when I myself left the dampers out of two experimental hearing aids, and listening to their harsh, distorted sound, concluded that something might be wrong with the amplifier chip design.

An overly fast recovery time on the compression program can smear the sounds of drummers' cymbals, and independent-compression action in multichannel compression can amplify the high-frequency harmonics of instruments or piano strings to produce a nasty tone. I listened to two different recent models of digital hearing aids at a New Year's Eve dinner party. The six-piece band started in with 95 dB(C) frequent peaks, making conversation virtually impossible across our table. Even when the band dropped to 85 dB peaks at our request, both hearing aids made a cacophony of the otherwise excellent band, with the compression covering the sound with a smeared sound as from the drummer. A third hearing aid and my open ears were free of that problem. The point of the anecdote is that test box measures on all three aids looked reasonable.

Which leads to the conclusion that the only safe judge is the human ear, which can rate sound quality quite accurately, even with little training (witness the 17% returns for credit in digital hearing aids). The superiority of the human brain over computer judgment was illustrated years ago. The "Thinking Machine" super-computer with 64,000 processors working simultaneously was "so close to human performance that it could accurately recognize a face in 30 seconds." Impressive, except a human baby can do it in less than one second. Similarly, trained listeners can accurately rate the fidelity of a sample of music lasting only a few seconds. So can untrained listeners, after a little practice, which is more important to our quest.

Since we are stuck with human ears and brains, the challenge becomes: Where can I find a collection of sound samples that I and my patients can listen to over a few minutes (about the same time needed for a 25-word NU-6 list) to rate the suitability of a hearing aid (and just as important, my own fitting)?

As a result of the Gudmundsen challenge, the author has been attempting to make a "musical obstacle course" CD that could be calibrated with a sound level meter so each reproduced track would represent a recording of live music at its original level as heard either in the audience or by the performing musician. The following is a report of (incomplete) progress to date.

The appropriate SPLs are easy. Figure 5 provides values similar to those found in Chasin[11] and to those reported for the Chicago Symphony Orchestra players[12]: "The maximum rms equivalent sound levels were 110 dB(A) or below for 76% of the samples, and the very highest value recorded was 115.5 dB(B). The great majority of peak SPLs were in the range from 115-129 dB(A)."

Unfortunately, the safest and most effective listening checks are made with a live source. Commercial CD recordings often include heavy phase shifting and compression to "pack in" as much audio as possible.[13] Similarly, in a personal communication, Larry Revit reported that "Many times, I have done the procedure you suggested, at home, only to go to Open Mike that evening and be sorely disappointed when the hearing aids that sounded okay at 105 dB at home (using very good broadband speakers) went SPLATT as soon as the band kicked in onstage (at 100 dB or so)."

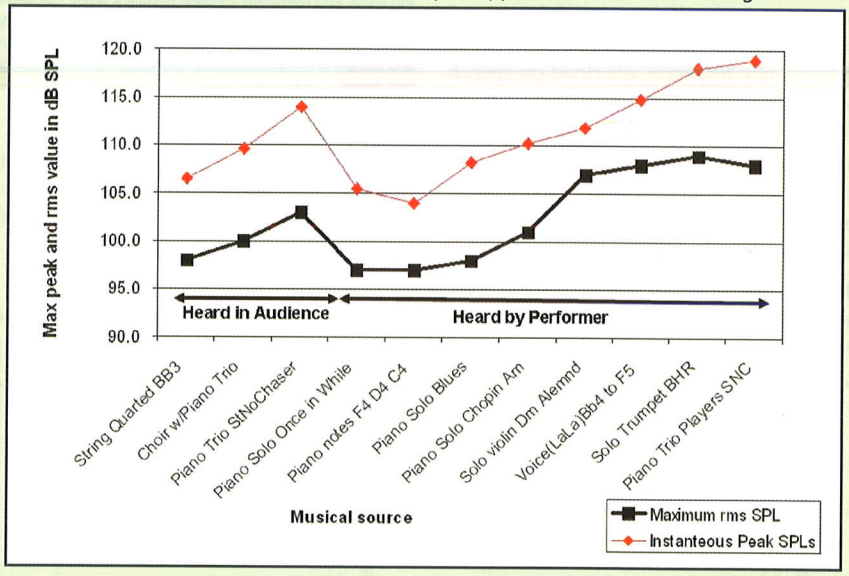

FIGURE 5. The maximum RMS SPLs and the instantaneous peak SPLs of various music and instruments as heard by both the audience and the performers playing solo or in small groups. This approximates earlier reports by Chasin,[11] and even higher levels were recorded by Royster et al[12] in a study involving the Chicago Symphony Orchestra.

Even when uncompressed recordings of live performances are used, the loudspeaker needs to be unusually clean in terms of frequency response and distortion. Although most experiments undertaken so far have used a KEMAR manikin and live performances, with equalization the speakers in hearing aid test boxes may prove adequate as high-intensity sound sources. The important thing is to compare the unaided and aided sound, listening for defects in the latter. (Safety note: Listening for short periods to the output of a hearing aid suitable for a patient with mild-to-moderate hearing loss is generally safe. Even a most-unlikely output as high as 120dB(A)SPL should be safe for 6 seconds of listening by NIOSH-98 standards—more than enough time to turn the hearing aid off or to remove it.

The key commitment is to use the ear *and* the brain, rather than objective reports from the test box. ◗

continued from page 22

orchestral music with perfect fidelity requires a frequency range of from 40 to 14,000 cycles [Hz].... " Harvey Fletcher[4] suggested 60 to 8000 Hz was enough.

In informal listening tests with 12 hearing aid wearers with mild-to-moderate hearing loss who were asked to remove their aids and listen to high-fidelity reproduction of the Oscar Peterson Trio at live (85 dBSPL) levels, two reported they could hear no difference between a 16 kHz and a 5 kHz bandwidth (typical for 1997 hearing aids), and two of those who heard a difference preferred the narrower (more mellow) bandwidth. When the eight who preferred the wider bandwidth were asked how much more they would pay for such hearing aids, two said $10,000 or more with a smile; the average for the remaining six subjects was $96.

A 16 kHz bandwidth has been readily available in hearing aids since the 1980s. The writer's question has always been: Why take full bandwidth reproduction away from *everyone* if a significant portion of hearing aid wearers might benefit from keeping it? It is easy to roll off the high-frequency response in the office, when necessary; but it is not possible to *add back* what has been designed out. Nearly every instance of feedback known to the author has been at frequencies well below 8 kHz, typically at 2.8 kHz in a well-designed hearing aid, which mimics the 15 dB open-ear resonance boost at 2.8 kHz.

Frequency response and peaks in the response. At one time, sharp response peaks were apparent in nearly every hearing aid. The peak at 1000 Hz was prominent in most BTEs. Although Sam Lybarger and others routinely damped the peaks with acoustic resistance (eg, Radioear hearing aids), for some 20 to 30 years the remaining industry waged a readily admitted horsepower war on the principle that "The greater the output on the data sheet, the more capable the hearing aid appears to be." Now most hearing aids have some degree of damping, from use of either internally damped receivers or external dampers. Even so, many current hearing aids have sufficient response irregularities to keep them out of the high-fidelity category.

Frequency response shaping. Hearing sensitivity—and acuity—for loud sounds of many hearing aid wearers is normal or near normal (presumably because they have retained most of the inner hair cells that send information to the brain). When that is true, the hearing aid should be transparent for high-level sounds: For high-level sounds, such wearers should ideally hear the same thing with the hearing aids in or out of their ears. More technically, the aided spectrum at the eardrum should match the unaided spectrum for high-level sounds. The coupler response required to achieve this result has been called CORFIG.[5]

One clear-cut case where digital processing provides a substantial advantage is in peak smoothing and response equalization. Near-perfect digital equalization of a hearing aid frequency response out to 14-16 kHz (including electronic response smoothing and CORFIG equalization)[6] can now be accomplished in less than 20 seconds from the time the "GO" button is pressed, even with traditional BTE hearing aids with built-in (as opposed to RIC) receivers.

Time constants. Nothing can destroy the enjoyment of music more than an overly fast recovery time in the compression operation. Given the many contradictory results of published studies, the only way known to the writer for deciding what is too fast is with listening tests, which every dispenser can perform (see below).

Is "What We Know" Valid? Live vs Recorded Listening Tests

The history of live vs recorded listening tests goes back over a century. Thomas Edison reportedly performed "live vs recorded" demonstrations with his cylinder phonograph, and listeners "found the playback indistinguishable from the live sound."[7] (They were undoubtedly shocked that they could recognize the same music!) More recently, Harry Olson conducted live vs recorded comparisons at Tanglewood in Massachusetts and listeners reportedly heard little difference.[3]

Somewhat more refined live vs recorded comparisons were designed by Edgar Villchur,[8] who used the Fine Arts Quartet as the live source and AR-3 loudspeakers located behind the players as the recorded source. (In another case, he used the large organ at Boston Symphony Hall as the live source, with a previous recording of its organ reproduced through four loudspeakers.) In each of the Villchur live-vs-recorded concerts, it shortly became clear that few members in the audience could hear any difference. For the final demonstration in the Fine Arts Quartet concerts, a Bartok movement was reproduced by the loud-

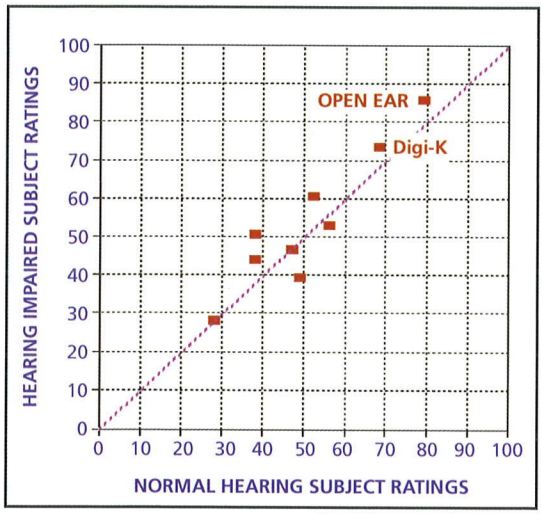

FIGURE 2. Correlation between percent-fidelity ratings obtained from 19 normal-hearing subjects and from nine hearing-aid wearers. Both groups listened with open ears to approximately original-level reproductions of KEMAR recordings of live performances. From Killion 2004.[9]

speakers while the players would alternately pretend to play or put down their bows. (This was done to smoke out the few diehards who raised their hands confidently as having heard a clear difference all along.) At that point, it was announced that the entire movement was played over loudspeakers, not by the string quartet.

Simulated live vs recorded. Villchur once demonstrated that a good AR-3 loudspeaker could reproduce itself and reproduce the sound of an inferior loudspeaker, while an inferior loudspeaker could not reproduce its own sound on re-recording. At Etymotic Research, we have used the same technique with KEMAR® to demonstrate the strong "coloration" in many commercial in-ear earphones. Since the AR-3 loudspeakers survived true live-vs-recorded listening tests, the writer used AR-3 loudspeakers as surrogate live sources during his 1979 research. As a check, for one set of comparisons, an actual live voice spoke the classic Bell Labs test sentences *"Joe took father's shoe bench out. She was waiting at my lawn,"* as a true-voice reference for the A-B-A voice recordings. (As a side note, Sam Lybarger often used the passage *"Jules, the big fat ape, shook and chuckled in secret at many awful things,"* which also contains all of the phonemes of spoken English in a single sentence.) The resulting surrogate live-vs-recorded listening comparisons that had been recorded on a KEMAR manikin were subsequently used to obtain fidelity ratings of hearing aids, headphones, and loudspeakers. Pleasantly enough, the experimental high-fidelity hearing aids were rated higher in fidelity than the most popular studio monitor loudspeakers used in the Chicago area at that time.[2]

True live vs recorded. Fifteen years later, the writer and colleagues made true live-vs-recorded A-B and A-B-A comparisons using a string quartet, which comprised three players from the Chicago Symphony Orchestra plus David Preves, who once soloed with the CSO, and a jazz piano trio made up of three professional musicians from the Chicago area. The reason for recruiting high-level musicians was because it was critical to the experimental design for them to play *exactly* the same way in each of roughly a dozen repeated performances. Each of the eight hearing aids under test was recorded on KEMAR with a new performance of a given musical selection. As a check on the musicians' reproducibility, an open-ear recording made at the beginning of the series was compared to an open-ear recording of each musical selection made near the end of the series. The resulting average fidelity rating from listening-test judges was 80% for the comparison of the two different open-ear recordings, and 90% for two identical open-ear recordings, indicating good consistency in musical performance. A DVD that contains the resulting comparisons (video and audio) of eight digital hearing aids, one analog hearing aid, and two open-ear same-same recordings is available.[6]

Results with normal vs hearing aid wearers. The results of the live-vs-recorded listening tests confirmed that it is possible to make a 16 kHz bandwidth digital hearing aid with adequate headroom and response smoothness to qualify as high-fidelity. The most interesting finding, however, was that several hearing aid wearers, listening without their hearing aids to reproductions at original levels of the A-B comparisons, gave quite similar fidelity ratings to those of the normal-hearing judges listening under the same conditions.[9] The selections were easily heard without their hearing aids by the hearing aid wearers, who had only mild-to-moderate hearing loss, because the live piano trio hit peaks of 102 dB(A) and the string quartet reached peaks of 97 dB(A) measured with a sound level meter at KEMAR's front-row listening position.

The obvious implication of the results shown in Figure 2 is that hearing aid engineers can listen *themselves* with confidence for any defects in response smoothness, distortion, headroom, and bandwidth in a laboratory hearing aid design before it reaches production. Just as important, it means that *the dispenser can listen to the hearing aids before they are dispensed*, confident that, if the aids sound bad to their own ears, then the aids will undoubtedly sound bad to the patient. The author has had students rate a single set of comparisons on several occasions, and most do quite well at separating low- from high-fidelity sounds, even without prior practice.

Informal listening checks. For some time, the writer has used an informal listening test to evaluate the suitability of a hearing aid for reproducing music. These musical materials included singing, playing a piano, a high-quality violin, a trumpet, and listening to music in an automobile. The background noise level in most cars at 70 mph is about 70 dB(A), which makes a good music-in-noise listening test.

As a check on the 2004 listening test results reported in Figure 2 and Figure 3, the author has recently listened carefully to three state-of-the-art digital hearing aids. All three hearing aids were "First Fit" programmed for a 40 dB flat loss, the settings used with all hearing aids evaluated by the author. He is happy to report that one of them passed all of the informal listening tests except for its somewhat muffled sound from its roughly 6 kHz bandwidth. The other two did not pass. One made music played on an excellent grand piano sound as if had been played on a honky-tonk piano. The other would produce the sounds of two notes in quick succession when only one was played on the piano for certain keys.

Objective Prediction of Listening Test Results: A Further Check

The Consumers Union 21-band Accuracy Score and the 25-band Accuracy Score. Some 30 years ago, Consumers Union (CU) described a Stevens[10] Mark VII loudness-based Accuracy Score that they reported could predict the results of listening tests on loudspeakers within +/-8 percentage points.

In 1979, the author extended the CU 21-band method to 25 bands to include a wider band of frequencies.[2] The new design did an excellent job of predicting the fidelity ratings of the various headphones, loudspeakers, and hearing aids.

The same good predictive result

appeared in the recent true-live vs recorded listening tests of digital hearing aids, as shown in Figure 3. Hearing aid #7 not only had a ragged real-ear response but an extremely fast recovery time, so that the swish-swish of a drummer's cymbal became a steady shshshshshsh sound.

Prediction of intelligibility-in-noise from fidelity ratings. The single most surprising result of the formal live-vs-recorded fidelity-rating experiments is that the ability of hearing aid wearers to understand speech in a background of 85 dB(A) four-talker babble (similar to cocktail-party noise) was predicted quite accurately by the fidelity ratings given the various hearing aids by normal-hearing listeners (Figure 4).

The results shown in Figure 4 do not support a common belief that there is a necessary trade-off between fidelity and intelligibility in noise. Perhaps aberrations in frequency response, overload on speech peaks at crowded social gatherings (85-95 dB average SPLs), and low-fidelity time constants combine to degrade the speech of the target talker in multi-talker background noise, much as they degrade the fidelity ratings for music.

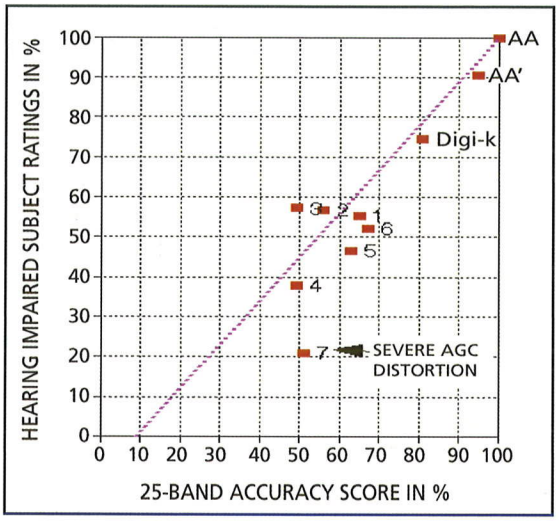

FIGURE 3. Correlation between fidelity ratings for string-quartet and jazz-piano-trio music and calculated 25-Band Accuracy Score[2] calculated from the insertion response on KEMAR of each hearing aid obtained from a spectral analysis of the music aided vs unaided. The fidelity ratings are averaged across all string-quartet and piano-trio comparisons, and normalized so the AA same-same open-ear ratings are set to 100% (top right).

Conclusions

Although for a while the emphasis in hearing aid design appeared to have been in favor of speech at the expense of music fidelity, there seems to be no evidence to support the need for a trade-off between high fidelity for music and high intelligibility for speech in noise. Fortunately, A/D converters in hearing aid circuits are now available with adequate dynamic range, and hearing aid circuits with 32 kHz sampling rate—allowing nearly 16 kHz bandwidth—are also readily available.

With a reported 17% return-for-credit rate for digital aids and another 16% of aids in dresser drawers, it may be time to abandon the assumption that most users can't hear the difference in bandwidth, response smoothness, time constants, and overload for high-level sounds. All evidence suggests that what is good for music is good for speech. Fortunately, high-fidelity hearing aids meeting these criteria are already available to performing musicians.[13]

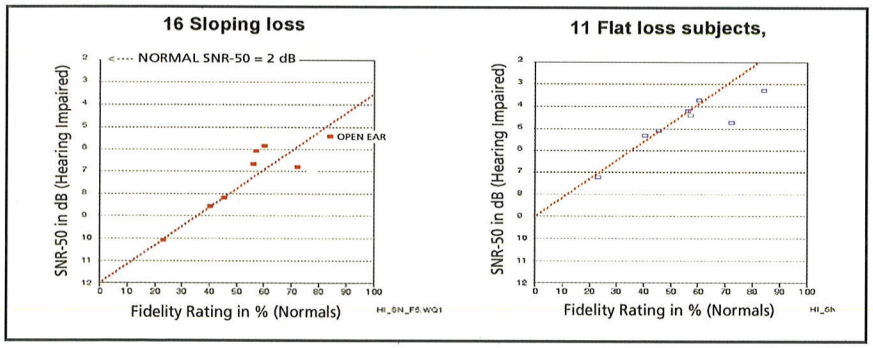

FIGURE 4. Correlation between intelligibility-in-noise scores for hearing aid wearers and Fidelity Rating scores for music from normal-hearing subjects. The signal-to-noise ratio required for 50% words in sentences correct on QuickSIN lists recorded through each hearing aid is plotted against normal-hearing subjects' fidelity ratings for the same aids.

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Topics related to this article, as well as many of the sound samples discussed, will be presented in an ***HR Science and Technology Thursday Podcast*** available at **www.hearingreview.com/sciencetech.**

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