CHAPTER FOURTEEN

Research and Clinical Implications for High Fidelity Hearing Aids

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This chapter reviews surprising evidence that a hearing aid user's ability to understand speech in noise can be predicted from the *fidelity ratings for high-level music reproduction* when normal-hearing and hearing-impaired subjects listen to the same hearing aid. Listening to a hearing aid has fallen out of favor.

Two appendices at the end of this chapter contain recent information on Hearing Loss from Noise and Over the Counter Hearing Aids that the writer was allowed to add.

Why our Patients Do Not Properly Appreciate our Best Efforts

This is the primary problem addressed in this talk. Evidence for its existence is: a) manufacturer's report a 26% return for credit with our premium fittings (Hearing Industries Assn. 2007); b) Kochkin (2000) reports another 17% of hearing aids are in dresser drawers; and c) Adrian Davis (2006) reported that in England 25% of the hearing aids are in drawers (4% of the population own hearing aid(s); 3% of the population use them).

There are many possible reasons for our failures. Many of those being discussed at this conference are summarized in figure 1. The patient's personality (see

Figure 1. Possible Reasons our patients don't appreciate our efforts.

PATIENT'S PERSONALITY (COX; SOUSA)

FAILURE TO DO PROBE MEASURES (MUELLER)

FAILURE TO DO REHAB (HAWKINS; SWEETOW; PICHORA-FULLER)

FAILURE TO ADD FM OR WIRELESS (BOOTHROYD, CHISOLM & McARDLE; SOLODAR)

USE OF WRONG FITTING FORMULAE (SEEWALD & SCOLLIE; KEIDSER & DILLON)

FAILURE OF FIRST-FIT TO PROVIDE AUDIBILITY (HAWKINS & COOK)

FAILURE TO RELIEVE OCCLUSION EFFECT (KILLION, WILBER, & GUDMUNDSEN)

OTHER (McCARTHY, DAVIS; BORETZKI & LAUNER; BENTLER; JENSTEN; RICKETS; FABRY; THIBODEAU; HUMES; ABRAMS & McARDLE, BOYMANS & DRESCHLER, PALMER)

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Chapters 1 and 4 in this proceeding); failure to do probe measures (see Chapter 12 in this proceeding), failure to provide rehabilitation counseling and training (see Chapters 6, 25, and 27 in this proceeding), to provide adequate signal-to-noise ratio (SNR) improvement (see Chapters 18, 19, 20 in this proceeding), to adequately reduce the occlusion effect through deeply sealed or heavily vented earmolds (Killion, Wilber and Gudmundsen 1985). This is hardly the end of the list, as indicated by other papers in this proceeding.

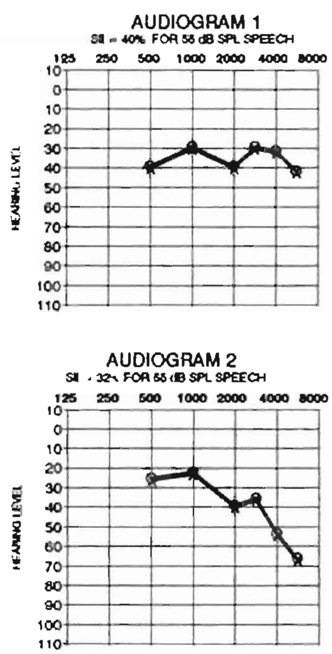
The failure to provide adequate audibility in some "first fit" programs was dramatized recently in the reports by Hawkins and Cook (2003) and by Bentler (2006). Both reports present data indicating that a significant number of "first fit" programs end up providing aided thresholds which fail to make up to 70% of quiet-speech cues audible. In the case shown in figure 2, the aided sound-field thresholds are poor enough that most audiologists would recommend that anyone presenting with those thresholds would benefit from hearing aids. This is particularly ironic, since one of the problems solved by the introduction of wide-dynamic-range compression was that of providing adequate gain for quiet sounds without excessive gain for loud sounds, a feature that every modern hearing aid has adopted as an option.

In addition, the design of many digital hearing aids suggests the designer's belief that a bandwidth of 5 or 6 kHz is adequate as long as the hearing aid can be labeled digital (Bentler, Niebuhr, Johnson and Flamme 2003). This may be true for some adults who have already acquired language, but Stelmachowicz, Pittman, Hoover and Lewis (2001) report that young children listening to a female talker will exhibit a 25 to 39 percentage points decrease in their ability to recognize the "s" sound when listening through hearing aids having a 6 kHz bandwidth compared to one having a 9 kHz bandwidth. See figure 3.

Figure 2. Some hearing aids don't make quiet speech sounds audible unless the audiologist intervenes.

(TOO MANY AUDIOLOGISTS DON'T, AND DON'T DO PROBE OR SOUND FIELD CHECKS)

First-fit aided audiograms: Their hearing aids need hearing aids!



A 29%	H 41%	O 68%
B 30%	I 47%	P 75%
C 74%	J 36%	Q 22%
D 77%	K 23%	R 31%
E 42%	L 36%	S 75%
F 33%	M 81%	T 40%
G 37%	N 71%	U 40%

TABLE 1. Audibility (SII) values for 55 dB SPL male speech for 14 digital hearing aids programmed to their default "First-Fit" settings. (Note: 21 SII values are shown because some aids were programmed for two different audiograms.)

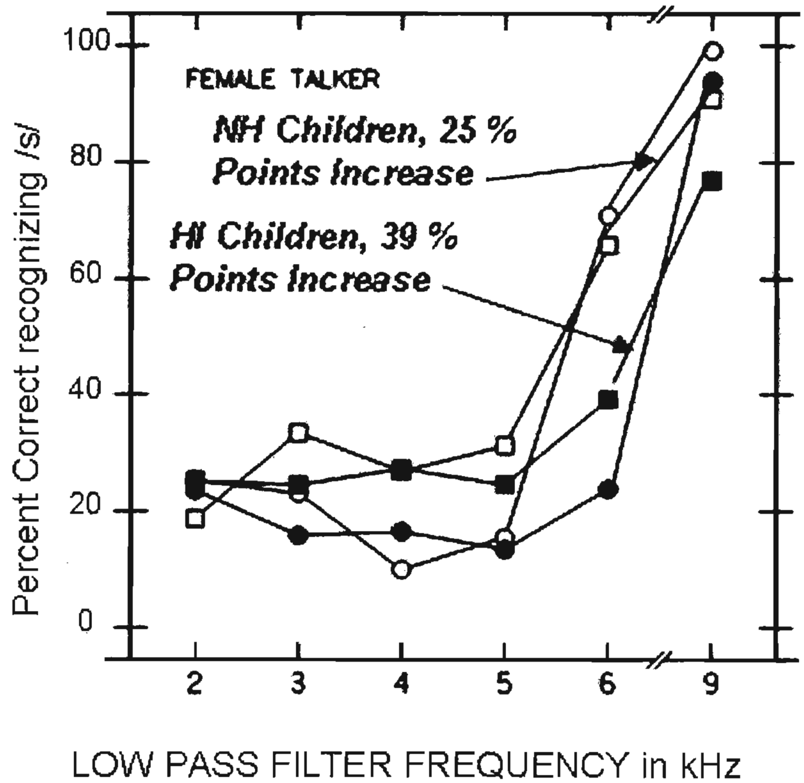


Figure 3. The importance of high-frequency amplification for young children (After Stelmachowicz et al., 2002)

Although there are many possible explanations for the fact that our patients do not appreciate our best efforts, my personal favorite reason is that some hearing aids simply do not sound good. An A-B comparison illustrates this point and can be found at www.etymotic.com/download/06HiFiHA.ppt. (The audio can be played by left-clicking on the appropriate speaker icon.)

The reference sound (1) in each of these comparisons was recorded through KEMAR's open ear, while the test sound (2) was recorded through the hearing aid. The two comparison recordings used a live piano trio and a live string quartet, respectively. A digital hearing aid from a different manufacturer was used for each comparison, but both of the hearing aids had been extensively advertised as having "CD quality." Despite the enthusiasm of the advertising agency, these hearing aids do not have anything approaching CD quality. This poor sound quality is unfortunately not rare, as demonstrated by the judgments of hearing aid wearers themselves (Killion 2004; and see below).

Why would anyone buy a digital hearing aid that sounded like those? Perhaps because the buyer was looking for better intelligibility in noise, encouraged by advertisements that associated digital with better intelligibility in noise. Another demonstration found at www.etymotic.com/download/06HiFiHA.ppt is a comparison between a hearing aid advertised as having "11 dB digital noise reduction" and a hearing aid with simple wideband, high fidelity reproduction. It is evident that the simple high fidelity reproduction provides better intelligibility in noise than the aid advertised as having "11 dB noise reduction." The effective SNR of the "11 dB noise reduction" hearing aid was actually 2–3 dB worse than simple high-fidelity reproduction. The advertised and the actual performance of this hearing aid were not the same.

This result was confirmed in extensive experiments with hearing aid wearers as subjects, as reported to the ANSI S3.35 Standards Committee (Killion et al. 2005; Kirsch and Fortune 2005). The complete report can be downloaded at www.etymotic.com\download\11dB_S3_35Final.ppt.

What about the idea that patients have to accept poor sound quality in order to obtain better intelligibility in noise? This once-popular belief is simply contrary to all recent experimental results. In all of our tests, no digital hearing aid has provided better intelligibility for either normal or hearing-impaired subjects than unprocessed amplification of the signal from KEMAR's open ear, often not as good, except when switched to a directional microphone. In other words, the experimental finding is that the *best* that digital signal processing can do in high-level noise is not to *degrade* the signal compared to high fidelity amplification. This surprising result makes more sense once one realizes that in a noisy social gathering, most people can use their ability to listen selectively, and choose to switch their attention from a tedious speaker who has trapped them to someone else talking at the same time. At some time in the future, it may be possible to communicate to the hearing aid which voice belongs to the talker of interest and which voices are "noise." Until then, however, there is no way for the hearing aid to know which voices to filter out and which one to preserve.

The fact that many digital hearing aids degrade speech intelligibility is not the fault of digital processing per se, of course, but the consequence of design tradeoffs that have resulted in narrow bandwidth, inability to handle high-level sounds without distortion (poor headroom), and distortion introduced by digital noise reduction and digital feedback circuits.

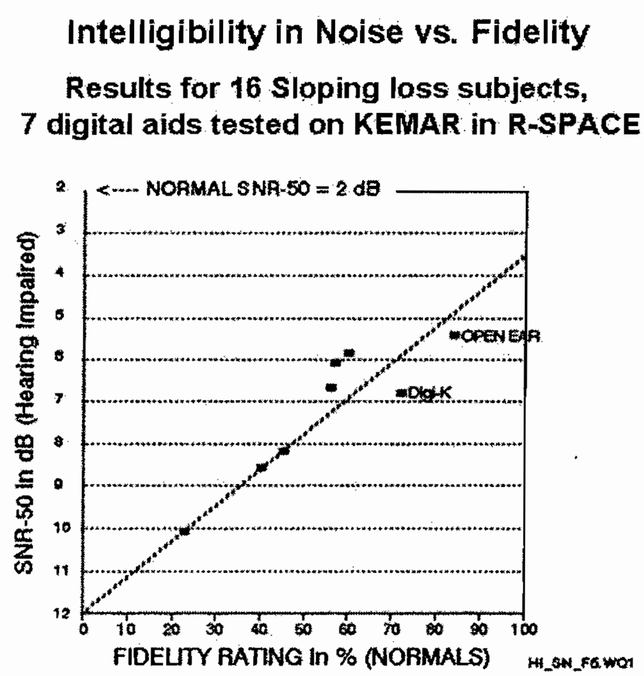
Figures 4 and 5 plot intelligibility measured in noise as a function of the fidelity of the various hearing aids as judged by normal-hearing listeners. Figure 4 shows the data for 16 sloping-loss subjects and figure 5 shows the data from figure 4 compared to the data for another 11 flat-loss subjects. These figures have been intentionally plotted with the decreasing signal-to-noise ratio at the high end of the Y-axis. The poorest hearing aid requires

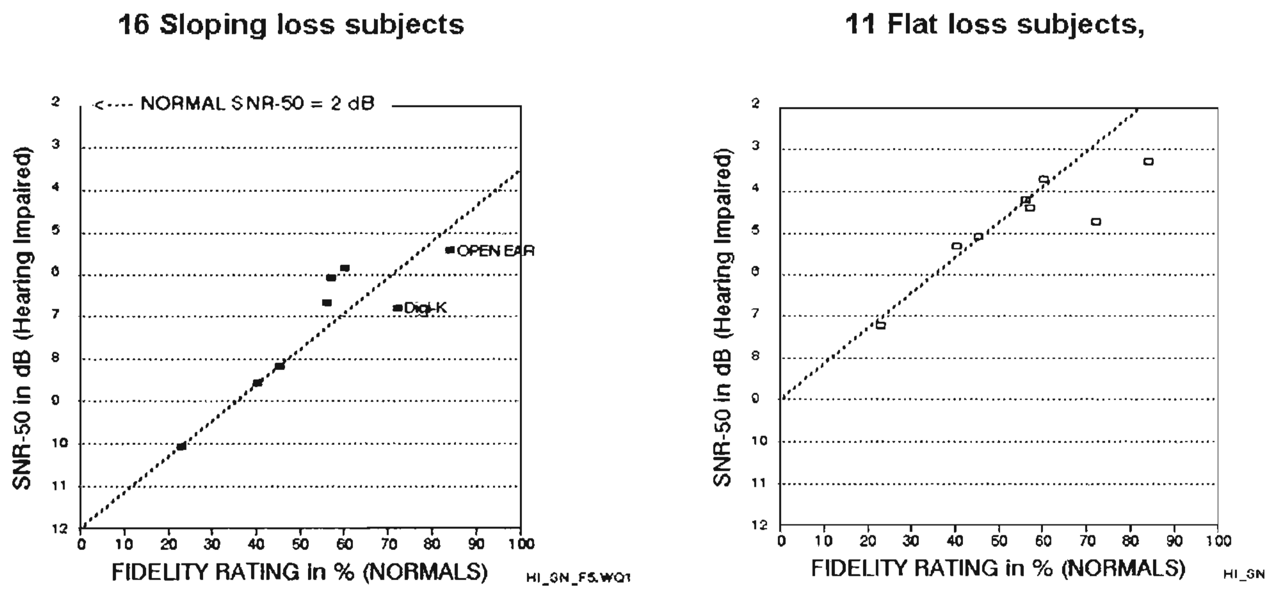
Figure 4. Do patients have to accept poor sound quality in order to obtain better intelligibility in noise?

No, but they may have been misled into thinking that "digital is better" (Bentler).

In all of our tests, no omni-mic digital hearing aid has provided better intelligibility than KEMAR's amplified open ear (or even as good).

(For one thing, they lose 1-2 dB from BW)





The astonishing result is that there is nearly a perfect correlation between a) the hearing aids' ability to deliver high intelligibility in noise and b) the fidelity ratings on live music of *normal-hearing subjects*.

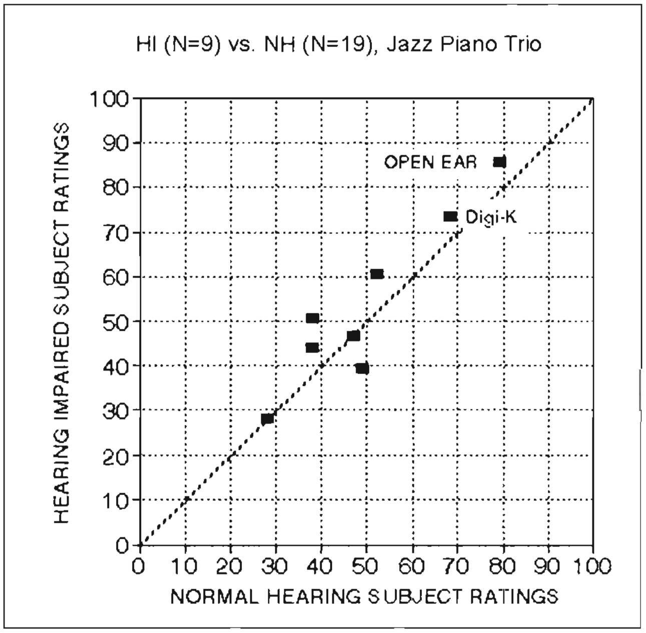
Figure 5. The same relationship between intelligibility and fidelity holds for both sloping-loss and flat-loss subjects.

a 10 dB signal-to-noise ratio for the subjects to get 50% correct scores. For the 16 sloping loss subjects, on average, the open ear recordings required only about a 5.5 dB signal-to-noise ratio. The flat loss subjects showed a similar result, although they had less difficulty hearing in noise.

There is a nearly perfect correlation between a) the fidelity ratings on live music of normal-hearing subjects and b) the hearing aid's ability to deliver high intelligibility in noise for hearing-impaired subjects. This is so surprising a result that it bears repeating: **Normal-hearing subjects judging the fidelity of music through a variety of hearing aids can predict almost perfectly the relative ability of hearing-aid wearers to understand speech in noise with those same hearing aids.** Even more surprising is that the same statement holds if "Hearing impaired subjects" is substituted for "Normal-hearing subjects" in the preceding sentence. That conclusion is based on the data of figure 6.

All known experimental evidence points to the conclusion that intelligibility in noise, patient satisfaction,

Figure 6. Percent fidelity ratings comparison.



and sound fidelity are highly correlated. The best intelligibility is achieved with the highest fidelity. Twenty to 40 years ago Edith Corliss and Ed Burnett (Corliss, Burnett and Stimson 1986), Jim Miller (1974), and Tom Tillman and Wayne Olsen (1973) all reached the same conclusion, a conclusion that unfortunately did not influence the design of some hearing aids.

So what can be done? The answer is surprisingly simple: do not give your patients hearing aids with poor sound quality. This advice is easier to follow than one might think, because hearing aids with good sound quality exist. Fortunately, as shown in figure 6, the average person with normal hearing can predict quite well the fidelity for a hearing aid wearer.

Similar evidence comes from dollar-value judgments. If you are asked how much you would pay for something that sounds like each of several hearing aids, your answers, as suggested by figure 7 will place about the same dollar value on the different aids as your patients do. These data were obtained from an experiment similar to that performed by Catherine Palmer (Palmer et al. 1995), when she told subjects that hearing aids cost as much as $700 (this was quite awhile back) and asked them to state how much they would be willing to pay for a hearing aid that sounded like this (music plays). She then presented a recording of the hearing aid under test. As seen in figure 7, dollar ratings by hearing-impaired subjects and by normal-hearing subjects are virtually identical when the hearing aids are high quality. I have intentionally blocked out the low-quality end to emphasize the good correlation for high quality hearing aids.

Figure 8, however, shows where the correlation breaks down. Hearing aid subjects are less willing to pay for low fidelity sound than normal-hearing subjects would expect, perhaps because they know they have to wear the aids. One can estimate that somewhere between a half million and a million persons have worn hearing aids that our hearing-impaired panelists judged were worth only a few hundred dollars.

One final comment on fidelity: although digital noise reduction schemes have never been shown to improve the intelligibility of speech (compared to properly fitted high-fidelity digital or analog amplification with wide-dynamic-range compression), there is an easy procedure that does. Bringing the microphone closer to the talker can work wonders. This is true both in noise and in reverberation.

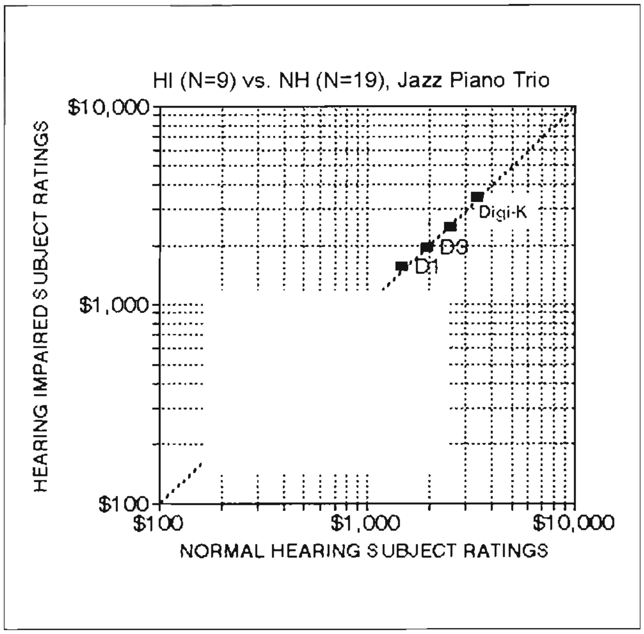


Figure 7. Dollar Ratings: Hearing aid wearers vs. normal hearing subjects.

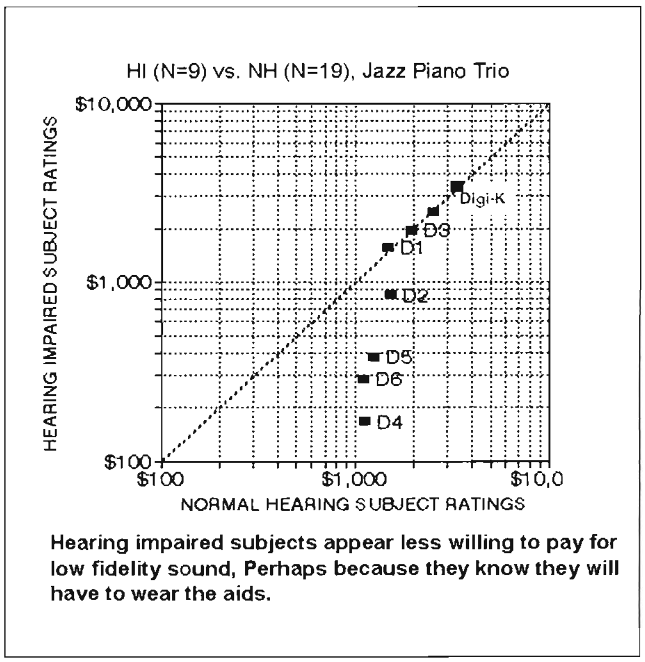


Figure 8. All dollar ratings: Hearing aid wearers vs. normal hearing subjects.

We have recently been conducting a study of experimental acoustic treatments for Chicago-area classrooms. The next A-B comparison that can be found at www.etymotic.com/download/06HiFiHA.ppt shows the enormous difference in intelligibility for QuickSIN sentences recorded in a room with a 1.3 second reverberation time compared to a room with low reverberation or – the equivalent – with the microphone substantially closer to the speaker's mouth than the "critical distance" in the room.

Although this benefit has been limited in the past to a single talker with an FM microphone, it is now possible to have three talkers wired with frequency-hopping 2.4 GHz transmitters, allowing several persons to converse with a 15–20 dB improvement in signal-to-noise ratio.

Two stories finish the talk. Story 1: One of our colleague's patients, now a 90-year-old gentlemen, saw an interview with an audiologist on local TV and decided he wanted to try these new digital hearing aids that could "think for you" and were described as "well worth their price of $8000." He ended up rejecting them, but I was curious about the claim that this digital circuit was wonderful for musicians. So I tested the equivalent hearing aid from the same manufacturer. The next recordings at www.etymotic.com/download/06HiFiHA.ppt show that on certain notes played individually, the "musical hearing aid" produced a very raucous distorted sound. This same distorted sound could be heard in the recording of a solo jazz pianist played through the hearing aid worn by KEMAR. These hearing aids could not be recommended to anyone who liked music.

Story 2: I recently borrowed another hearing aid, made by a different major manufacturer, from a local audiologist who reported good success with this particular model. I applied my standard musical tests (grand piano, violin, and singing and whistling loudly) and found no defects except that it sounded a little dull because of its limited frequency response. I wore it for a day with a foam earplug in the other ear. I had no trouble hearing in noise. I had no trouble recognizing voices and it easily passed the DHTTDTGTLWI (does not have to turn down the gain to live with it) test. I was surprised at how well I got along with this hearing aid. Overall, I would not hesitate to give a pair of these hearing aids to someone I liked.

Musician's quick predictive evaluation:
- Piano sounds: Even a scale is useful, augmented with chords
- Violin double stops high on E string
- Singing and speaking loudly (as in a noisy cocktail party)

But the real tests are:
- Wear them in the real world
  - Localization OK? (it should be)
  - Naturalness (forget that old "It's supposed to sound bad.")
  - Drive car; turn on radio (speech & music)
- Would you pay $8,000 for these aids?

Figure 9.

Conclusion

There are now at least two models of digital hearing aids with good fidelity. They sound good. How do you find them? Easy. All you need to do is wear them and listen. Figure 9 gives both musical and non-musical listening tests.

Appendix A

Hearing Loss From Noise: Latest Reports

Recent research on hearing loss indicates that most age-related hearing loss is, as one paper title put it, "evidence of a misspent youth" (Kujawa and Liberman 2006). Figure 10 gives a pictorial summary of these findings. In words, the story goes like this: excessive noise causes the stereocilia on the hair cells to turn to spaghetti. The body sends in a rescue squad to administer Bcl-2, glutathione, and the like. Some hair cells recover completely. A few die despite the rescue attempt (see Cheng, Cunningham and Rubel 2005 for a more complete treatment of cell death and protection). My statistically based, but not peer-reviewed estimate for one example of overdose is that each two overdoses cause the loss of one hair cell. For example, an exposure of 97 dB for eight hours, instead of the NIOSH (1998) recommended maximum of 85 dB, is a sixteen-times dose, which causes the death of nearly eight hair cells on the average. Dan Johnson (2003) provided a similar estimate in a paper titled: "One rock concert = 2½ years of aging."

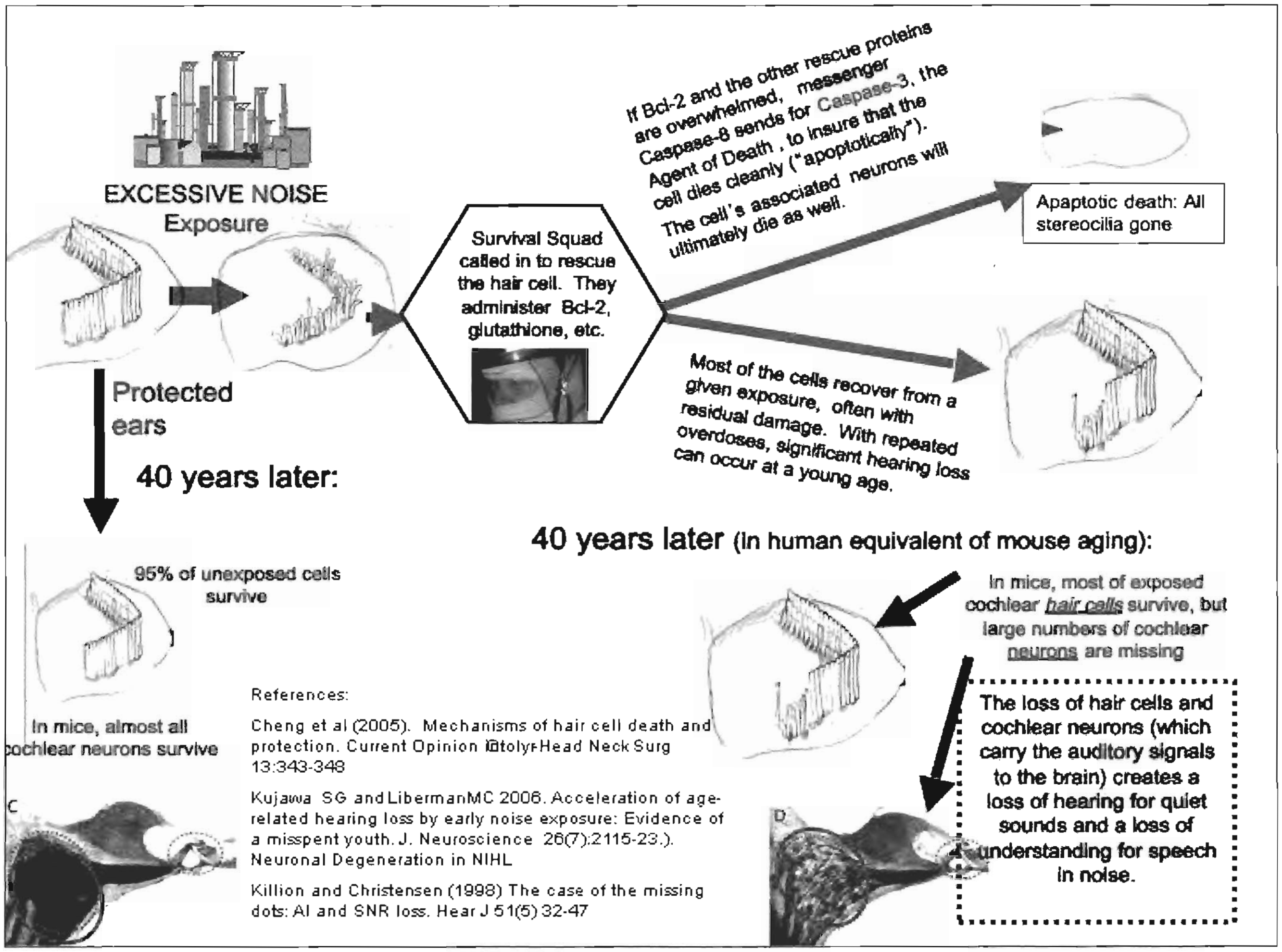


Figure 10. The composite story

In addition to the hair cells that die, many more are damaged. Some of them recover completely, but others only partially, with some of their stereocilia clumped together. In the latter case, normal incoming sound no longer opens enough ion channels to let a sufficient number of potassium ions into the hair cell to cause the associated neuron to fire. Over a period of 40 years (in mice-equivalent age), perhaps half of the neurons associated with those partially recovered hair cells say: "I seldom get any calls, I must be superfluous," and they die.

Although the loss of one or two hair cells or neurons is not a significant event, the attendance at two Slipknot rock concerts a year – a colleague recorded 116 dBA at one of them – may result in the direct death of 320 hair cells. Ten years of such activity may result, therefore, in the loss of 20% of the 15,000 hair cells we start with. If an equal number of neurons die years later, roughly a third of the hair-cell information will be lost, with an attendant threshold shift and – more importantly – a loss of ability to hear in noise.

Appendix B

Over-the-Counter Hearing Aids

The immediate virtue of over-the-counter (OTC) hearing aids is their ease of purchase without loss of safety. They are already widely available, of course. You can buy over-the-counter hearing aids as hunter's aids at sporting goods stores. They are usually found near the gun cabinets. (See figure 11).

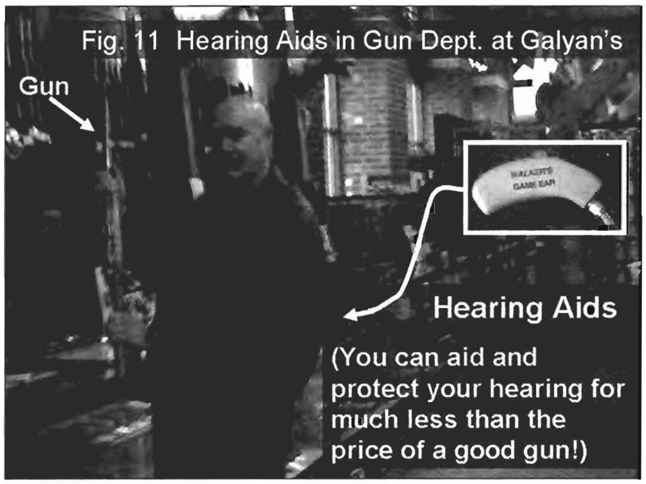


Figure 11. Hearing aids in gun department at Galyan's

Unfortunately, the Food and Drug Administration (FDA) answered both the OTC petitions (Killion and Gudmundsen 2003) with a single objection: "The buyer should see a medical doctor first." This, despite the fact that individuals who buy FDA-approved hearing aids from a licensed dispenser or audiologist may sign a waiver rather than see a medical doctor, and that no one dies from problems of the ear. Although the latter is the weaker argument, it is interesting to note that the Government of British Columbia (2001) keeps complete records on cause of death in its 3.5 million population (www.vs.gov.bc.ca/stats/annual/2001index). In 2001 there was a grand total of 28,104 deaths.

There were no reported deaths for diseases of the eyes and ears (figure 12).

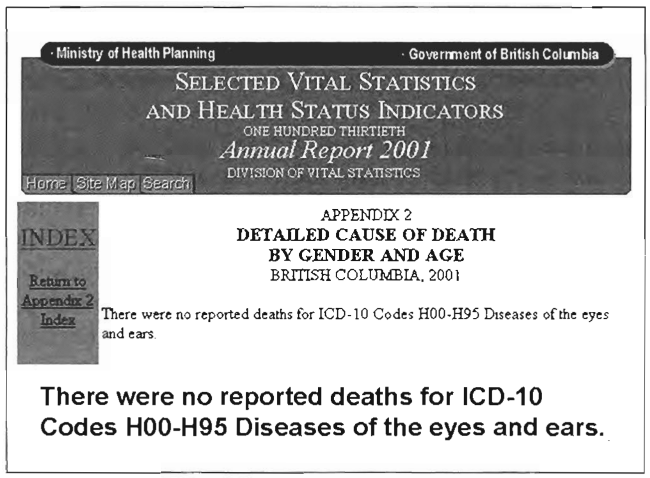


Figure 12.

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