FIGURE 24. One subject's word-recognition scores when tested with the two frequency responses shown inset (after Skinner, 1980).

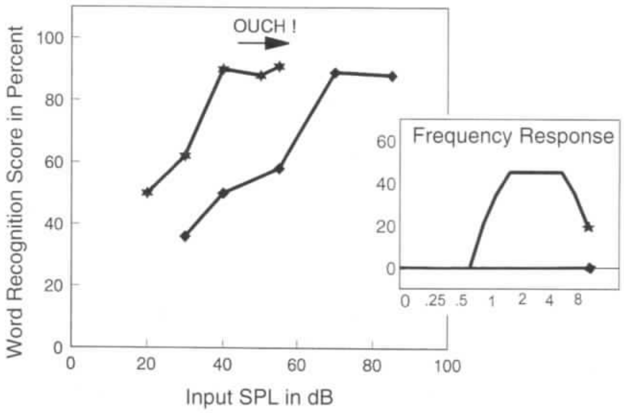


FIGURE 25. Relative gain and frequency response of the K-Amp circuit for different input levels.

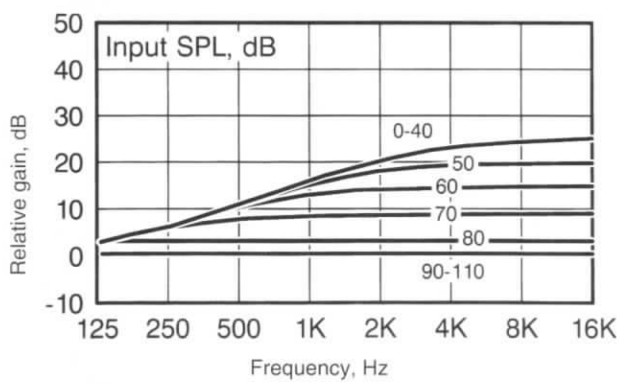
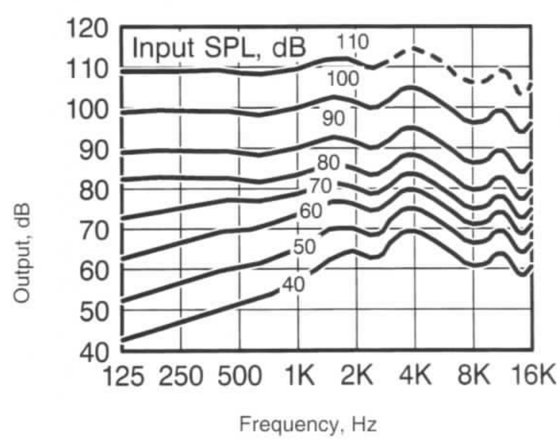


FIGURE 26. Real-ear output curves for complete K-Amp hearing aid with 40 to 110 dB SPL inputs.



phone Etymotic Research we will send you a couple. Our fantasy is that every dispensing office in the United States will have this poster prominently displayed.)

The K-Amp chip can't work by itself, but needs to be mounted to a ceramic "hybrid" circuit that contains the necessary capacitors and has solder pads so it can be wired into a hearing aid. Figure 28 shows the three K-Amp hybrids that have been produced to date. The first one, the 19D, was designed by one of our fellows, Jonathan Stewart; the second one, the 24D, by Andy Joder and Chris Conger of Rexton (who correctly believed they could make a much smaller one), and the even smaller third one, the 28D, by Tony Becker of TEC. The 28D uses a buried capacitor substrate (BCS) construction in which all of the capacitors are contained in one monolithic block of ceramic.

The 28D makes possible the tiny K-Amp hearing aid that is shown in my ear and on my finger in Figure 29. This is what several of us suggested be called a CIC hearing aid, a Completely In the Canal hearing aid. (To qualify as a CIC hearing aid, all parts of the hearing aid—including its volume control, battery drawer, etc.—must be 1–2 mm inside the entrance to the ear canal). This particular CIC hearing aid is a work of art (and quite expensive). Indeed, to make such a K-Amp hearing aid with present-day parts requires a sculptor who is willing to spend hours visualizing how the parts might be placed and sculpting the shell so that it slips in smoothly without pressing against the skin in the bony part of the ear canal. Mine slips in and is completely comfortable, with relatively low occlusion effect. I'm grateful to Randolph Giller for proving that it was possible. (As an added flourish, Giller included the BF-1743 metal damped coupling assembly, an assembly some manufacturers have claimed was too large even for ITE hearing aids.)

The CIC hearing aid may be difficult at the moment, perhaps, but once something is proven possible, improvements follow rapidly. It is only a matter of time before

FIGURE 27. Poster showing enlarged view of K-Amp integrated circuit chip.

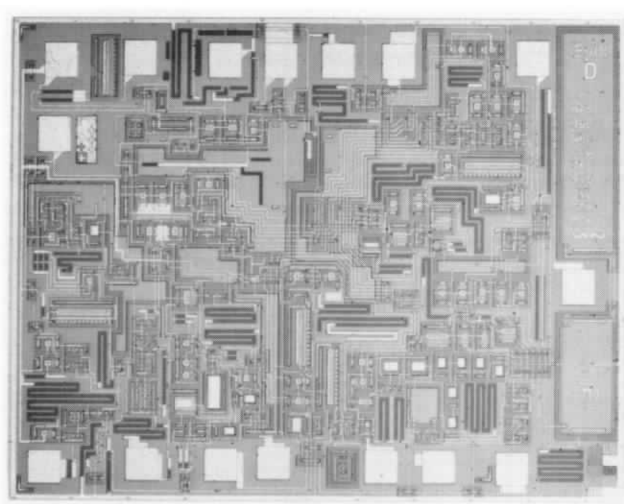
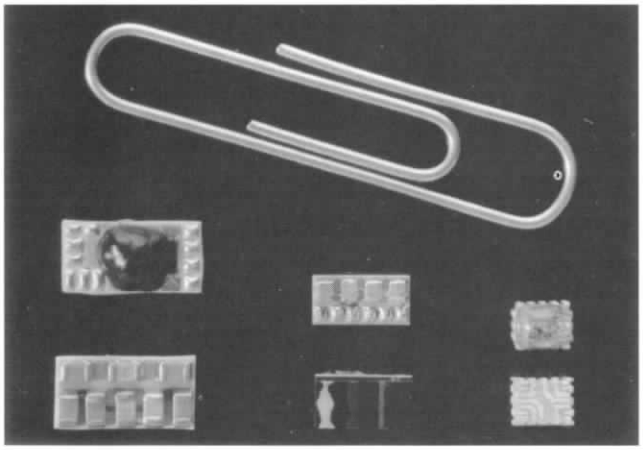


FIGURE 28. Enlarged view of three K-Amp hybrids: the 19D, 24D, and buried-capacitor-substrate 28D.



even smaller parts will make it possible—on a regular production basis—to put hearing aids inside the ear so deeply that you can ask someone to look at your hearing aid and have them say "what hearing aid?" And really not be able to see it unless they pull your ear back.

Two Features Contributing to High Fidelity

Two circuit tricks have contributed substantially to the overall fidelity of the K-Amp circuit. First of all, I mentioned earlier that the input circuits of many hearing aids typically overloaded at 85–90 dB SPL. The circuit trick that was part of the first K-Amp patent added 30 dB of undistorted input range, illustrated in Figure 30. Instead of overloading at 90 SPL, the circuit itself can go up to 120 dB. Dave Preves, who was kind enough to have the first K-Amp hearing aids built for me 3 years ago, also made coherence measurements on them. Figure 31 shows those results, verifying that at 90 dB SPL input the complete K-Amp hearing aids had a coherence of essentially 1.0 (i.e., zero noise and zero distortion) out to 13 kHz.

The other circuit trick, patented by Dave Hotvet, is called Adaptive Compression (a registered trademark of Telex Communications). In his article, Harry Teder (1993) told you why Adaptive Compression was so good, and I have to agree with him, but Harry didn't tell you how it worked. I'd love to explain that, so I'm going to.

FIGURE 29. Completely-In-Canal (CIC) hearing aid made possible by the small size of the 28D (not to mention the small size of the microphone, receiver, trimpot VC, and battery) and an enormous expenditure of time.

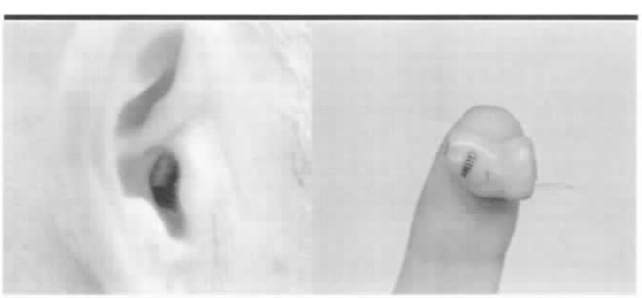
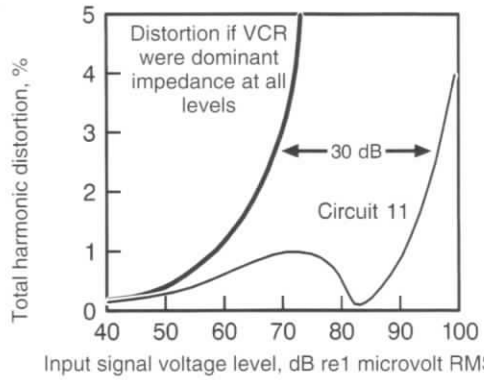


FIGURE 30. Reduced distortion for high-level input signals in K-Amp, compared to typical hearing aid input amplifiers.

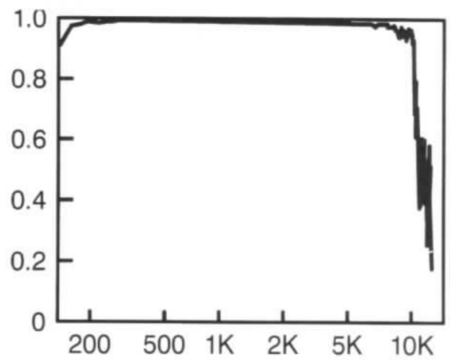


First, let's review the dilemma in trying to choose a single time constant when you don't have Adaptive Compression. If you choose a fast time constant, background noise rises up immediately when the talker pauses, giving rise to what is called "pumping" of the gain. In Chicago, for example, baseball broadcasts are made with an extremely short-time-constant compression amplifier (I'd guess 50 msec or less). When the announcer says "Johnson is coming up to bat" and pauses, the crowd noise comes up as soon as his voice stops. So what you hear is "Johnson is coming up to bat...KHSCCSKCHSCK.. .and he swings...KSSKHSKHHKHSS...and misses...KHSS KSKHHKHSS..." with the...KHSSKSKHHKHSS...of the crowd noise as loud as the announcer's voice. The broadcast engineers could solve that problem any time they wished, but it's apparently a part of the Chicago baseball mystique, intended to convey some of the excitement of the game, I guess.

Exciting for baseball, perhaps, but such a fast time constant can be especially irritating if you're listening to a live lecture, for a reason that I'll explain in a moment. We learned about this problem the hard way while we were relearning the importance of actually wearing samples of the hearing aid designs we were working on. We had spent hours and hours in the laboratory listening to the K-Amp circuit over very-high-fidelity loudspeakers. We listened to classical orchestra, jazz ensembles, male and female voices in quiet and with cafeteria noise, street noise, and indeed everything we could think of in the background.

Based on these listening evaluations, we convinced ourselves that the K-Amp hearing aid did not need Adaptive Compression, even though Harry Teder thought I was crazy (I think those were his exact words) not to consider it seriously. I explained to Harry that because the K-Amp circuit used a wide-dynamic-range compressor with a relatively low compression ratio—just a little over 2:1—the gain change was spread out over such a wide range of input levels that "his" problem wasn't a problem for us. Adaptive Compression made a dramatic improvement with a high-compression-ratio output limiting circuit such as Telex used, but our listening tests convinced us that we didn't need it in the K-Amp circuit. (We weren't the only ones. We recently obtained a U.S. patent on Adaptive

FIGURE 31. Coherence measurements on first K-Amp hearing aid: 90 dB SPL input.



Compression used with wide-dynamic-range compression amplifiers that increased the gain for quiet sounds, successfully arguing that all previous uses—broadcast, recording, and hearing aid—had been restricted to compression-limiting circuits that reduce the gain for loud sounds [Killion, Teder, Johnson, & Hanke, 1992].)

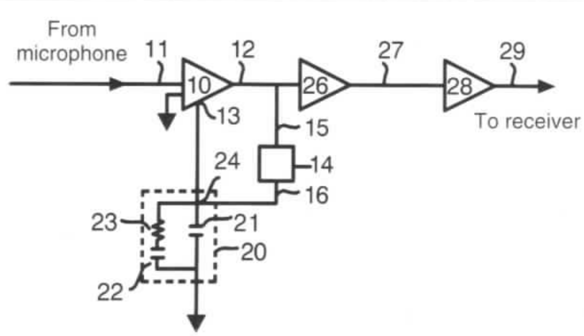
The problem with our listening tests was that they used loudspeakers. This is fine for checking fidelity and the like, but with all sounds coming from one source location the sounds combine into one gestalt and the "pumping" effects of compression are less noticeable. In real-world listening with a fast-time-constant compressor in headworn hearing aids, however, it becomes very irritating when the voice of the lecturer up in front modulates the shhhhh of the projector fan on your right. There's no problem when both come together from a single source location, but once you have normal localization in a real room, it is very unnatural for the sound of the projector to modulate up and down as the lecturer speaks. The SHHHshhhshhhhhhhhshhhSH HHHshhSHHHHshhSHHshhhhhSHH sound from the projector becomes annoying. You can live with it; you can get used to it; I got used to it in the first week or so of 3 months wearing K-Amp hearing aids, trying to convince myself that it was not really annoying, but it was.

During this denial period, Harry Teder finally convinced me to come up to Telex for technical assistance and to seriously consider adding Adaptive Compression to the K-Amp circuit. We both became convinced that in the real world, wearing headworn hearing aids that allow you to localize different sound sources, Adaptive Compression made a significant improvement to the K-Amp circuit. (An interesting postscript to the story: When Harry and Art Johnston and Steve Hanke and I finished the day at Telex, we set out to demonstrate to management what a big improvement we had. We wired the K-Amp circuit up for a demonstration using—you guessed it—loudspeakers, and then spent about half an hour trying to find demonstration conditions that would clearly illustrate the improvement. We ended up with a weak demonstration that was not convincing at all, even to us. But if you put an On-Off switch on the Adaptive Compression in a pair of K-Amp ITE hearing aids and wear them, it's a night and day difference.)

When you don't have Adaptive Compression, the standard solution to the pumping problem in audio equipment is to use a long, slow time constant, perhaps 2 to 3 sec. You'll find that sort of time constant in every one of the portable cassette tape recorders we all use. They don't have a recording volume control, only a high-compression-ratio compressor with a long recovery time. So why not do that in hearing aids? The problem is that if you have a 2–3 sec recovery time, every loud, sharp click or snap will take you "off the air" for a second or so. Telex has a nice demonstration cassette that illustrates this phenomenon.

So with regular compressors you're caught between the devil and the deep blue sea: pumping sound or off-the-air-with-every-click sound. The Adaptive Compression solution illustrated in Figure 32 is really cute. Hang in there with me and I'll explain it simply. See the two capacitors labeled 21 and 22? Capacitor 21 is a small one, which gives the standard fast-recovery-time (50-100 msec) behavior typical of hearing aid circuits. (With capacitor 21 alone, the hearing aid is never off the air, but listeners complain of the pumping sound. A few listeners would even rather have linear circuits.) When a loud sound comes along, the voltage on capacitor 21 is yanked down—so the gain of the hearing aid goes down—and then you have a current source that is pulling it back up so that 50-100 msec later the gain will be restored. When you add the large capacitor 22 and resistor 23, what happens with a loud click is that the small capacitor goes down quickly just as before, but the big capacitor doesn't know anything has happened, it's just sitting there fat and happy because the resistor isolates the big capacitor from sudden transients. But now the big capacitor has its normal voltage and the small capacitor has a low (low-gain) voltage and so a relatively large current (10 times normal) immediately flows from the big one into the small one to help it recover. In effect, the big capacitor reaches down and yanks the little one back up! The result is that instead of having a 50–100 msec recovery time after a short intense transient, you have a 20 msec recovery time. In fact, if you're listening in quiet and you have 25 dB of gain and you snap your fingers, it sounds as if nothing happens. The gain drops 25 dB and recovers so quickly your ear doesn't know anything has happened. It is a magic circuit for handling

FIGURE 32. Adaptive Compression circuit (after Hotvet, 1988, U.S. Patent 4,718,099).



transients. (There is solid psychoacoustic evidence to substantiate this somewhat loosely worded explanation, incidentally.)

For prolonged steady sounds, on the other hand, the big capacitor gradually discharges and then holds on to the small capacitor to prevent the gain from pumping up and down. With the big capacitor as an anchor, rapid changes in gain are held to 5–6 dB, which are not perceived as pumping. As Harry argues, these rapid changes may even operate to improve speech intelligibility. In ongoing speech, the weaker consonant sounds after strong vowels have a rapid gain recovery of 5 or 6 dB. This 5–6 dB relative boost for weaker consonants could act as consonant enhancement.

What Adaptive Compression does in terms of sound quality is circumvent the time-constant dilemma by making the fast recovery time constant even faster and the slow recovery time even slower, as shown in Figure 33. For short (1–10 msec long) transients, you have about a 20 msec recovery time. For prolonged sounds, you have about a 500 msec recovery time. For speech sounds such as vowels, you have roughly a 100 msec recovery time. By the way, this provides the basis for a quick listening check of a K-Amp hearing aid to see if it is working properly. This is what I call the "long loud aaaaaah test." You say a loud aaaaaah long enough (1 to 2 sec) to shove the voltage on the big capacitor down completely, and then listen for the momentary delay you should hear before the background noise comes back up.

95% Success Vs. 50% Success

So we have a hearing aid with a 16 kHz bandwidth, no audible distortion, a sensible level-dependent frequency response, and Adaptive Compression. That combination was so successful in the hands of the leading-edge dispensers who started using K-Amp hearing aids that they kept pushing the envelope and fitting it on more and more people. And after a while, they were reporting 90-95% success rate on almost everyone they put the K-Amp hearing aid on. Those dispensers were carefully reading the articles and data sheets and Etymotic's first Ordering and Fitting Guide (which wasn't particularly easy to read).

FIGURE 33. Recovery time vs. transient duration: variable recovery time of K-Amp Adaptive Compression circuit.

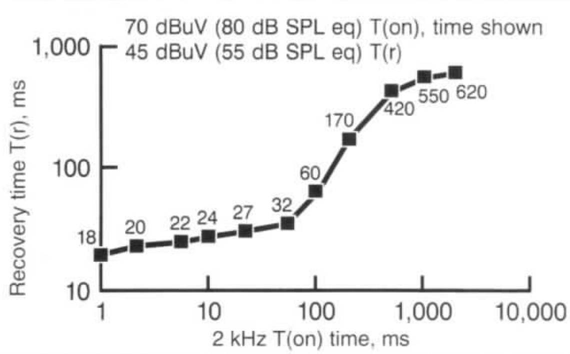
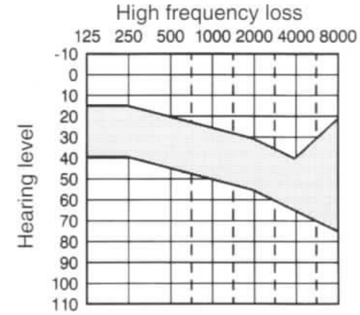


FIGURE 34. Low-risk fittings for K-Amp hearing aids: moderate high-frequency losses have a high probability of a successful fitting without special effort.



Order standard K-Amp response with LFC and TK trimmers

They called the factory when they had a problem, did real-ear measurements, and became sophisticated at modifying and adjusting the aids.

Any manufacturer who has introduced an innovative new design can tell you the next part of the story. The second generation of dispensers, hearing that the K-Amp hearing aid was a panacea that solved all problems, started dispensing them on their clients with difficult hearing losses, but didn't read the data sheets as carefully (after all, they heard it was supposed to almost fit itself), they didn't call the factory to find out how to adjust the trimmers, and the hearing aids didn't work. The manufacturers starting seeing 20–30% overall return rates.

So we have now taken a somewhat more cautious, sadder but wiser approach, and have attempted to separate high-risk from low-risk fittings. For the range of hearing losses shown in Figure 34 we said OK, based on our experience and what we learned from our customers; this is a low-risk fitting. With a loss in this range, you probably don't have to read the data sheet or even adjust the trimmers. You can probably take the aids as they come from

FIGURE 35. High-risk fittings for K-Amp hearing aids: moderate-severe flat losses that require special transducers, circuit modifications, and/or counseling.

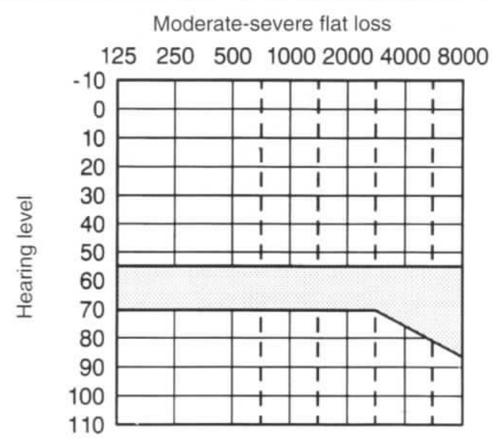
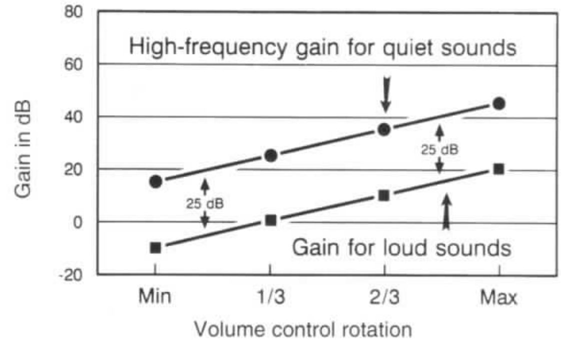


FIGURE 36. Automatic 25 dB increase in high-frequency gain is unaffected by volume control setting.



the manufacturer, put them on someone, and with an adjustment of the volume control they'll probably be a happy camper.

Figure 34 showed one of the low-risk fitting categories. The other two were both shown in Figure 21: Mild-moderate flat loss and mild-moderate reverse loss.

High Risk: Moderate-Severe Flat Loss

Figure 35 shows a high-risk fitting. You need to use a high power receiver and you're pushing the envelope, but there are thousands of these that are highly successful K-Amp fittings, individuals who report that these are better than anything they've ever heard. But there are also thousands of aids ordered for losses like those that have come back to the factory. I would like to just take a few minutes describing how to keep them from coming back.

First of all you need to understand the volume control in a K-Amp hearing aid. We have spent so much time talking about the fact that the ideal K-Amp hearing aid doesn't amplify loud sounds that some dispensers think that, no matter what you do with the volume control, K-Amp hearing aids won't amplify loud sounds. If you ask what the volume control does, the answer is that it makes things louder, except loud sounds don't get any louder. Now that's a little too much. In fact the volume control is there to allow you to achieve the doesn't-amplify-loud-sounds result should you want to.

Figure 36 illustrates the action of the K-Amp volume control on the standard-power version measured on an average ear. If you set the volume control for about 1/3, you will produce 0 dB gain for loud sounds (everything from 90 dB SPL on up will come out unamplified). You will get 25 dB more gain for quiet sounds.

If you turn the volume control all the way down you will have a hearing protector. The K-Amp hearing aid will actually attenuate loud sounds by about 10 dB and give you about 15 dB gain for quiet sounds. If you turn the volume control all the way up, on the other hand, you can have 20 dB of gain for loud sounds and 45 dB for quiet sounds. What is fixed here is the 25 dB difference in gain for loud sounds and quiet sounds. What is not fixed is the overall gain. Technically, the K-Amp hearing aid is an input-compression aid, so that the volume control determines the output range into which the compressed input range will be fitted.

Now we can see how we might fit someone with the moderate to severe flat loss shown in Figure 35. Clearly they need more than 25 dB of gain for quiet sounds; something like 40 or 45 dB would be more appropriate. They will obtain that when they turn up the volume control, but if they do that, loud sounds will be made louder also, as shown in Figure 36.

So we start by asking whether or not we are going to get into trouble when they choose 15 or 20 dB of gain for loud sounds. Fortunately, it looks as if the answer is generally no. The data that Barfod accumulated back in the '70s on the level at which complete recruitment sets in (which means loudness comes back to normal) are shown in Figure 37. His data showed that by the time you have a 70 dB hearing loss you need about 14 dB of gain for a 90 dB input in order to reach full normal loudness. Will 14 dB of gain for loud sounds cause discomfort for very loud sounds? Pleasantly enough, we have the impeccable loudness discomfort data of Pascoe (1988), shown in Figure 38, obtained on 500 ears at four frequencies: 500,

FIGURE 37. Level at which complete recruitment (return to normal loudness) occurs as a function of hearing loss, from all subjects and frequencies (from Barfod, 1978).

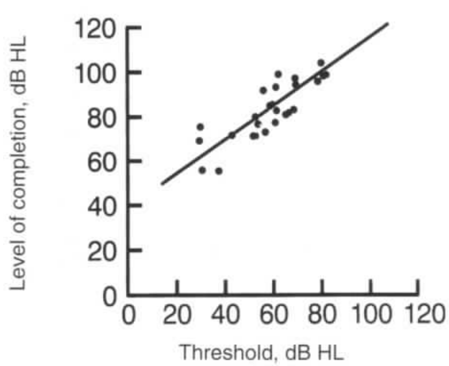


FIGURE 38. Mean comfort and discomfort levels for pulsed pure tones as a function of hearing loss, from 500 subjects and four frequencies. Data above 120 dB HL extrapolated from lower-level loudness-scale judgments (from Pascoe, 1989).

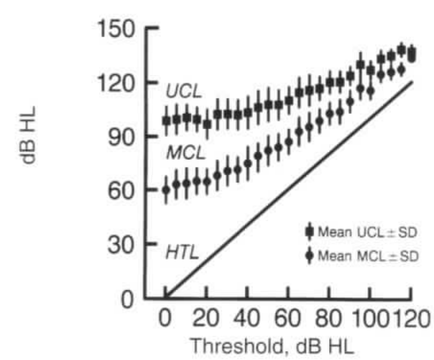
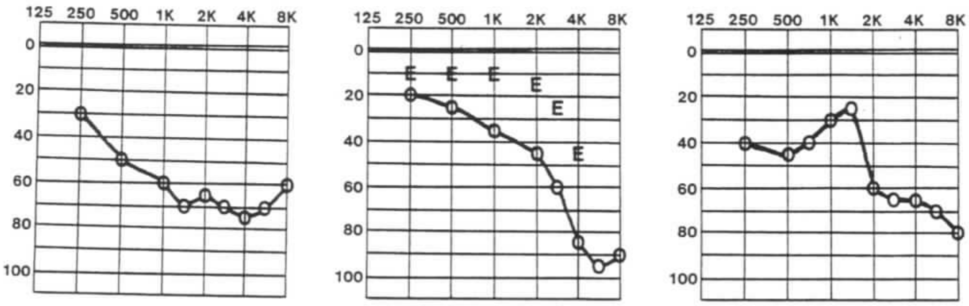


FIGURE 39. Audiograms of three successful K-Amp hearing aid wearers ("E" stands for Expected aided threshold).



1000, 2000, 4000. Pascoe's data indicate that the average individual with a 70 dB hearing loss has a loudness discomfort level that has been elevated by 17 dB.

We conclude that the person with a 70 dB loss, using 14 dB of gain for all loud sounds, would have no less headroom with regard to discomfort (actually 3 dB more) than the person with normal hearing without gain. The nice thing about this way of looking at the problem is that the answer doesn't depend on input level: Whatever a person with normal hearing would be exposed to would cause no more discomfort to the person who wears a hearing aid than to the person with normal hearing.

Moderate-Severe High Frequency Loss

Figure 39 illustrates another high-risk category, individuals with a moderate-severe high-frequency loss. The middle audiogram is an experienced dispenser who has tried many different hearing aids over the years, and reports that the K-Amp hearing aids are overall the best yet.

But fitting someone like this is even trickier than the moderate-severe flat loss individuals, and you need to know how another K-Amp control works. This one is what we call the low-frequency control, the LFC trimmer. In the standard high-fidelity version of the K-Amp hearing aid, this trimmer is wired in series with the volume control. Most hearing aid engineers think this is a questionable design: it's not a good response control because it interacts with the volume control. When the volume control is turned down near minimum, for example, the LFC trimmer has very little effect on the response, as shown in Figure 40. (We have received phone calls to say the tone control doesn't work; they can't see much difference at either extreme setting.) If you turn the volume control all the way up, on the other hand, the LFC trimmer has a lot of effect, some 30 dB range at 125 Hz as shown in Figure 41.

Having a tone control interact with the volume control may or may not be a disadvantage but, following the Tektronics adage (if you can't fix it, feature it), we choose to feature it. At the minimum-bass-response setting of the LFC trimmer, it turns the volume control into a treble boost control. This is shown in Figure 42. When you have individuals with the audiogram I just showed, who never need any low-frequency gain, you can now give them a volume control that allows them to decide for themselves just how much boost they want for loud sounds at high frequencies (and they're always going to get 25 dB more high-frequency gain for quiet sounds).

Figure 43 shows the insertion response available at the extreme settings: You can have a hearing aid that gives you 20 dB of gain for loud sounds and 45 dB gain for quiet sounds at high frequencies, without ever giving you any low-frequency gain. I believe the reason that the K-Amp hearing aid has been so successful on moderate-severe high frequency hearing losses is that it can provide the flexibility just described when it is properly adjusted. Needless to say, if you don't adjust it properly it probably is not going to be the right hearing aid for those types of loss. (Unlike

FIGURE 40. LFC has little effect at low volume settings.

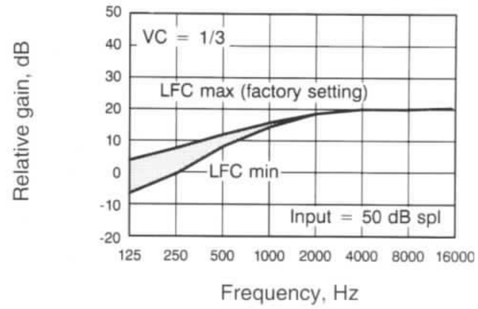
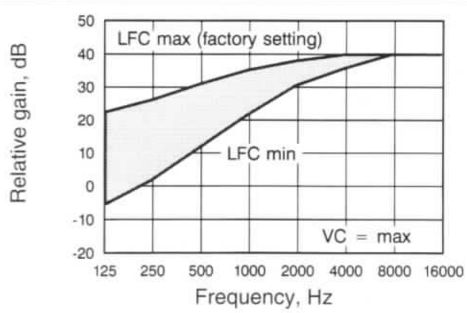


FIGURE 41. LFC has large effect at high volume settings.



typical hearing aids, a K-Amp hearing aid operated near full-on volume setting may be perfectly reasonable. Nonetheless, the high-power receiver is a good choice for this type of loss because it gives 5 dB more gain margin.)

When Not to Order K-Amp Hearing Aids?

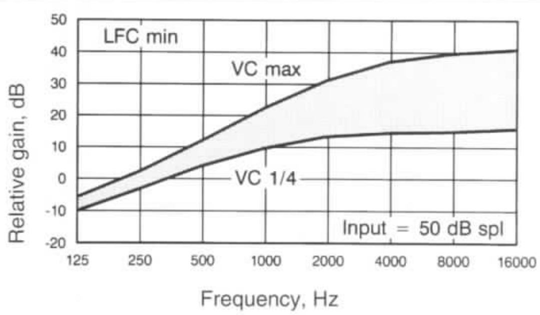
When do you not need a K-Amp processing? When is it you don't want a wideband response; when is it you need compression limiting or a narrower-band response? The narrowband, wideband answer is usually obvious. If you have no useful hearing above 3 kHz, or if you have a 90 or 100 dB loss at 4 kHz, there's no point in going out to 16 kHz in the hearing aid; any feedback that occurs will be heard only by the neighbors and not by the person wearing it. When extreme low-frequency gain is needed, narrow-band is better. Both Poul-Eric Lyregaard and Harry Teder have published papers showing that you can roll off the highs and get more gain at the remaining frequencies.

The question of compression limiting versus wide-dynamic-range compression is a little more subtle. We don't do much of it over here in the United States, but in Europe they do a lot of word-recognition measurement at a variety of levels.

The person illustrated in Figure 44 has word recognition scores that are climbing all the way into the discomfort zone. In fact, if that person were willing to put up with discomfort, he or she could understand speech in noise even better. Now, a person like that doesn't have too much of a problem in quiet when there are plenty of redundant cues available, but does have a problem in noise. In order to survive at a cocktail party, that person would need to run the volume control up and down to keep everything right below discomfort. Otherwise, he or she won't be able to carry on a conversation with you. And that's a pretty inconvenient thing to do, as Harry Teder points out; and I agree.

I believe the person illustrated in Figure 44 is best suited with a compression-limiting design, and I agree that it should be Adaptive Compression; it's a much better circuit. With compression limiting, the individual in difficult circumstances can push the volume control up so that everything sits right up against his or her maximum word recognition score. And so in this case I would send you to Harry.

FIGURE 42. Volume control becomes treble boost control at reduced LFC settings.



What's Wrong With K-Amp Hearing Aids?

I don't want to spend much time on this topic, but there are some limitations that should be mentioned.

Real-Ear Response Irregularity. The typical real-ear response of the K-Amp hearing aid has a dip at 2.5 kHz and a boost at 4 kHz. That is a receiver problem that Knowles will solve shortly, I believe.

Ultrasonic Alarms. Ultrasonic burglar alarms and ultrasonic light-control sensors can affect the hearing aid gain. Harry Teder pointed out this problem to me some 15 years ago; it's not just a problem for the K-Amp hearing aid. The level of the 25 kHz or 40 kHz ultrasonic signals can exceed 100 dB SPL, and every small motion in the room affects the ultrasonic level at the hearing aid input (and thus the gain). There are two solutions: Roll off the high-frequency response of the microphone (Etymotic makes a glue-on microphone filter that we have used successfully for this purpose) or, with the K-Amp circuit, you can use what we call the Loudness Boost switch. With this, the user can flip in a fixed amount of gain for those circumstances when an ultrasonic system would otherwise run the gain up and down.

FIGURE 43. Insertion response available at extreme settings of LFC trimmer and volume control.

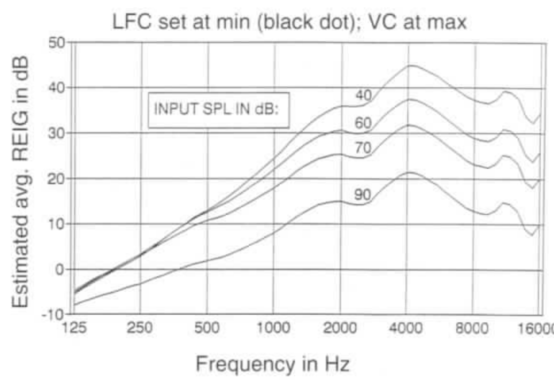
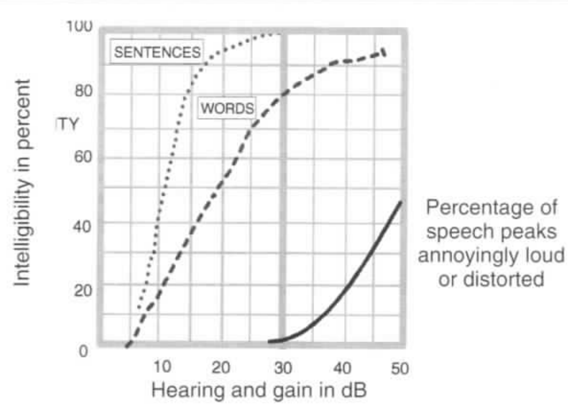


FIGURE 44. Estimated relationship between hearing aid gain, speech intelligibility, and annoyance for user with 60 dB sensorineural hearing loss in conversational setting (from Killion, 1982).



Increased Feedback Problems. Increased difficulty with feedback is absolutely a problem with the K-Amp hearing aid and with any hearing aid that makes it practical for the wearer to obtain the gain needed for quiet sounds. If the user doesn't have to turn down the gain to live with it, he or she probably won't. This means the user is going to be dealing with more gain, and thus you're going to have more trouble with feedback. You're going to have to get a better fit and you'll have more trouble juggling the amount of venting vs. the occlusion effect. (I recommend Etymotic's foam E-A-R rings for temporarily stopping slit-leak feedback as a diagnostic measure.)

Occlusion Effect Not Solved. The occlusion or hollow-voice problem has not been solved by the wideband response of the K-Amp hearing aids, although at first we thought it might have been. Adjustment of the low-frequency response with the LFC trimmer often relieves the problem, as it does in any hearing aid, but appropriate venting is still the first line of attack.

Response-Smoothing Dampers Get Clogged. We have a couple of new damper removal tools that ease the problem somewhat, usually making it possible to replace the dampers in the office rather than sending the hearing aid back in for repair. The dampers make great wax traps, saving an expensive receiver replacement, but become clogged sooner than the more deeply placed receiver would. Some manufacturers have switched to a modified-response receiver from Knowles. This gives a reasonably smooth response without the need for dampers.

FIGURE 45. TK (Threshold Knee) trimmer reduces high-frequency gain in quiet by as much as 12 dB.

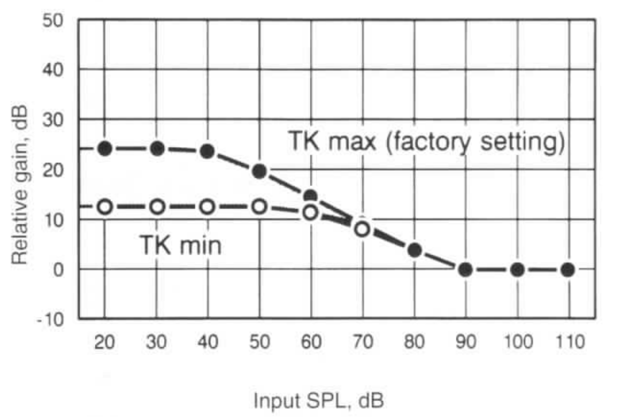
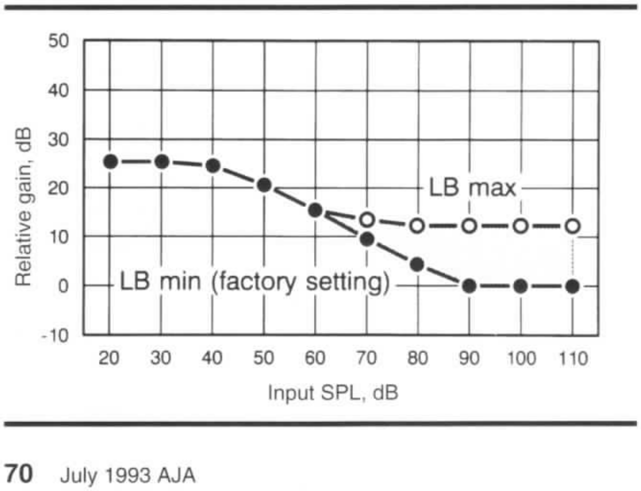


FIGURE 46. LB (Loudness Boost) trimmer increases gain for loud sounds by as much as 12 dB.



Noise Complaints: Circuit Noise. Circuit noise and background noise are the basis for the two types of noise complaints. A person with a region of normal hearing, or someone with a mild hearing loss who turns the volume control way up, may indeed be hearing circuit noise. Precisely speaking, it's the amplified microphone noise that they hear; the circuit noise is much below that. One possibility is that the person is used to linear hearing aids and has turned the gain up too high, trying to make loud sounds sound as loud as they do with the old linear aids. The solution here is to counsel them that even though they are used to a lot of loudness, they don't need loudness but rather clarity, and to turn the gain down. That may solve the complaint.

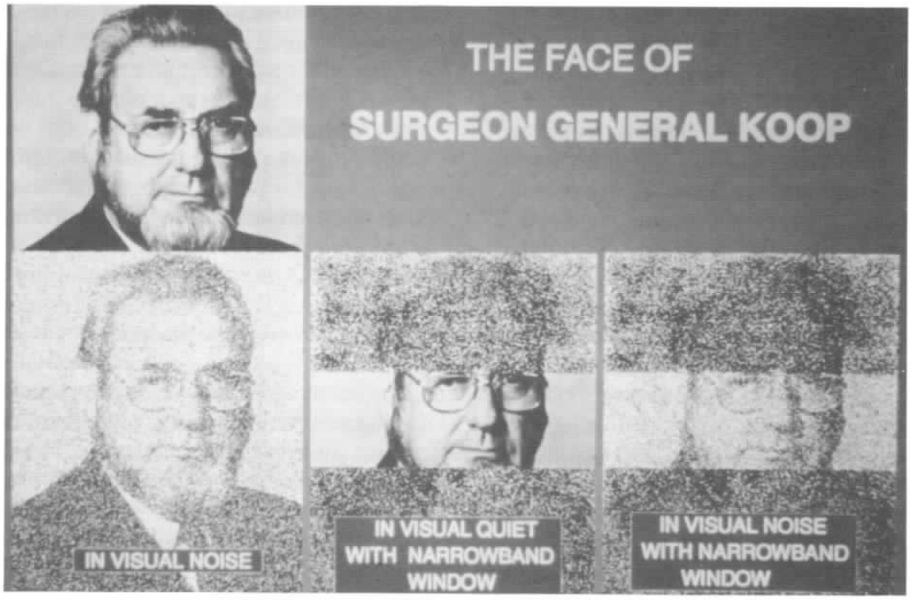
Another reason for a circuit noise complaint is that someone has a region of normal hearing and receives too much gain increase in a quiet room. For that individual, an adjustment of the Threshold Knee (TK) trimmer is required. This TK trimmer is a poor man's compression-ratio control.

As shown in Figure 45, instead of changing the K-Amp's 2.2:1 compression ratio itself, you change the lower threshold knee so that the gain stops increasing as the level drops below 65 dB SPL. Instead of increasing 25 dB over the entire range from 90 dB down to 40 dB SPL (TK min setting), you have only a 12 dB increase from 90 dB down to 65 dB SPL and constant gain below 65 dB (TK max setting). If you take the average gain change over the full 90 to 40 dB range, it effectively works out to reducing the average compression ratio to about 1.5:1.

But your client doesn't care about compression ratios. The point is that with the TK trimmer turned up, your client won't have as much gain in quiet and won't hear the circuit/microphone noise. For someone who really wants more loudness, on the other hand, the loudness boost (LB) trimmer illustrated in Figure 46 may be even more useful. The LB trimmer also acts to reduce the average compression ratio, but instead of reducing the gain (and high-frequency boost) for quiet sounds, the LB trimmer can be used to increase the gain for loud sounds.

Noise Complaints: Background Noise. The other type of noise complaint comes from background noise in the room. When an individual hears noises but can't localize them because they haven't been heard for a long time, you may hear complaints that the hearing aid is noisy. You can check this out by simply having such individuals put their fingers over the microphone inlets. If they put their fingers over the microphone inlets and the noises go away, the noises are not in the hearing aid! Those people may tell you that it sounds like noises in the hearing aid, but that's because they just can't localize such noises anymore. The noises they hear are actually out in the room. We have a relearning problem.

FIGURE 47. A visual analogy to the problem of hearing in noise with narrowband hearing aids.



Learning to Hear Again in Noise

Our first temptation is to attempt to filter out the noises. What we all would like is a hearing aid that would accept speech and noise at the input and give only filtered speech at the output, giving a noise-free speech signal at the output.

Unfortunately, you can't have it both ways. As Villchur explained, you can suppress the noise, or you can hear speech clearly in noise, but not both.

Filter the Noise or Hear Clearly. Figure 47 provides a visual example of the problem. In the upper left picture, you see the face of [former] Surgeon General Koop clearly in visual quiet. You can still make him out in visual noise, as shown in the lower left picture. You can also still make him out if you cut out the highs and lows, as in the lower center picture (sort of a visual analog to a narrowband hearing aid). But if you have a narrowband look in noise, you have trouble. In quiet, you can get by with a narrowband hearing aid or a narrowband visual system, but in noise you run into trouble. With a narrowband system, you've lost the redundant information that allows you to hear in noise or see in noise.

Figure 48 provides another example that Don Wilson made from Dave Pascoe's visually noisy illustration of the sentence: "Words that are not clear when they come into the hearing aid will not be clear when they come out of it." When Don masked off the highs and the lows in visual quiet, you don't have any trouble. But in visual noise, it is virtually impossible to determine what those words are when you've knocked off the visual analog of the high frequencies and the low frequencies.

FIGURE 48. Another visual analogy to the problem of narrowband hearing aids (adapted from Pascoe, 1991).

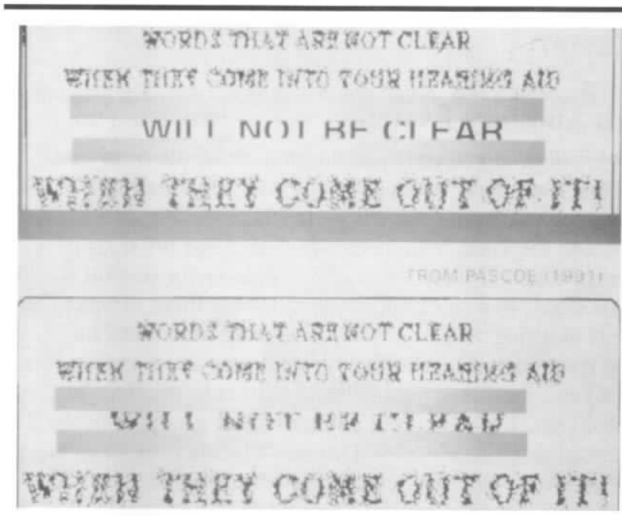
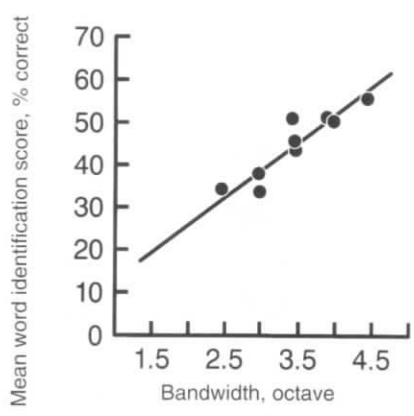


FIGURE 49. Intelligibility vs. bandwidth for two hearing impaired listeners (Skinner, Karstaedt, & Miller, 1982).



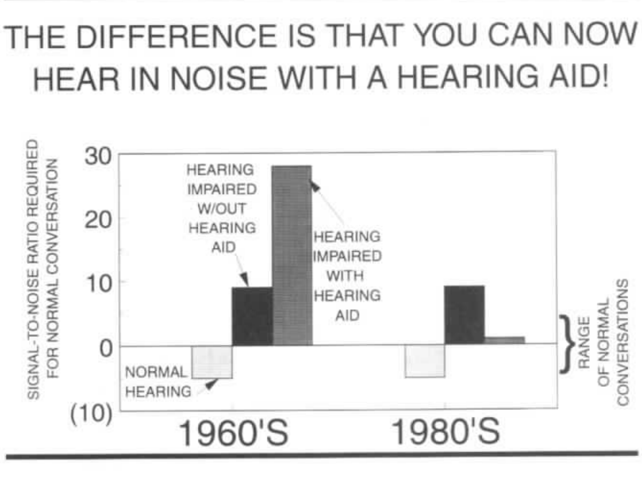
This brings us all the way back to Skinner, Karstaedt, and Miller's (1982) data, summarized in Figure 49. In a series of experiments in which they rolled off sometimes the high frequencies, sometimes the low frequencies, and sometimes both, no matter what they rolled off, the word recognition score went down. By the time they got down to the bandwidth of the old-fashioned hearing aids, the score had gone way, way down.

ABONSO: The Only Solution. We would like to have a good noise filter that makes speech clearer, but we don't have one. As Villchur has argued, we've been taking the wrong approach to the problem. The problem is hearing clearly in noise, and the problem of the person with impaired hearing that she or he has lost ABONSO: the Automatic Brain Operated Noise Suppressor Option.

That can happen to people with normal hearing. In fact, if you take some of the narrowband, peaky, distorting hearing aids that you used to put on people, and you wear them yourself, you'll find that you go through several weeks in which it sounds as though you have noisy hearing aids. A few weeks of wearing them and you'll recognize that it's the air conditioner, and the fan in the ceiling, and the hard-disk drive in the computer. But at first the noises seem to all be in the hearing aids. You've changed the spectral pattern of all those sounds and it takes quite a while for your brain to learn the new patterns. So people with normal hearing can lose ABONSO. I experienced that for myself the first time back in the '60s when I wore a pair of lumpy-response, distorting, standard-issue hearing aids for some months to see what it was like to wear hearing aids. At first I was surrounded by a sea of noise from sources I couldn't identify or localize. After 6 weeks I got used to the sound of the aids and they subjectively disappeared; I could identify and localize all the noises. (But I still couldn't understand speech in noise, of course.)

How Likely Are We to Get a Real Noise Suppressor? The most powerful supercomputer today, the Thinking Machine, has 65,000 computers wired together, operating simultaneously on a problem in an attempt to mimic the brain. It takes one-half hour to recognize a face, something a baby can do in about one-half second. Yet we have been

FIGURE 50. The difference between the old days and now.



hoping for something that will operate on a 10A battery, fit in your ear, and replace the brain!

I'd be foolish to say it can't happen, but the number-crunching noise reduction system that Harry Levitt was talking about would require some 40,000 hearing aid batteries a week to keep it alive if it were to be operated from hearing aid batteries. And even with all that horsepower, it doesn't improve the intelligibility of speech in noise—not for people with normal hearing or for people with impaired hearing. It reduces the noise, but it doesn't clarify the speech.

Why the Brain Wins. The reason the brain is so hard to replace is that it is so incredibly powerful. We're so used to the miracle of speech perception that we take it for granted. I'd like to give some quick examples from vision that illustrate the powerful processor we all carry around. You can take inverting glasses, tape them on your forehead, and at first you can't read (unless you're a salesman), you can't write, you stumble around, and you certainly can't ride a bicycle. Yet in 4–6 weeks of constant wearing of those inverting glasses, you become able to do all those things. The world is back to right side up. When you finally take the glasses off, however, you go through a period of time in which you can't ride a bike, read, write, etc.! (The experiments were motivated by an interest in whether the inverted image on the back of your retina is hard-wired to appear right side up to the brain, or if the necessary visual inversion can be learned.)

Here's an even more powerful example. You can take glasses that distort differently depending on whether you look to the left or the right. So if you're looking at a building of windows, the windows on the left might exhibit barrel distortion, and the windows on the right exhibit pincushion distortion. Worse, if you look straight ahead and move your head quickly back and forth, the shape of the windows goes through wild gyrations. After 6 weeks of wearing these funny glasses, however, the windows all look square and you can move your head quickly back and forth while looking straight ahead and the windows don't move! Your brain, in real time, can deconvolve all of that and filter it out so that everything stands still! (When you first take the glasses off, the windows go through wild gyrations when you move your head back and forth quickly.)

An Auditory Example

I will give you only one auditory example of my own. When I was first working on high-fidelity hearing aids a decade or so ago, I wore a pair of ITE hearing aids with smooth response but a response that rolled off sharply above 8 kHz. I wore those aids regularly for several weeks. One night, in a fit of enthusiasm, I wore them to bed. The next morning when I got up, I had forgotten that I had them on, turned on the shower, and was about to step into it when I suddenly realized I was about to ruin two hearing aids. I quickly took them out, and all of a sudden heard a very-high-pitched ssssss. I couldn't locate it. It wasn't quite located in my head, but I couldn't find it in the room. I spent two minutes walking around the room, cocking my head, listening to this very high frequency ssssss. Then, suddenly, it swept up to the shower and joined the broad-band shhhhh of the shower, clearly localized at the shower head. In just a few weeks I had lost the ability to localize the octave band of sound between 8 and 16 kHz! Now, it didn't take me months to get the ability back, it was only minutes, but when you have someone who hasn't heard high-frequency sounds for several years, experience teaches us that it may take several weeks before that person relearns the task, even if you could give him or her perfect hearing aids.

> Pascoe's conclusion: Success in using hearing aids is learning to ignore the background noise and forgetting that you have them on.

Wear It a While and You'll Get Used to It? So we're back to saying "Wear it a while and you'll get used to it." But we've been saying that since the 1940s. What's the difference?

The difference is that now you can hear in noise with a hearing aid, whereas back even in the 1960s somebody without a hearing loss needed the 9 dB signal-to-noise ratio shown again in Figure 50, and with a hearing aid they needed an impossible 27 dB signal-to-noise ratio. Today, with the right hearing aid you can bring them down close to 0 dB signal-to-noise ratio, as shown in Figure 50. You aren't going to bring them to normal in most cases, but depending on the loss and how well you select and adjust the hearing aid, you can bring them down into the region of signal-to-noise ratios where people with normal hearing operate.

The difference is that now you get comments such as, "Now at square dances I can stand in the back of the room with the normal-hearing people and still hear the caller," or "With these new hearing aids I can go to a ball game and carry on a conversation," or "I can enjoy a conversation in a noisy restaurant; I never thought I'd hear this well with hearing aids," or "One hearing aid wearer has actually accused another of pretending to hear in situations that are impossible to hear with a hearing aid." We employed a consultant recently whom we fitted with high-fidelity K-Amp canal aids. Connie Miezio, our office manager, told me that he was almost in tears telling her how much better his new aids were than the (linear) canal aids an audiologist had dispensed to him just 6 months ago. To me, personally, he complained that he now had a new problem: he was not getting adequate sleep. He was staying up every night listening to all the CD's in his music collection because they sounded so beautiful.

The summary I have is simple. The world's most powerful data processor (the one in your head) can do almost anything, including learning—in a few weeks—a completely new set of speech patterns. You can get used to even the worst hearing aids. What the brain can't do is separate speech from noise when it is starved for information.

Dave Pascoe, who has dispensed some 10,000 hearing aids in addition to providing some of our fundamental research findings, has written a delightful little book that I recommend (Pascoe, 1991). The quote on this page is from that book. "Success in using hearing aids is learning to ignore the background noise and forgetting that you have them on." That is a lot easier with high-fidelity hearing aids. And with properly adjusted high-fidelity hearing aids, your brain will no longer be operating on a starvation diet. Thank you.

Acknowledgments

I would like to acknowledge that much of what I say today as if I had thought of it myself is based on the thinking and research of others. A few of those others have been especially important to me personally in shaping my own thinking, and I would like to acknowledge them: Elmer Carlson, Hugh Knowles, Edgar Villchur, Dave Pascoe, Margo Skinner (who has my vote as the world's best experimentalist), Tom Tillman, Sam Lybarger, Jesper Barfod, and Hy Goldberg.

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