Hearing Losses - Cause and Effect

by David Clark

28 February 1995

"Something In The Air"

Few things in life can compare to the excitement of creating your music, loud and proud (yes, there are other things, but you may prefer to choose a different magazine, wrapped in plastic, from the rack above this one). Whether you've found that point of endless sustain in your guitar, twenty-five feet from your 100-watt stack, or you've felt the visceral crunch of kick and snare through 30-plus thousands of watts of sound system outdoors, or achieved the magic balance of instruments filling all of the available frequencies at 115dB from the main monitors, or felt the earth shake during the cannonade in the 1812 Overture, executed by a naval destroyer close by, then you've probably experienced the rush that loud music can give. It's hard to resist the urge to push that fader up one more notch!

Hopefully, this article will help you resist. The advent of electronic amplification has allowed the musically/technically-inclined to join the ranks of boilermakers, truck drivers, artillery gunners and others whose occupations have rendered them partly or effectively deaf. We've done it to ourselves and we're doing it to our audiences in our ignorance.

This article will describe how the hearing system works, how it gets damaged and how the damage affects us in our professional and daily lives, as far as I have been able to determine. Some of the information is fact and some is theory, a condition which is characteristic of the ongoing investigations of hearing in a technological environment. Some facts will become theories and vice versa. You will see a simple model of hearing damage, based on audio conventions. Such simplicity does not do justice to the complexity of the human hearing system, so the model will undoubtedly prove erroneous, but hopefully its simple message will give pause to the sound technicians and engineers who might otherwise pursue the destruction of their most valuable tool, their hearing.

How The Hearing System Works

Our hearing responds to oscillations in the air, which we interpret as sounds. The oscillations we can hear vary in frequency from approximately 35Hz to 15KHz (depending on age and losses) or, equivalently, in wavelength from 31ft. to 7/8in. Most eight-year-olds really can hear the nominal 20-20KHz we see in specs. The mechanisms of the hearing system are remarkable in their ability to sense oscillations so different in scale.

The mechanical structure of the ear is a chain of transducers (energy converters) which convey the oscillations of the air to the sensors of the nervous system for data gathering and subsequent interpretation by the brain. Like other audio systems, the entire hearing system is subject to problems such as distortion, noise and progressive and catastrophic failure, however, if the system is operated within its design parameters then it will work well for a long time. Understanding the parameters will give you the knowledge you need to make judgments about your own sonic environment.

Parts Of Speech and Hearing

The function of the hearing system has been developed by evolution to serve, among other needs, our need to communicate, so speech and hearing are linked. Understanding the functions of the hearing system helps one to understand the causes and effects of hearing loss.

The hearing system is divided into two subsystems which respond to the two modes of speech. The low frequency subsystem identifies pitch and the characteristic resonances of the person speaking (vowels, chest and head tones), while the high frequency subsystem identifies stops and starts (consonants, mouth sounds). The brain integrates and interprets both modes to form an image of words.

Why We Like It Loud

It turns out that loud sounds directly affect our autonomic nervous system (also called involuntary - it controls the body functions that you hope never stop, like breathing and digestion), in a way similar to many stimulant drugs. Adrenaline is released, the heart rate speeds up, the guts tighten up and move. This is the rush you get from loud music – it's real and it's beyond your conscious control. Sounds addicting, doesn't it?

The Chain of Transducers

The structure of the ear forms a series of transducers to convey information about oscillations to the brain. The system converts motion in compressible fluid (the air in the outer ear) to motion in a mechanical system (the levers of the middle ear) to motion in non-compressible fluid (the fluids of the inner ear) to electrochemical impulses in the nervous system.

The outer ear carries the oscillations to the eardrum via the ear canal, a passive acoustic filter which imparts a pre-emphasis between 1KHz and 4 KHz. In the middle ear, the vibrations of the eardrum (a vibrating elastic membrane) are conveyed to the oval window (another, more delicate, vibrating elastic membrane) via the ossicles, bones which together form a series of levers to match the acoustic impedances of the two membranes and the fluids beyond them (air being the fluid beyond the eardrum, from the ear's point of view).

In the inner ear, the conversion takes place from hydraulic oscillations to nervous system signals. The mechanical structure of the inner ear resembles a snail-shaped tunnel through the bones of the skull, which is called the cochlea. The cochlea is filled with fluids, separated by membranes, which, when energized oscillations at the oval window, generate oscillating motion in the membrane that separates them by virtue of their different fluid densities. The relative motion between the membranes and fluids is detected by the cilia (hair cells) which wave about in the fluid and fire the neurons of the nervous system.

The low-frequency subsystem is an analog-to-digital system which operates below approximately 1KHz, a natural consequence of Nyquist's theorem, which states that the sampling frequency required to convert analog signals to digital signals must be at least twice the highest frequency of interest. In the case of the ear, because the sampling rate of our nervous system is approximately 2KHz (slow, because of the nerves□ electrochemical transmission medium), there is an upper bound of 1KHz on the conversion capabilities of the analog-to-digital system. The energy below about 1KHz is sampled by cilia in the cochlea in the fashion of simple A/D conversion systems, mapping amplitude to strength of periodic nerve impulses.

The multi-channel high-frequency subsystem consists of a series of thousands of filters of narrow bandwidth, a mechanical/hydraulic system which operates above 1KHz. Each cilium (hair cell) in this system reports the amount of activity at a particular frequency, depending on its distance along the cochlea from the oval window. High frequencies are thought to be reported by the cilia closest to the oval window (although all of the cilia appear to have multi-frequency capability and adaptability. An increase in the amount of energy present in each filter's pass band is reported to the brain as an increased rate of impulses being generated by the associated neural channel. One can think of this as a graphic analyzer display having a very high horizontal resolution. It is this subsystem that is most liable to be damaged by exposure to loud sounds.

While we are alive, the nervous system maintains a certain level of random background activity. Close your eyes in complete darkness - the sparkles you see are the random impulses generated by your visual nervous system. The hearing system also generates background noise (more about this later).

Causes of Hearing Damage

Leaving out trauma (explosions, sharp sticks in the ear, etc.) and disease, the reason our hearing is deteriorating is simple. The music is TOO LOUD for TOO LONG. There's a trade-off between how loud the music is and how long you are exposed to it. Ignore this fact and you will progressively go deaf.

The cilia of the inner ear are directly affected by the amplitude of the oscillations in their environment. If you make them wave too vigorously for too long, they break off, never to return.

It is well understood in the industrial health and safety sector that damage is a function of energy over time. On the ramp of an airport, where the ground crews load and unload passengers and baggage from aircraft, the safety committee makes sure everybody wears earmuffs to protect against the full-bandwidth noise of jet engines in close proximity. Of course, even though attenuated significantly by muffs, this level could be damaging if endured for long periods of time. However, because this sound varies in level throughout the shift and the crew waits between flights in relatively quiet surroundings, the total exposure of the workers over the course of the shift is deemed acceptable. In contrast, consider the average bar band sound technician. Early in the evening, he enters the bar to put up the mics. The dance music starts up. Then the band. They alternate for six hours, during which time the sound technician can't leave the bar because the mics might get stolen, besides, he's trying to pick up a date for later. Between his own sound and the dance music, his cilia don't stand a chance. The answer would appear to be obvious - wear muffs to reduce the level, just like the ground crew, right? In principle, yes, but the practice is a bit different, for many reasons. In an industrial setting, nobody takes off their earmuffs to better hear the nuances in the timbre of the punch press. In a music production setting, this happens all the time. We like it loud and we care about the separation between the kick drum and the bass guitar in 18" loudspeakers, each soaking up 500 watts of power. Loud is what it's all about. Besides, it's hard to get picked up while wearing earmuffs.

Sound energy at any frequency will damage your hearing, the question is - are some frequency ranges more damaging than others? The jury is out on this one, but it is well known that the sensitivity of the ear varies with overall level and with frequency (the Fletcher-Munson curves). Generally speaking, we hear the upper mid bands louder than the other frequencies and we hear the sub-bass and highs less, meaning that the upper mids will hurt long before the bottom or top end. Therefore, if we control the upper mids in the mix, then we can achieve a very loud mix with punishing bottom and brilliant highs that appears painless - never mind that we are pouring all that energy into the hearing system. The bottom line - just because the bass doesn't hurt as much, don't discount it. It's probably doing just as much damage to our hearing as the upper mid is.

Defense Mechanisms - Just A Warning!

The hearing system has evolved a couple of mechanisms to protect itself from damaging noises in the environment. Of course, amplified music wasn□t a factor in that evolution, so the hearing system's defenses tend to be inadequate to fend off the assault. The lever system of the ossicles and their associated muscles act as a limiter and a circuit breaker to protect the oval window and structures beyond from any damaging energy present at the eardrum. One muscle group damps the movement of the ossicles when levels get too high, raising the impedance of the mechanical system and reducing the energy passed through the eardrum. The damping occurs within minutes of exposure to high level oscillation and but lasts only for roughly fifteen minutes. Another muscle group is thought to disable the mechanical link through the ossicles, breaking the connection between the inner ear and the outside world, when extraordinary levels are encountered such as explosions or heavy metal music can produce. The sensation experienced is complete deafness in the affected ear, disorientation and loss of balance. This effect lasts for several hours before hearing returns.

Effects Of Hearing Loss

To understand the effects of hearing loss, the idea of thresholds should be understood. One threshold is sensitivity - how quiet a sound can you hear at some frequency? Another threshold is pain - how loud can you stand it at some frequency? Some thresholds, sensitivity for one, can be shifted. What I could hear yesterday, I can't hear today, because the music was too loud. Maybe I can hear it tomorrow (if I'm lucky). Maybe not.

The first threshold shift to be experienced on the way to hearing damage is termed TTS, temporary threshold shift, which is characterized by a "cotton wool" sensation, accompanying loss of sensitivity and possible ringing sounds (more about this later) that one experiences after enjoying loud music or heavy machinery operation. If you have experienced this, then change your listening habits, or one day you'll wake up and realize that the effects haven't gone away!

The first sign of permanent hearing loss is a shift of the sensitivity threshold in the upper mid frequencies (around 3 - 4KHz), which sounds like a loss of brilliance in quiet music. It's ironic that a preference for loud bass may result in losses in the highs! For many, this loss may be accompanied by tinnitus, a ringing tone or tones, typically in the upper mids, that is heard at first in quiet surroundings. Tinnitus sounds like pink noise passed through a single filter on a graphic equalizer, ringing constantly in your head. It stays with you regardless of head position. It only "goes away" when it is masked by a louder noise. It can get louder, depending on the influence of other things which, independently, can also cause tinnitus. For example, caffeine or aspirin can make the damaged-induced tinnitus louder and can add new frequencies to the mix. These effects pass with the influence that started them, leaving you with your own private test tones.

WHICH NEVER GO AWAY.

You'll recall that the hearing damage is physical, the loss of the cilia. Tinnitus can occur because the brain has lost signal down that channel, so it cranks up the gain to compensate (see diagram). Just like any other audio system, when you turn up the gain to amplify a weak signal, you increase the noise level. The loss of part of the hearing mechanism has the effect of decreasing the signal-to-noise ratio (S/N) at the affected frequency band. Such tinnitus is the amplified background noise of the nerve channel that is connected to the damaged cilia..

Sensitivity threshold shift is easy to measure and increases as damage increases. Similarly, as damage progresses, the tinnitus gets louder and increases its bandwidth.

The other effect of the increased gain is a loss of dynamic range at the affected upper mid frequencies, called recruitment, an increase in the perceived loudness of sound, in this case in the upper mid frequencies. A person so afflicted is more easily irritated by upper mid frequencies than a listener with normal hearing. If the upper mids hurt your ears, don't be too quick to congratulate yourself on the pristine qualities of your hearing, compared to those deaf guys you've heard about. Think again; maybe get your hearing checked. You could be experiencing recruitment.

Once away from the mixing environment, the effects of hearing damage become obvious, particularly in the interaction with speech. The two modes of speech are critical to communication. If we lose signal from either speech mode, understanding is diminished. If the low frequencies are attenuated, we cannot distinguish the words in two competing signals (the cocktail party effect), because we can't assign the sounds to particular sources. As an example, a telephone or tinny paging horn sounds clear by itself, but can't be understood when other people are talking in the same room, even though the talking people can be individually understood. This particular loss is uncommon. If the high frequency mode is compromised, we hear low frequency noise but no information, so we lose intelligibility. The importance of adequate high frequency level is well understood in audio design. Loss of the high-frequency mode is the most common form of hearing loss. Victims of this impairment hear the sounds, but can't make out the words. Because of recruitment, speaking louder may only cause irritation. "Speak up and quit mumbling! Whoa, you don't have to shout!"

Next issue, we'll look at damage prevention, some social, moral and legal issues and where to go to find out more about your ears. In the meantime, I'll try to muster the courage to get my hearing tested again, something I've avoided for ten years. My losses were moderate then, but I think I've shaved a few cilia since. I'll let you know how it goes.

Thanks to Joanne Deluzio, Audiologist, Canadian Hearing Society; Marshall Chasin, Director of Research, Canadian Hearing Society; Bob Ghent, for his article "Healthy Hearing and Sound Reinforcement", *Mix Magazine*, March 1994; the past graduate students of the Institute of Biomedical Engineering, University of Toronto, Prof. Patrick J. Foley, Industrial Engineering, University of Toronto. The inaccuracies are mine.

Rev: Feb. 15/96