An Acoustician's Journey into Hearing Aids

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My title may not sound like a topic for Reproduced Sound but I think it is. After all, the best reproduced sounds help us to hear. Hearing aids do just that. And one of the best centres of hearing aid progress is here in Southampton at ISVR. The author is a graduate of ISVR, as is his wife. I'm the one who is the acoustician and she's the one who is the audiologist. An acoustician should never be seen wearing hearing aids. At least that's the popular perception. But I have been prescribed hearing aids by Jacqueline, my wife. I shall never regret it and am proud to show them off. Hearing aids create a better life. Not just for adults but, much more importantly, for children who are just starting school. There's something called neuro-plasticity. The brain is a bit like a muscle and if parts of it aren't exercised they fade away. The young years are the most plastic of neuro-plasticity. And this is where Reproduced Sound can help out, as can audiologists – as, indeed, they already have. This paper will try to present the importance of sound in a large auditorium, which the author is familiar with, but also encourage an area where we seldom work – elementary schools where children are living in the most critical time to learn speech and language.

1 INTRODUCTION

Many of you, perhaps most of you don't know me from Adam. My name is John O'Keefe and I've been attending IOA meetings for at least 20 years. But on the Building Acoustics side of things. And I must say that as an international member, someone outside looking in, as it were, I have so much respect for this institution. As do so many of my other foreign colleagues. You are very lucky to be members of this organization. Or perhaps it's not luck because you built it! My paper is really about a personal journey, so I apologize in advance for what may seem a less technical presentation. Perhaps some of you may have been on a similar hearing journey. Some, perhaps, without knowing it. But, don't worry; this is a technical paper so I will throw in a little science here and there. Some familiar material, some perhaps not.

I am keenly aware that this is a conference on Reproduced Sound and that is not, strictly speaking, my field. But I feel, quite strongly, that one of the most important forms of reproduced sound is the hearing aid. It's quite an advanced technology and can have a profound affect on old fellows like me and, I dare say, on one or two people who might be reading this. But, much more importantly, hearing aids can have a profound affect on children as they are learning how to talk; something I'll be getting into later.

There is a misconception, I suggest, that acousticians must, of course, have golden ears. I'm sure the same is true for those of you in Reproduced Sound. Perhaps more so for the person working in the control room or on the mixing desk at a concert. But nothing could be could be further from the truth. And this has been a fallacy for over fifty years. At least in my little world of concert hall acoustic design.

You've all heard wonderful sound coming from aging musicians who may not have the physical equipment they once had. But it's the grey matter in between the ears that matters. That is, in my opinion, the brain is more important than what might be called the physical barrier between the environment and the way we interpret it.

2 THE EAR

So, we'll go over some homework. How sound is transmitted to the brain. We perceive sound through our ears so let's start with that first. Please see Figure 1.

2.1 The Outer Ear

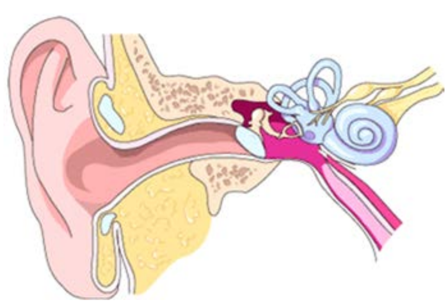

Figure 1. The human ear.

The outer ears or pinna play a role in the localization of sound and, due to head diffraction and resonance effects, they selectively enhance incident sound. The study now known as auralization has found just how important individual pinna are. It turns out that front to back location of sound is rather difficult in auralizations. Efforts have been made to define a standard of average pinna but it turns out that there's really no substitute for your own pinna.

I'm interested in this as a designer of concert halls, where something like an auralization allows us to "hear" a room before it is built. But it is the world of computer games that is really driving this technology. Financially, we acousticians are just hanging on for the ride. Jens Blauret and others in the 1970s devised the idea of a Head Related Transfer Function or HRTF.[1] A typical HRTF is shown in Figure 2. Note how it's quantified only in terms of azimuth, i.e. the horizontal plane and not the vertical plane. That's because our hearing is not sensitive to the vertical plane. We have ears on the sides of our heads, not on the top and the bottom.

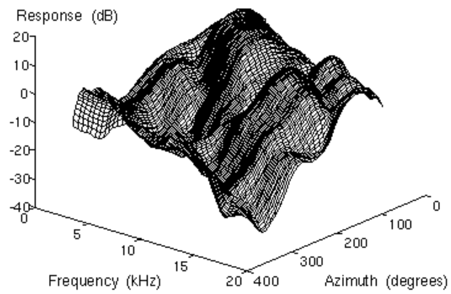

Figure 2 Head Related Transfer Function (HRTF).

And, incidentally, while we're talking about the outer ear, it's not uncommon to perforate the tympanic membrane (or ear drum) without catastrophic consequences. It results in a temporary hearing loss between 100 and 1000 Hz. The membrane heals itself in a few weeks or a few months. It's a bit like cutting your finger. It is often caused by middle ear infections, generally a build up of puss that is too hard for the tympanic membrane to hold. This often happens to young children. The Eustachian tube in adults tilts down to the throat and nasal passage – about 45 degrees – and allows the puss to drain. As shown in Figure 1. It also allows us to establish a pressure equilibrium across the tympanic membrane. You've experienced this on airplanes or fast moving elevators. The solution is to swallow and relieve the pressure across the tympanic membrane through the Eustachian tube. In children however the Eustachian tube is horizontal and infections tend to build up in the middle ear, resulting in pressure on the middle ear and sometimes perforation.

This can be relieved by tubes surgically inserted through the tympanic membrane to relieve the pressure. Our daughter Kate had the operation two or three times. Much to the disgrace of her parents – an audiologist and an acoustician – who didn't recognise the symptoms the first time and wondered why she couldn't stop crying and wouldn't go down for her nap!

2.2 The Middle Ear

The middle ear forms the link to nerve receptors cells in the cochlea. It matches the low impedance, large area tympanic membrane (air filled) to the high impedance small area cochlear oval window (fluid filled). The air to fluid loss is approximately 35 dB. The transformer like ossicular chain removes some of this loss. In three ways:

- The area of the tympanic membrane is 17 times that of the oval window. This results in a 23 dB amplification.
- Lever action is good for about 2 dB but recent work shows that this can vary with frequency.
- Middle ear efficiency peaks at 1 kHz which, of course, is one of the frequencies we are most sensitive to.

In the middle ear, mammals are unique in having three ear bones, which allow for finer detection of sound. The tympanic membrane, as I mentioned, is a low impedance system exposed to air and the oval window of the cochlea is a high impedance system exposed to fluid. The ossicular chain works to overcome this impedance mis-match. Finally, the ossicles can also reduce very loud sound pressure levels by uncoupling from each other through particular muscles. This is called acoustic reflex or Tympanic reflex. It saves the very sensitive nerve endings in the cochlea. If the tympanic membrane moves too much the ossicular chain says: "Hold on. Wait a minute!" and tries to protect the cochlea.

2.3 The Inner Ear.

The inner ear consists of semi-circular canals (superior, lateral and posterior), the vestibule (the space behind the oval window joining the cochlea to the semi-circular canals) and the cochlea (2 ¾ turn shell structure). The cochlea is the "body's microphone" in that it converts mechanical motion to electrical signals. The cochlea is a conical, bony material and fluid filled. The basilar membrane stretches down the middle of the cochlea for its entire length. Tiny hair cells are attached to the basilar membrane, which move back and forth in the fluid in response to acoustic excitation. Through a rather complicated process, action potentials are fired down the XIIIth cranial nerve – the so-called acoustic nerve. This is how acoustic information in its mechanical form is converted to electro-chemical information that the brain can then analyse.

Figure 3 shows a view of the cochlea. High frequency sounds are detected at the base of the cochlea and low frequency sounds at the apex.

When these hair cells are stressed by too loud of a sound (i.e. too much motion in the fluid) they simply burn out. "Burn-out" of the hair cells results in two phenomena. Tinnitus is the ringing you hear from time to time. The ringing sounds tinny, hence the name "Tinnitus". When you have Tinnitus, what has happened is

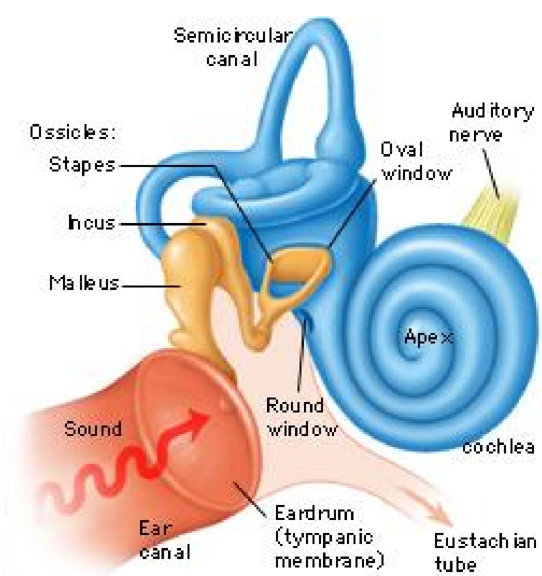

Figure 3. The cochlea.

one or several of your 20,000 hair cells have died. That leaves its neighbours freer to move around in the fluid – so they do! And when they do that they enervate the XIIIth (auditory) nerve and you perceive a pure tone. Or close to it.

Prolonged exposure to loud sounds continues to burn out the hair cells and results in what is known as Noise Induced Hearing Loss – which is the legal term, I suppose – but the more accurate clinical term is Sensi-Neural Hearing Loss. Which, until recently, was something that simply couldn't be fixed. We cannot regrow hair cells in the cochlea that have been destroyed.

Well, at least we couldn't.

Researchers have recently identified a mammalian gene that normally acts as a molecular switch to block the regrowth of cochlear hair cells in adult humans. Recent work has established an inhibitor for this gene that has been demonstrated to reactivate hair cell growth in mice. They can unlock it! And, as we know, there is now the increasingly available access to cochlear implants. Continued exposure to loud sounds, and the experience of Temporary Threshold Shift will eventually lead to a Permanent Threshold Shift and then you're done for. You've burnt out your cochlear hair cells. And right now, if you want to get them back, you have to be a mouse! After exposure to very loud sounds for a certain time, other quieter sounds don't sound so loud.

A patient of Jacqueline's, an 8 year old ice hockey goalie, was hit by a puck in his left temple. It turns out his helmet wasn't as good as it should be. The original 35 dB temporary threshold shift became 20 dB the next day. The Hearing Loss didn't look like something caused by a head injury. It looked like long term Noise Induced Hearing Loss. It turns out that a goalie mask is designed to distribute shock along the jaw. In the case of the little boy's mask, the foam pads were no longer soft. He suffered a trauma to the cochlea not through *airborne* excitation but rather through *mechanical* excitation generated by the impact of the puck. Remember that all sound is created by some form of vibration.

Which brings us to something called Presbyacusis. Children hear better than adults. And older women hear better than older men. As we age, the high frequency cochlear hair cells wear out faster than the low frequency cells. The result is a high frequency loss; predominate in men more than women. This is a finding established in the mid 20th century where men in industrial or military work were more exposed to louder noise than women. Noise levels that are illegal now. At least in industry. One would hope that this might change in the 21st century.

3 THE JOURNEY

I mentioned that this was a journey. And I don't mind telling you that it was a scary one.

I was eased into my journey into hearing aids by a woman I consider to be one of the best audiologists in Canada. But I must confess to being a bit of a biased opinion. Because she's my wife. We met at ISVR, on the last day of classes, and we've never been apart since. For 32 years. ISVR is, at least for me, the best blend of the acoustical sciences. Because they have, for over 50 years now, brought together both the physical and health sciences of sound. In acoustics; one is lost without the other.

Jacqueline, who is a hard nosed Lancastrian, took a surprisingly delicate approach over the dinner table, saying occasionally: "You didn't get that did you." At dinner, a couple of years ago she suggested that I had a 35 dB loss at 2 kHz. When she measured my hearing a few months ago, it turns out she was spot on. 35 dB down at 2 kHz. That's pretty good!

The design of the modern hearing aid is a thing of wonder. Things keep getting smaller and smaller. And imagine the modern feedback control prowess. A microphone located about a ½ inch from the loudspeaker is no small challenge. Especially when you're dealing with gains of 35 dB or more. But firms like Widex, Unitron, Siemens and others have got that one figured out. The world of Reproduced Sound could learn a thing or two from the hearing aid industry and their formidable research programmes.

Figure 4 Hearing Aids, 20th Century.

Within living memory, this is what a hearing aid looked like. Please see Figure 4. Perhaps this led to the phobia about wearing hearing aids. But I've always been struck that it's okay for an architect or a visual artist to wear glasses but it's not okay for a sound professional to be seen wearing hearing aids. Only three acousticians that I know of in North America wear hearing aids. Well, two actually. Sadly we lost Leo Beranek a little while ago. 102 years young!

There are five or six models of modern hearing aid. The three most popular are shown in Figure 5. The size of the hearing aid depends on the hearing loss. I have the bigger version. It's called Behind the Ear. The smaller versions in planted inside the ear, or inside the ear canal.

4 MODERN ACOUSTICS

The discovery of the importance of lateral energy is probably one of the most important acoustical developments of the 20th century.[2] I have a colleague who is an acoustician. He spent his entire career in acoustics measuring, analyzing and designing concert halls. Recently he lost his hearing in his right ear. It's pretty hard to hear spatial sound with only one ear. But for my friend, hearing aids can't restore the spatial hearing experience. Hearing aids can do some things but they can't do all things. At a party or in a pub they can't overcome the Lombard Effect.[3,4] The Lombard Effect typically occurs in loud rooms where one person tries to talk louder than the next. It's just human nature. The eventual result is a cacophony where people have to yell to be understood. And despite the wonderful research done in the hearing aid world, there seems little hope to solve this problem.

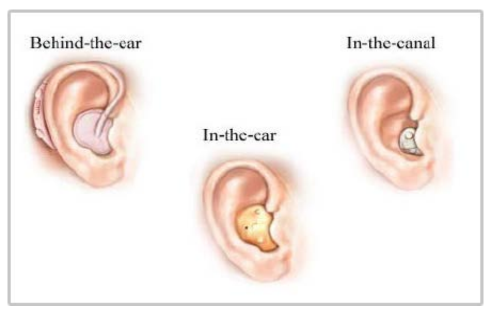

Figure 5 Modern Hearing Aids

I should point out to you who are interested in speech intelligibility and musical clarity in stadia and arenas. We acousticians call early sound beneficial and late sound detrimental. For speech, the threshold between the two is 50 ms. Please see Figure 6. For musical clarity it's a bit longer at about 80 ms. This early to late energy representation points out a fundamental misunderstanding with many PA system designs.

It's not the Reverberation Time of the venue that matters but rather the ratio of early to late sound. Detrimental late sound is surprisingly deficient in large arenas or stadia. If indeed you can calculate an

RT in an open air stadium. Computer programmes like CATT, Ease and Odeon help to solve the problem but they too have their acoustical compromises.

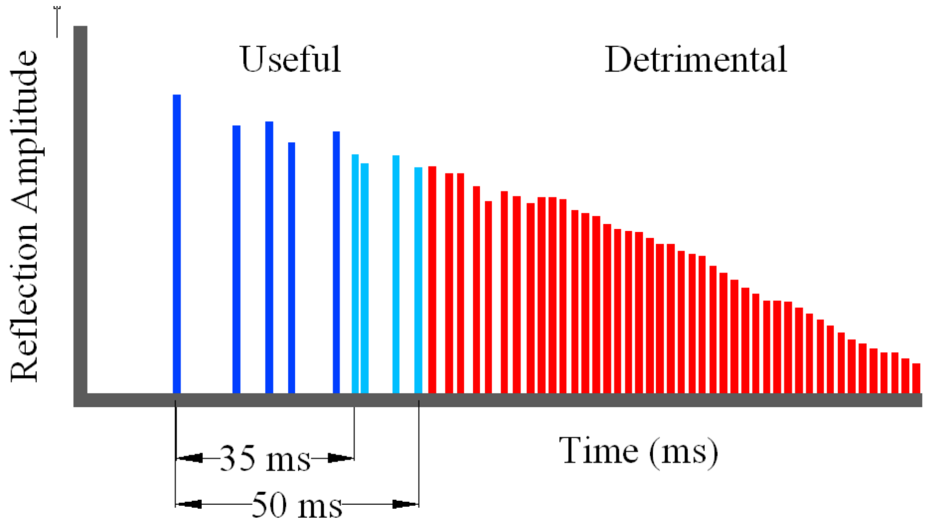

Figure 6. Useful to Detrimental Sound

And, surprisingly, this brings up the subject of hearing and children. Which, I grant you is somewhat foreign to this forum. Nonetheless, I'm convinced it is very important. Well, what does all this mean? For those of you involved in what I might call "Big Sound", it's obvious. Hearing protection when you're at work! But there's another aspect of Reproduced Sound that perhaps we all underestimate. Primary schools.

I have spent a lifetime pre-occupied with sound. A career focussed on the acoustics of theatres, concert halls and the like. But, these days, having done all those big splashy rooms, I'm now more interested in the acoustics and reproduced sound in children's classrooms. Here's the reason why.

5 THE CHILDREN

There is a stigma that still persists about wearing hearing aids and it extends to children. Research has shown that a hard of hearing child needs to hear a word three times more frequently than a normally hearing child in order to understand that word and to incorporate it into his or her lexicon.[5] Some parents with a hard of hearing child don't want to admit it. That's a mistake. And the child will pay for it, for want of a good education. During elementary school they're effectively behind a heavy wooden door, standing outside in the corridor. It's pretty hard to hear the teacher that way. And in the early years – the most plastic of neuro-plasticity – they are still forming language. If they can't do that during the critical early learning period, they're going to have trouble with learning throughout their education, which, indeed, they may shorten to their own detriment.

But the stigma about hearing aids may be changing, hopefully for the better. A few months ago, Jacqueline prescribed hearing aids for a little boy. His mother wanted skin toned hearing aids, perhaps thinking that they wouldn't be noticed. But the child wanted none of that. He wanted the purple dinosaur hearing aids because they were cool. As indeed they are.

I decided against the purple dinosaur hearing aids!

Many of us are fortunate enough to have done the big name jobs. But you still have to pay the bills and, from time to time, we all have to do the smaller work. That includes schools and perhaps even day-care centres. And, as I suggested, as I get older and hopefully wiser I think that speech intelligibility in a kindergarten classroom is just as important as the acoustics in a major concert hall.

I'm not making this up.

The audience in a concert hall has heard it all before. But the kids in the classroom may not have heard many of those words before. This is where a sound system designer can do more than just pay the bills.

If I can be so bold; he or she can make the world a slightly better place by designing a distributed system in a classroom and provide the requisite early energy required for good speech intelligibility and help children to learn.

6 CONCLUSION

Our goal, either as people working in my world of natural acoustics or in the powerful world of Reproduced Sound is to help people hear. I don't care if it's a stadium of 75,000 or a classroom of 25 kids. And, what I've learned in my dotage is that teaching a child to talk and subsequently to read and write is better by far than all the best concert hall acoustics, all the best stadium concerts and all the best recordings. Teaching a child doesn't earn you the big bucks or big accolades. But – as any mother or father who has raised a child will tell you – it's worth the effort. It's what we do and it can be done for the good.

7 ACKNOWLEDGEMENTS

I should like to acknowledge the contributions of my wife, audiologist Jacqueline Hayden who gently guided me on this journey and who provided help both technically and, as always, in her review of the text.

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