THE ACOUSTICIAN WHO HAS TO WEAR HEARING AIDS

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1 INTRODUCTION

Most of the public presume, perhaps erroneously, that concert hall acousticians must have hypersensitive "golden ears" hearing. They can hear things that others can't. While it is true that there is no substitute for learning about concert hall sound than by listening, it is also true that the great progress we have seen in concert hall design can be attributed to knowledge based scientific developments over the past seventy or so years.

So much of hearing is a learned, neural activity. Take for example, the young music student taught to tune his or her instrument by listening to beat frequencies. The same is true for the concert-goer, who has a whole new experience open up after the phenomena of spatial sound are pointed out. Beethoven had a very poor pair of ears to work with but his neurological processing was – to use an overwrought word – genius. But let us, at least for now, consider some of the physical aspects of hearing.

2 THE EVOLUTION OF HEARING

Like most of animate life our hearing started out in the primordial soup of the seas. 500 million years separate the motion sensitive hair cells in the lateral line on the side of a fish from similar sensory cells in the inner ear cochlea of vertebrates.[1] When fish moved from water onto land, they needed a new mechanism to detect vibrations in air. Hence the evolution of reptilian and eventually mammalian hearing.

Mammals are unique among vertebrates in that they have the three bone action of the ossicular chain inside the middle ear. Birds and reptiles, for example, only have a single bone. The lever action of the mammalian ossicles helps to amplify high frequency sounds, above 10 kHz in humans[1] and to ultra-sonic frequencies in other mammals[2], for example echo-locating bats. It is thought that this was an evolutionary benefit to early mammals, who were mostly small nocturnal insectivores.

With the aid of Figure 1, mammalian hearing may be succinctly described as follows. Vibrations in the air are channelled to the tympanic membrane by the pinna and the ear canal. The energy is then amplified through the air filled middle ear to the fluid filled cochlea. The amplification is in the order of 25 dB, only 2 dB of which is due to the lever action of the ossicles. The rest is due to the area ratio difference between the tympanic membrane, operating in air, and the cochlea's oval window, operating in a fluid. In this sense, the ossicular chain may be seen an impedance matching system between the excitation in air and the detection in a fluid.

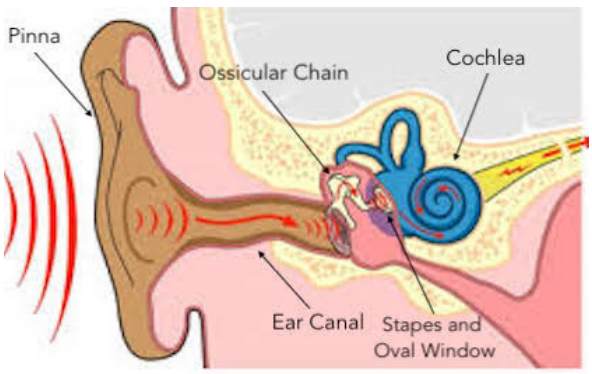

Figure 1 Section of the human ear. The outer, middle and inner ears are shown in brown, pink and blue respectively.

Two of the three bones in the ossicular chain evolved from the jaws of reptiles into the middle ear of mammals[3]. Reptiles have a single bone, similar to our stapes, attached to the oval window of the cochlea. In mammals two more small bones evolved, one from the lower jaw and one from the upper. The evolution of the tympanic membrane and the ear canal is more complicated but it is known that the tympanic membrane in mammals lies deeper in the skull than other vertebrates and hence the longer ear canal and pinna, both of which play a role in localisation.

3 THE EVOLUTION OF THE CONCERT HALL

3.1 General

The evolution of the concert hall over the past few centuries belies the notion of a room with perfect acoustics. Perfection, in both the life sciences and the design of concert halls, precludes the improvements we have seen in the past centuries, and hope to see more of in the future.

It is thought by many that what we consider to be the modern concert hall evolved out of the high ceiling ballrooms of the aristocracy.[4] Other large volume venues already existed. For example, the 16th century Great Hall at Hampton Court would have been an excellent venue for large symphonic music. But neither the repertoire nor instruments powerful enough for this space existed at the time. It's unlikely that many of the listeners could hear the minstrels in the gallery and it's equally unlikely that they cared.

As music moved from the private to the public, numerous large rooms for music were constructed and large number of them were lost. A great many to fire. If a room was good for acoustics it would be replaced by a similar shaped venue. Thus, through attrition, a great assemblage of good concert halls developed. Old concert halls aren't good because they're old, they're old because they're good.

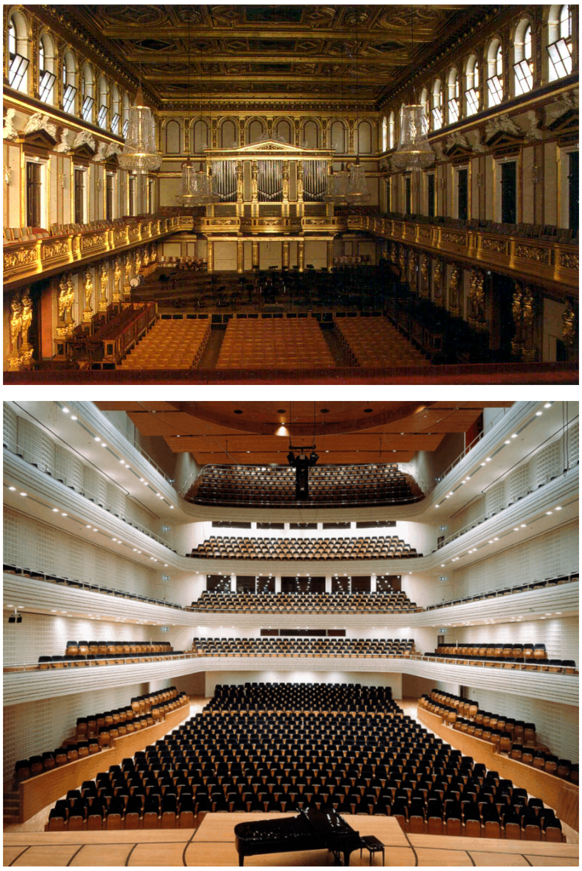

Figure 2 Musikvereinssaal, Vienna (top) and Lucerne KKL (bottom)

While many think of the modern concert hall format as a product of the late 18th and early 19th centuries, Polack points out that the movement from the private to the public was initiated in mid-17th century England when Cromwell did away with court society.[5] Readers interested in the history and evolution of concert halls are recommended to Polack[5] as well as Clements' very interesting histories of Vienna's Musikvereinssaal[6] and Amsterdam's Concertgebouw.[7]

One of the more important developments in concert hall design was, interestingly enough, the recording and re-production of the gramophone record around the turn of the 20th century. It was about this time that composers stopped writing music for buildings, as Bach did for the Thomaskirche in Leipzig[8] but, rather, rooms were built for the extant repertoire – the great bulk of which was from the late classical and romantic eras of the 19th century.

The 20th century saw a wide array of experimental concert hall shapes, many from the post-World War II era[9] and many of which were acoustical failures. The lamented ones lasted in part because modern fire codes prevented their early demise. Only three accepted concert hall geometries survived into the 21^{st} century: the shoe-box inherited from 19^{th} century, the vineyard step format initiated by the Berliner Philharmonie[10] and the directed energy hall pioneered by Marshall in the Christchurch Town Hall[11]. The so-called lateral energy thesis development by Marshall and Barron,[12,13,14] explains why the shoe-box and vineyard step formats work so well and in the latter case of Christchurch, actually directed the design. The lateral energy thesis is surely a seminal moment in the application of deductive scientific reasoning to the design of concert halls.

The evolution of these three surviving formats deserves some consideration. Few would see much of a difference between Vienna's 19^{th} century Musikvereinssaal and Lucerne's early 21^{st} century Kultur- und Kongresszentrum Luzern (KKL). Both are shoe-boxes, as seen in Figure 2. But Lucerne demonstrates two very significant developments in the shoe-box format. It's quieter, down to the N1 threshold of hearing criterion. Note, in contrast, the open clerestory windows in Vienna. And Lucerne has a highly developed variable acoustics system. The celebrated recordings of the Vienna Philharmonic are rarely done in the Musikvereinssaal because it is far too reverberant in its unoccupied state.

Likewise, the apparent difference between the Berliner Philharmonie and the Walt Disney Hall in Los Angeles belies their common genus, Berlin. Please see Figure 3.

Finally, Christchurch Town Hall and the new Paris Philharmonie, shown in Figure , share not only the same genus but the same acoustical designer, Harold Marshall. To the untrained eye, there are few visually apparent similarities between the two.

Figure 3 Berliner Philharmonie (top) and Walt Disney Hall, Los Angeles (bottom)

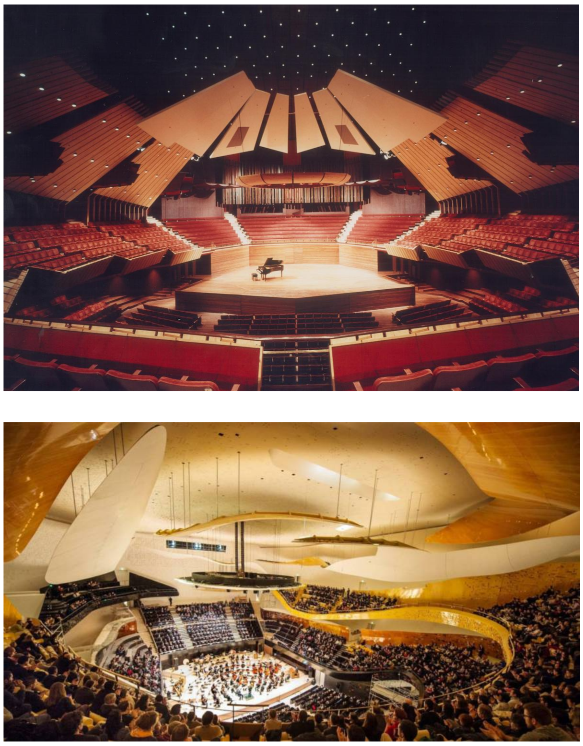

Figure 4 Christchurch Town Hall (top) and Philharmonie de Paris (bottom)

As for the future, the Paris Philharmonie[15] and its immediate predecessor, the Guangzhou Opera House[16], both relied heavily on Non-uniform Rational B-splines (NURBs) in their designs. NURBs allow acousticians to reliably calculate reflected energy off of curved surfaces, both convex and concave. For more than a century, concave surfaces have been thought of as an anathema in concert hall design. This despite the fact that there are many older examples of successful music venues with concave surfaces.[17],[18] Perhaps domes and barrel vaulted ceilings may be embraced once again.

3.2 The Fan-Shaped Auditorium

One concert hall format which didn't survive the 20th century is the fan-shape. The lateral energy thesis sounded its death knell. Few if any fan-shaped concert halls have been built recently. But they may still be useful in rooms for speech, e.g. lecture halls and perhaps theatres. Many claim that seating in a fan-shape room is more "democratic" and that more people are closer to the talker at the front of the room. Are these two suppositions true?

An algorithm has been developed to answer these questions and possibly more. In it, the source receiver distances for an audience of a given size are calculated in both fan and shoebox geometries. There are plethora of geometrical parameters that govern the two geometries so it's difficult to make controlled comparisons between the two. In the following example, the capacity has been set at 500 for both rooms and the width of the shoebox is set equal to the middle row width of the fan-shape. All the seats are on one level, with a 1 m long row to row spacing and 200 mm risers between rows. Two fan shaped angles were studied. The first has a 35° angle between the centre-line and the walls (for a total subtended angle of 70°) and is typical of the fan-shaped performing arts centres built in the post-war era. The second has a 90° angle between the walls and centre-line (for a total of 180°) and is representative of what might be found in a lecture hall or thrust stage theatre.

The findings are of interest when one compares the median source-receiver distance for the two geometries. The median distance locates the position where 50% of the seats are closer than the rest. In the 500 seat 35 degree fan-shape of our experiment, the median source-receiver distance is 15.04 m. The middle row of that fan is 12.5 m wide, which governs the width of the subsequent shoe-box geometry. The 12.5 m wide, 500 seat shoebox has a median source-receiver distance of 12.82 m. That is to say, half of the people in the shoebox are within 12.82 m of the sound source. In the fan, that distance is further away, i.e. at 15.04 m. In the 500 seat shoebox geometry, this translates to 92 seats that are closer than they would be in a fan-shaped geometry.

There is a caveat however. The geometry of the fan in the example above assumes that the fulcrum of the fan is located at the position of the sound source. That is, on the centre-line at the foot of the stage. Many fan-shaped auditoria place the fulcrum behind the foot of the stage. For example, in Toronto's former O'Keefe Centre[19] (now the Sony Centre) the fulcrum is about 11 m beyond the foot of the stage. The stalls level of this room seats 2,146, compared to the 500 seats in the experiment. Using the Sony Centre as a guideline, it was decided to locate the fulcrum of the 500 seat fan at 2.0 m behind the sound source. In this scenario the median source-receiver distance for the fan-shape is 13.46 m, compared to 12.82 m in the shoebox. This translates into 31 seats that are closer in the shoebox than they would be in the fan.

The final comparison is between the shoebox and a 90 degree fan-shape, one where the audience surrounds the presenter. In this, the shoebox geometry does not fare nearly so well. In fact, things are the other way around, the 500 seat fan-shape now has 227 seats closer to the talker than the shoe-box.

So the answer to the question of which geometry brings listeners closer to the source is that there is no answer. At least no single answer. It will depend on the shape of the fan and the many geometrical parameters that define it. For example, the angle of the fan, the width of the fan in the middle, the width at the front, etc. But it is clear that the canard that a fan-shape will always bring more listeners closer to the front is just that – a canard.

4 HEARING LOSS QUANTIFIED

Figure 3 shows the progression of the author's hearing over the three year period since the Hearing Loss (HL) was first diagnosed in 2015. For visual clarity, only data for the right ear has been illustrated. Hearing Loss in the patient's left ear is similar to the right. Audiological HL levels are considered to be normal between 0 and 20 dB. The 2015 data indicates that the author has normal hearing up to approximately 1,500 Hz. At that point, there is a dramatic increase in HL, by as much as 35 dB.

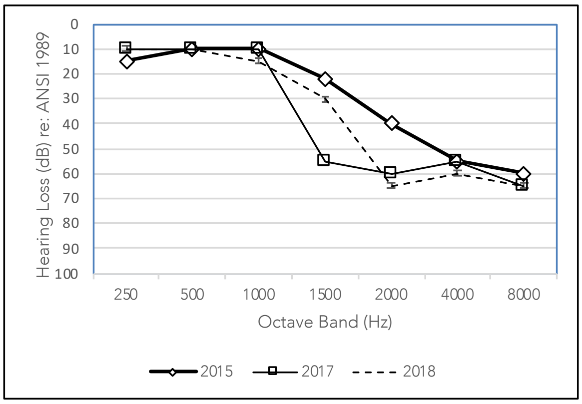

Figure 3 The author's Hearing Loss measured over a period of three years. 1dB JNDs for concert hall Loudness are just barely visible on the 2018 data (dashed line)

Three things should be pointed out about the HL data. First, although there are many ways to quantify HL, the most common is by the detection of pure tones. Both Figure 3 and Figure 4 were measured with pure tones. Second, the centre frequencies on the abscissa do not follow a normal octave band progress. Note the 1,500 Hz data between 1,000 Hz and 2,000 Hz. When there is a difference of 20 dB in successive octaves, professional practice requires the audiologist to measure half way between the octaves to fill in the "fine grain" of the audiogram. This typically occurs at 1.5, 3 and 6 kHz. Finally, the HL increase of 35 dB, although not out of the ordinary for an audiologist, seems absolutely enormous to an acoustician.

To put this into context, the 2018 data for both Figure 3 and Figure 4 have the Just Noticeable Differences (JNDs) for Sound Strength (G) or Loudness in a concert hall superimposed with error bars. The JND for Strength in a concert hall is taken to be 1.0 dB for total sound[20,21] and 0.25 dB for early reflections.[22] The ±1 dB error bars are just barely visible in the two graphs. Again, a 35 dB HL is not unexpected for an audiologist. What is described as a "profound" HL starts around 80 dB or more.

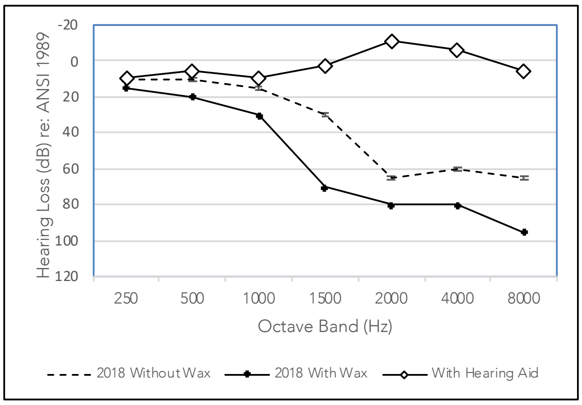

Figure 4 Hearing Loss in the author's right ear with and without wax occluding the ear canal and with the hearing aid in place

The major difference between the 2015 and 2017 data is at the frequency where the dramatic increase in HL begins to occur. In 2015 the increase in HL starts at 1,500 Hz. In 2017 that had worsened to 1,000 Hz. This was cause for concern as it was thought that the patient's HL might be progressive. Measurements in 2018 dispelled this somewhat as the "knee" in the graph had returned to 1,500 Hz. This apparent lack of measurement resolution is not uncommon. And the problem is not so much with the measurement procedure as with the patient. For example, the presence of wax in the ear canal.

Leading up to the 2018 measurements, the patient had experienced a build-up of wax, visible to (trained) naked eye. Figure 4 quantifies the difference in HL before and after the wax was removed. A difference between 15 and 40 dB is seen, depending on the frequency.

Finally, Figure 4 shows the results of what are known as "Real Ear" measurements. These are performed when a patient is wearing his or her hearing aid. Measurements are performed with a tube

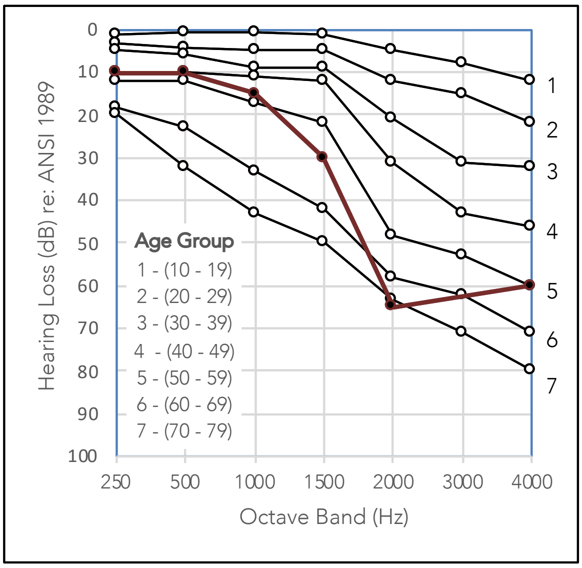

Figure 5 Presbycusis curves superimposed with the author's HL (thick line) as measured in 2018.

microphone located just in front of the tympanic membrane. The upper line in Figure 4 indicates that the prescribed hearing aids are amplifying sound pressure levels into the range of what is considered normal hearing.

Figure 5 shows some very interesting comparative results. And somewhat of an afterthought in the preparation of this paper. The author's HL, measured in 2018, is compared to the HL of the general population.[23] The general population data is for males and shows signs of presbycusis. The author, who was aged 60 at the time of the measurements, shows a HL consistent with his age group. It's slightly better at low frequencies and slightly worse at 2,000 Hz.

5 CONCLUSION

Amongst the general population, there is still a stigma associated with hearing aids. They are visible evidence of an invisible handicap. The stigma is, if anything, more pronounced amongst those who should know better – acousticians. As acousticians reach their most productive age, the effects of presbycusis, as seen in Figure 5, are bound to become apparent. Perhaps if acousticians could embrace the need for assisted hearing, the general public might do so as well. Hearing the wind in the trees and listening to the summer rain makes it all worthwhile.

6 ACKNOWLEDGMENTS

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