USE OF A 3D PRINTED ARTIFICIAL EAR SIMULATION IN MEASURING HEARING RISK IN YOUNG PEOPLE

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Hearing loss affects 9 million people, in the UK, and recreational noise exposure, such as concert attendance and personal media player (PMP) use is known to be the biggest preventable contributing factor. Noise induced hearing loss is also known to be on the rise among young people, with a prevalence $14.9\,\%$ rising to $19.5\,\%$ over a 9-year period among adolescents in the US. Young people are particularly at risk due to the length of time they listen to PMPs such as the iPod and mobile phones. Since the release of the iPod, owing to the battery life and storage improvements, the time that an individual can be listening to music while mobile has increased dramatically, which means that young people are now able to put themselves at much higher hearing risk, daily. This rise of hearing loss in young people raises the pressure to educate young people on the dangers of loud music listening. This pressure however, is met by the resistance of the cost implication on educational facilities, which means that young people are unable to access the tools needed to make an informed decision on their listening risks. This paper discusses the use of a cheaply-manufactured coupler that acts as a direct replacement to standardised, expensive acoustic fixtures in the measurement of listening levels among young people, and shows the results of an initial study, where 82 subjects had the loudness levels of their headphones measured. Data is also shown on the validation process for the coupler, where the performance was tested against a standardised, commercially available coupler.

Keywords: Hearing loss, safety, risk, education

1. INTRODUCTION

1.1 The Prevalence and cost of Hearing Loss

Hearing loss is a health condition that affects 10 million people in the UK, or one in six[1] and is the third most prevalent chronic disability in the United States, affecting 29 million Americans between 20-69 years[2]. Hearing loss also seems to be increasing among the younger demographic, with $8.5\,\%$ showing a hearing loss between 20-29 years in the American NHANES (National Health And Nutrition Examination Survey), although more contemporary large scale data is now needed due to the age of the study[3].

Superficially, hearing loss is an easily diagnosed and managed condition, but there are links to a wide variety of social and personal health conditions. The axiomatic symptom of hearing loss is a serious reduction to the communication capabilities of the sufferer. As a result of this, those suffering from a hearing loss condition can be categorised as a high risk of social isolation[4], which leads to a separate set of personal and social issues in itself.

The economic cost is an estimated £1,800 per person with hearing loss per annum as found in Australia in 2005[5, 6]. The UK spent an estimated £450 million as direct costs to the health service according to the National Health Service (NHS) themselves, though undiagnosed individuals are thought to have the potential to double this cost[7]. When considering that the overall cost to benefit ratio for a national hearing screening programme is estimated to be 8:1[8], it is clear that hearing health represents a substantial global cost burden and that the value of prevention dramatically outweighs the value of subsequent treatment .

1.2 Causes of Hearing Loss

Hearing loss is a complex condition — there are various reasons that have been shown to cause damage to hearing. The most common reasons, however, are age (presbycusis) and exposure to loud noise (Noise induced hearing disorder). Noise exposure is identified as the single biggest preventable cause of hearing loss. It is estimated that $25\,\%$ (estimates range from $23.5\,\%$ to $29.9\,\%$) of cases of hearing loss in the US are attributable to noise induced hearing loss alone[3, 9].

There is some risk of mild hearing damage to people who are regularly exposed to average levels (LEQ) exceeding $80\,\mathrm{dBA}$ (A-weighted sound pressure level), while most people will suffer some degree of hearing loss if regularly exposed to average levels exceeding $85\,\mathrm{dBA}$[10]. The Control of Noise at Work regulations [11] suggest a dose exchange system as levels increase beyond the $85\,\mathrm{dBA}$ average level, whereby an increase of 3 dB reduces the time taken to exceed a safe daily dose by half [11].

Over the past few decades, the primary risks to hearing have been occupational, where workers are exposed to high noise levels as part of their job. However, the regulation of noise exposure in the workplace has reduced this risk significantly, while leisure based noise exposure has become an increasing issue.

Loud music has been identified as one of the two recreational noise sources most likely to be harmful[12], with the other being shooting. By the 1990s, concern for hearing loss and research was turned toward assessing potential risk by the use of personal music players, at the time being predominantly cassette based. A study in a community in Hong Kong showed that risk factor was low in most cases, but measured some hearing damage likely to have been caused by negligent listening patterns and suggested increased education on the subject[13].

Thirty years later, personal media player usage has greatly increased, with up to 100 million people using personal media players in the European Union on a daily basis[14]. The technology in music players has also advanced changing the potential listening habits of consumers; devices are capable of high music storage capabilities, longer battery life, and output very high sound pressure levels[15, 16]. This leaves young people very susceptible to hearing loss due to the prolonged listening to high sound levels that can be attributed to that particular age group[17].

Young people have also shown a negligent attitude to hearing safety, taking easily preventable hearing risks[18]. This behaviour seems to be common both before and during university age [10]. Although there is extensive research in this area, the information does not seem to be reaching the young people who are at risk. The World Health Organisation[19] states that 1.1 billion teenagers and young adults are at risk of hearing loss due to recreational noise exposure.

A web-based survey in 2004 revealed some of the listening patterns of young adults and showed that a majority of them had experienced hearing loss and / or tinnitus after listening to loud music, with many of these people open to wearing hearing protection after learning the risks[20]. Shargorodsky *et al* [21] reported that the compound effect of a lack of education and increasing potential for risk has led to an increase in hearing loss among adolescents in the US, from $14.9\,\%$ to $19.5\,\%$ of the demographic.

As leisure noise exposure is voluntary (rather than imposed on a person by an occupational environment), there is minimal legislative control over noise dose, and reducing risk becomes instead an awareness and educational issue. The majority of research undertaken in this field has been focused on laboratory measurement of device output or self reporting of listening durations/levels. This paper describes the initial development of and pilot data from a quantitative system that provides a cheap and reliable measure of noise exposure, and a comprehensible method to raise awareness to people of the dangers of high levels of noise exposure.

2. METHOD AND MATERIALS

2.1 Subjects

Data was gathered by use of a prototype headphone level measurement system in the lobby of the university building as part of a health awareness stand. Volunteers used their own music choice set at their typical listening levels on a personal media player. The data gathered serves as initial pilot data to a larger project, and guides

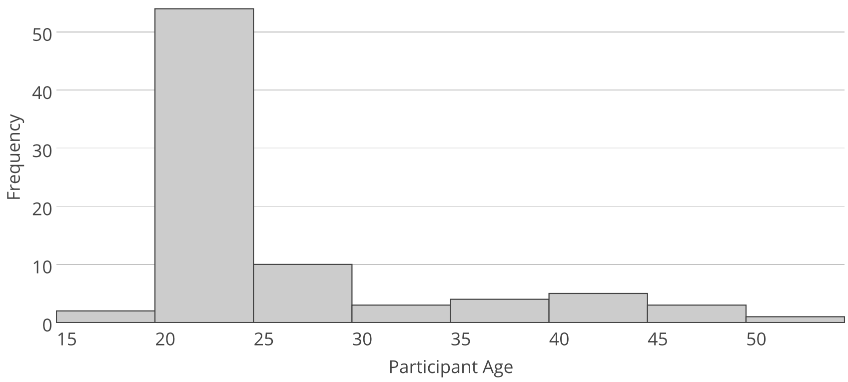
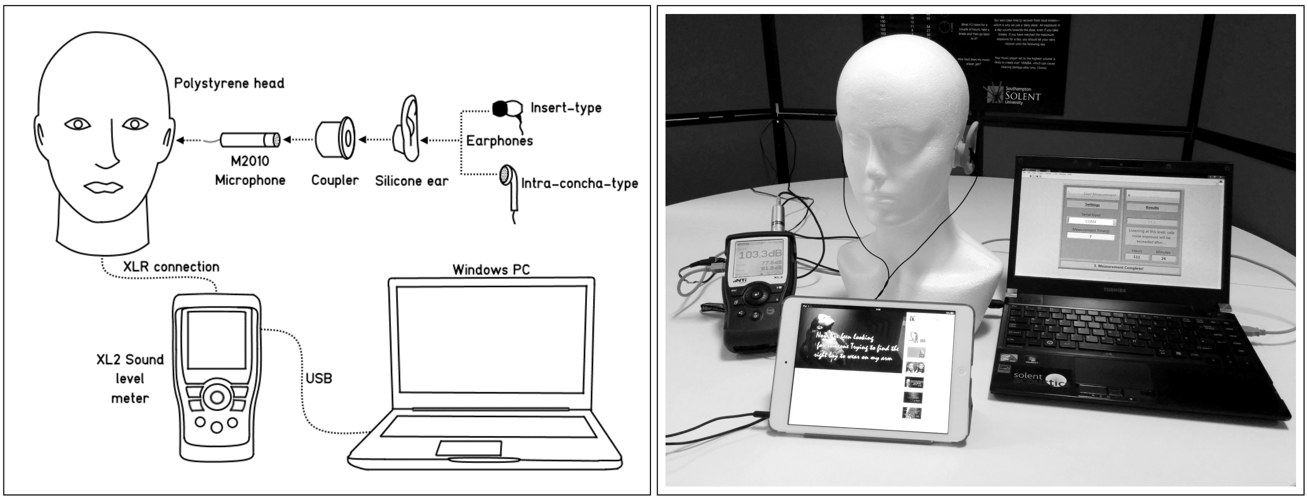


Figure 1: A histogram showing the distribution of participant age within the cohort.

further development of the system to gather large-scale hearing risk data from young people in the UK.

Eighty-two participants took part in using the measurement tool, over three consecutive weekly events. Participants had an age range of 18-50 (Figure 1), a mean age of 25.7, and a median age of 22. This demographic is considered typical of a university age cohort. Subjects were predominantly male (84 %). As participation was on a voluntary basis, the gender split was caused by self-selection, and is therefore not considered to be detrimental at this stage, though for more comprehensive studies ensuring a more representative gender balance will need to be considered. The participants were not screened for hearing acuity prior to measurement.

2.2 Instrumentation



(a) Diagram of system

(b) Built system in use

Figure 2: The measurement system (a), and (b) in use.

The system includes both hardware and software elements. Its basic premise is for the user to set some music (using their own player and headphones combination, or a unit provided) to the normal level of their listening, according to their own estimation. They would do this by listening to the headphones, and setting sound pressure level to the level that they consider normal using the volume control on the player. The subjects were instructed to "set the volume to your normal maximum listening level" to ensure uniformity in the instruction, so that people were finding the same volume parameter for themselves. The headphones were then removed from the subjects, and placed on measurement hardware, where the measurement procedure took place.

Participants were encouraged to use their own music source material for the test, so that they could choose volume levels from their own personal experience and were advised to avoid music that had a large amount

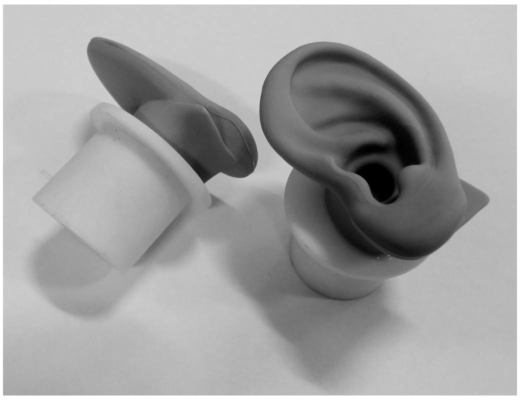


Figure 3: The 3D-printed artificial ear simulators.

of dynamic variation. While variation in the exposure level will be caused by variation in the music level over time, this is representative of the participant's level of risk, so was considered appropriate. The samples were measured over a 15 second measurement time, to allow a quick test turnaround for participants who were stopped in the lobby on the way into the university.

The most complex part of the system is an artificial ear designed as an analogue to the human ear to simulate the sound pressure that someone would be exposed to if wearing the same equipment at the same level. In this case, this artificial ear was 3D modelled and physically constructed via the use of a 3D printer. The principle behind this was to develop a system that was capable of being produced cheaply for parallel data capture, as artificial ear systems are typically precision stainless steel and expensive. This serves to increase its availability to educational facilities with lower budgets, and overall increase the propagation of the idea.

The ear simulation is designed to mimic the acoustic performance of an average human ear canal when using insert type earphones, and follows the dimensions specifications of BS EN 60318-5:2010 for ear simulations[22]. A mounting mechanism for the ear pinnae was made by use of a silicone formed ear model. This provides realistic external mounting for over-the-ear (circum-aural) and on-the-ear (supra-aural) type headphones, but also allows a mounting solution for intra-concha and intra-canal type earphones. This is in contrast to commercial options that give a poor mounting option for all types of headphones, earbud types in particular fit poorly in the BS EN 60318-7 [23] coupler. Headphones were provided for the participants in the form of Sennheiser HD202 circum-aural.

The sound pressure measurements are provided by the use of an NTi XL2 sound level meter. This is connected to an NTi M2010 measurement microphone, which was calibrated by the use of a Brüel & Kjær type 4231 acoustic calibrator. This allows the calibration drift of the meter to be eliminated by comparing the hardware sensitivity to a source that is traceably calibrated, and within its calibration period.

The meter hardware was connected via USB to a Windows tablet via standard serial port emulation on the XL2 sound level meter. This allowed the computer to run some specially developed software, using the visual programming language within National Instruments LabView. The software queries the XL2 over the serial interface and receives the sound pressure level that is measured, which is then used to calculate the exposure time on the computer.

The microphone is inserted into the artificial ear, which was mounted into a polystyrene hat mannequin, so that headphones can be easily mounted. This is the extent of the custom hardware, and aside from the calibrated microphone and sound level meter in use, the cost is negligible compared with commercial options.

2.3 Validation

A separate validation study was conducted to verify results against the artificial ear system defined in BS EN 60318-4 [24] and BS EN 60318-7 [23], when measured in parallel to the newly designed system. This was carried out by taking the system and the standardised measurement equipment to a local college (Brockenhurst College in Hampshire), and recording 19 data points from students, on both the system and the standard equipment.

The students were asked to partake in the study, and select their own music in the same way that the university cohort was, in order to measure the exposure that they are most likely to subject themselves to with their own

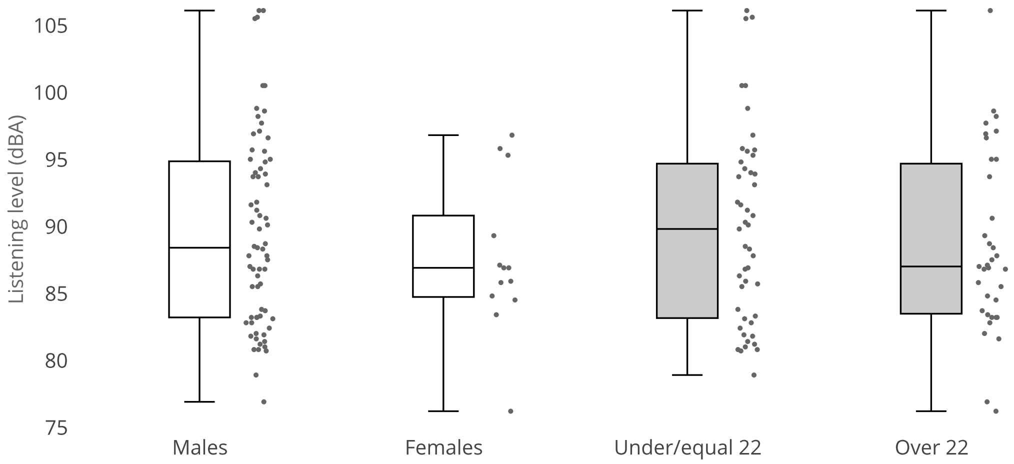


Figure 4: Box plot showing sample variation, for both gender and age divisions.

Table 1: Statistical variables for comparison between system and standard measurement apparatus

t-test Variable	N	M	SD
System	18	84	9.4
Standard	18	85.1	9.4

music choices. The measurement was then taken on a 30 second section of music, and then the music rewound to the same section, and measured again on the standard BS EN 60318 system.

Through development of the system and testing, improvements to the system will include a redesign of the 3d-printed acoustic coupler from that defined in BS EN ISO 60318-5, to the one specified in BS EN ISO 60318-4, as this will then follow the measurement procedure specified in BS EN ISO 11904-2, and also International Telecommunication Union recommendations P.57 [25] (Artificial Ears) and P.58 [26] (Head and torso simulator for telephonometry).

Another source of error in this testing is that the system is effectively giving the "eardrum amplitude" for the listeners. Unfortunately, at this time, the system is incapable of taking 3rd octave measurements, and so the free field correction cannot be applied to make a perfectly accurate noise exposure, according to BS EN ISO 11904-2:2004 (Sound immission from sources placed close to the ear). This will be corrected during further development of the system as this testing has shown it to be a concern.

Despite these disparities, the differences between the measurement with the recommended, standardised coupler and the system in development are within a reasonable tolerance, and a paired t-test showed that the two tests were statistically from the same population. In this case, the system in development was associated with a mean listening level of $84\,\mathrm{dB(A)}$ ($SD = 9.4$), while the standard measurement method was associated with a listening level of $85.1\,\mathrm{dB(A)}$ ($SD = 9.4$). The paired t-test showed an insignificant difference in samples $t(17) = -1.3, p = 0.05$, so the two data sets describe the same population, and the data is valid.

3. RESULTS

Superficially, the data shows that the highest concentration of sound pressures measured fell into the $80\,\mathrm{dBA}$ to $95\,\mathrm{dBA}$ range (Figure 5). The listening levels of fifty-six subjects ($68\,\%$) were measured at levels greater than $85\,\mathrm{dBLA_{EQ}}$, indicating that the majority of people are taking some level of hearing risk. Eighteen ($22\,\%$) of those sampled listened at higher than $95\,\mathrm{dBLA_{EQ}}$, which can be considered a significant hazard to hearing.

Sound pressure levels measured varied considerably from person to person. As can be seen from Figure 5,

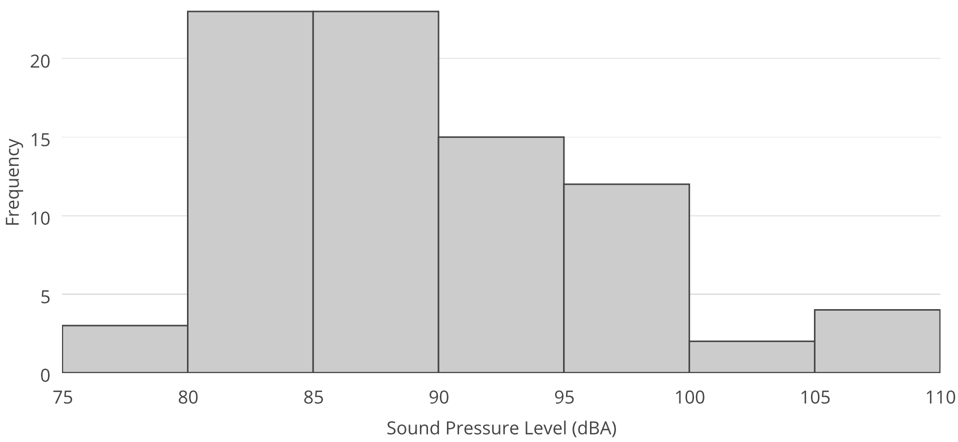


Figure 5: A histogram showing the distribution of listening levels within the cohort.

the distribution is slightly skewed, with gradually decreasing numbers of people, as the risk gets higher. There is a small peak in listeners around 110 dB, likely due to people opting to turn the music up to maximum level on the player.

Male and female listening levels were compared. The Male group ($N=69$) was associated with a listening level $M=89.4$ ($SD=7.2$). By comparison, the Female group ($N=13$) was associated with a numerically smaller listening level of $M=87$ ($SD=5.7$). To test for statistical significance in the differences between these means, an independent samples t-test was performed. The samples were assumed sufficiently normal for the purposes of a t-test, and homogeneity of variances was tested and satisfied using an f-test, $F_{67,12}=1.61$. The independent sample t-test was associated with a statistically insignificant effect on population $t(80)=1.1, p=0.05$. Thus the males and females listening levels are statistically similar, and belong to the same population.

Table 2: Statistical variables for gender comparison

t-test variable	N	M	SD
Male	69	89.4	7.2
Female	13	87.4	5.7

The same statistical checks for homogeneity were applied to participant age versus sound pressure level. The median age was calculated to be 22 years, at which the sample was divided into two groups, those above the median age, and those below or equal to the median age. The group aged 22 and under ($N=47$) was associated with a mean listening level of $M=89.6$ ($SD=7.2$). The older group was associated with a listening level $M=87.4$ ($SD=5.7$) which again is numerically similar. An independent samples t-test was performed for these samples, in which the samples were again assumed sufficiently normal, and homogeneity of variances tested via an f-test, $F_{46,34}=1.17$. The independent sample t-test was again associated with an insignificant difference in samples $t(80)=0.8, p=0.05$ and thus the older and younger groups are statistically similar, and belong to the same population.

Table 3: Statistical variables for age comparison

t-test variable	N	M	SD
Age 22 and under	47	89.6	7.2
Age over 22	35	88.3	6.7

The data were also checked against a previous study, in which a Brüel & Kjær type 4128 Head and torso simulator was used as the test apparatus[27]. This allows validation of the results against a measurement method that can be considered the gold standard for headphone sound pressure level testing. Again, an independent t-test was performed to check for population similarity. The statistical distribution was again assumed normal, and the f-test ($F_{81,26} = 1.73$) showed homogeneity of variances. The independent t-test was again associated with statistic insignificance $t = (107) = 1.33, p = 0.05$, showing the populations of both tests are similar. This means that the test method developed here produces the same results in the same population, as apparatus worth ten times the price.

Table 4: Statistical variables for comparison to previous study

t-test variable	N	M	SD
This study	82	89.1	7
Previous study	27	86.5	9.2

4. DISCUSSION

It is clear from this study that there is a wide range of listening levels amongst the initial cohort measured. However, from the initial data alone, it is clear that a high proportion of the sample were putting themselves at risk. 18 ($22\,\%$) of the sample had an average listening level of $95\,\mathrm{dBLA_{EQ}}$ or above. According to the guidelines in the Control of Noise at Work act 2005 [11], an average sound pressure level of $95\,\mathrm{dBLA_{EQ}}$ means that the noise dose limit will be reached in 48 minutes. The noise dose of the highest level measured in this cohort ($105.9\,\mathrm{dBLA_{EQ}}$) would be reached in just 4 minutes. 26 people ($32\,\%$) recorded a listening level which would be considered safe for all listening durations (LAeq lower than 85).

The cohort studied had an even distribution of sound pressure levels throughout, and showed no gender or age bias in the sound pressure levels they recorded. This shows that despite conventional wisdom of teenagers listening to louder music, this does not hold true when tested by the data. The age ranges in this case ranged from 18-50, with 13 ($16\,\%$) aged over 35.

This data was analysed in light of a previous survey in which students self-reported their durations of music listening. In that case $58\,\%$ reported listening to a personal music player for more than 1 hour per day, and $41\,\%$ listening for more than 2 hours [28]. These results would suggest that a significant proportion of the students whose devices were measured are putting themselves at risk, and either did not understand noise risk or chose to ignore it. This reinforces the evidence that raising awareness and an educational approach to the problem is key.

There was a general decrease in the proportion of students as the listening levels rose, however Figure 5 also shows an interesting peak in numbers at the top of the sound pressure level scale. This can be attributed to those people who admitted to turning the sound level up to maximum on whatever device they were playing music on. This is evidence of a significant lack of understanding of noise risk.

5. CONCLUSION

Results of the study show a substantial level of hearing risk is being taken by the cohort. While there was a third ($32\,\%$) of the cohort that reported no real hearing risk (with average levels lower than $85\,\mathrm{dBLA_{EQ}}$), $22\,\%$ of participants had measured listening levels in excess of $95\,\mathrm{dBLA_{EQ}}$ can be considered to be putting themselves at a serious level of risk of hearing loss. Those that fall between these extremes can be considered low to moderate risk.

This initial study shows that there is a considerable requirement for increasing education regarding hearing risk.

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