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# The influence of the acoustic properties of motorcycle helmets on temporary hearing loss in motorcyclists

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**Abstract**

Noise is an unavoidable component of motorcycling. The noise sources are varied, and include the helmet itself which also filters the noise passing through it. Here helmet noise transmission characteristics have been analyzed using insertion loss measurements and loudness matching in a behavioural study. Results demonstrate the action of the helmet as a spectral filter and confirm previously published data showing attenuation in the frequency range above 500Hz. Highlighted here for the first time is an amplification of noise below 500Hz. The loudness matching task data allowed the generation of equiloudness functions which show the effect of the helmet on riders' perceptions of loudness. The generated curves are here compared to the relevant international standard (ISO226) and show that loudness was strongly influenced by the helmet. The noise experienced by a motorcycle rider on a 30 minute journey can result in a temporary hearing threshold shift of over 15dB. Due to the filtering characteristics of the helmet this threshold shift is highly frequency dependent. To quantify the frequency dependence of the resulting temporary hearing threshold shift pure tone audiometry was conducted before and after exposure to white noise, with and without a helmet in a laboratory setting and after on-road noise exposure. Of particular note is the finding of increased hearing sensitivity at high frequencies following certain type of motorcycle noise exposure. The difference is discussed in the framework of the filtering characteristics of the helmet.

## 1 Introduction

Noise in motorcycling is known from numerous studies [1–10, 12–19] to be loud enough to cause hearing damage, leading to recommendations on hearing protection from medical experts [20, 21]. The problem has also been considered by motorcycling interest groups [22] and in the motorcycling press [23]. Previous studies have concentrated on measuring noise levels [19], and on reduction of noise exposure [24], with a view to limiting noise-related hearing damage.

Noise induced hearing loss (NIHL) is ranked within the top ten work-related problems that affect employees [32]. It may occur through exposure to a one off loud noise, such as an explosion, but more commonly occurs through continuous exposure to loud sounds over a longer period of time, or repeated exposure to multiple noise doses, and this includes motorcycling. Typically, noisy environments like these are workplace environments such as workshops and factories [33] and as such are the focus of legislation designed to limit the noise to which workers are exposed.

An initial temporary hearing threshold shift (THTS) may be defined as a loss in sensitivity in hearing after noise exposure. Recovery of hearing from this THTS back to the pre-exposure level depends on age of the listener, on the spectral content and on level of the noise to which they were exposed [29, 30]. A transition from a THTS to a permanent hearing threshold shift (PHTS) is a characteristic of NIHL caused by repeated periods of noise exposure. In addition to this, damage may come in the form of tinnitus—often experienced as a high frequency ringing, or noise in the ear or ears. Meyer et al [34] estimate persistent tinnitus in the UK amongst males aged 35-64 as 266,000 and in females in the same age range as 84,000. The noise experienced in motorcycling is well within a range and level sufficient to produce a THTS, but motorcyclists are presently inadequately represented in the relevant literature. The noise experienced by the motorcyclist is unique and is influenced by transmission through the helmet which is designed only to protect the rider in the event of a fall or crash. Important here is that the helmet itself is part of the issue and this research indicates why it should be considered when a solution to motorcycling related hearing loss is to be identified.

Surveys of riders [25] have reported rider hearing damage in the form of tinnitus, and the majority of riders express the desire for quieter helmets, with over half of them wearing earplugs when they ride as a noise reduction method. Ear plugs do not, however, distinguish between sounds and thus block sounds to which a rider may need to pay attention, such as some traffic noise and emergency signals. A knowledge of the acoustic response of the helmet as well as how riders perceive and respond to sounds while wearing a helmet is needed to better inform this drive towards noise reduction.

We report experiments conducted as part of a study of the causes and effects of motorcycle noise and, in particular, the short term response of riders to noise. This part of the study examines a psychophysical component of the problem, by making insertion loss measurements on helmets and comparing the results to those from a loudness matching task carried out with participants. This allows us to link the physical problem of sound propagation through the helmet with effects on the hearing of the rider.

As an investigation into the effects of motorcycle noise exposure on THTS, pure-tone audiometry was conducted before and after listeners were exposed to white noise with and without a motorcycle helmet in an investigation of the influence of the filtering effects of the the helmet on any THTS.

## 2 Experimental facilities and instrumentation

The tests were conducted in an IAC 250 series sound shelter which is designed to provide a controlled acoustic environment in which hearing screening can be undertaken. The internal dimensions of the sound shelter are 604mm x 860mmx 1680mm.Figure 1 shows a participant in the sound shelter during the loudness matching task. Due to the nature of the investigation, featuring participants wearing a motorcycle helmet, the loudness matching task required the presentation of free field sound at controlled levels. This was achieved using a purpose built speaker box with a Visaton BG 20 8Ω speaker. The speaker box was designed to be capable of providing sound of amplitude up to 100dB over the frequency range 100Hz–10kHz used in the loudness matching task.

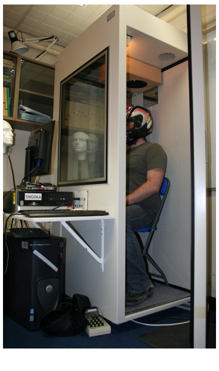

Figure 1: Participant in IAC 250 sound shelter

Table 1: PELTOR H7F attenuation properties

| $f$/Hz | 125 | 250 | 500 | 1000 | 2000 | 3150 | 4000 | 6300 | 8000 |
|---|---|---|---|---|---|---|---|---|---|
| $-\Delta$SPL | 16.1 | 23.9 | 34.0 | 40.1 | 37.0 | 36.8 | 37.7 | 38.8 | 39.0 |

Table 2: IAC sound shelter attenuation properties

| $f$/Hz | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|
| $-\Delta$SPL | 18.0 | 32.0 | 38.0 | 44.0 | 51.0 | 52.0 | 50.0 |

The calibration of the sound shelter was conducted using 1/4inch 130D20 PCB Piezotronics microphones mounted within a polystyrene mannequin head. These microphones were connected to a PCB 442B117 signal conditioner and the microphone data were acquired using a 16 channel National Instruments DAQ system. This system consisted of a personal computer (PC) and NI-PCI-MIO-16E-1 acquisition card and BNC-2090 connector box. The microphones were calibrated using a Larson Davis CAL200 microphone calibrator.

The sounds were produced using custom Matlab software on a PC with a Creative Sound Blaster Extigy sound card. The output of the sound card was fed to a Denon PMA-355UK amplifier and then to the speaker cabinet mounted in the sound shelter.

Pure tone audiometry was conducted in the sound shelter using a Kamplex KS-8 screening audiometer, compliant with BS EN60645. The factory ear-cups had previously been embedded into PELTOR H7F ear defenders prior to their calibration. This was to provide additional attenuation of external sound given in Table 1. This added to the attenuation levels of the sound shelter (Table 2) and, importantly for testing in the field, provided good attenuation levels at the frequency range assessed with the audiometer. The helmet used in the laboratory investigations within the sound shelter was taken from a series of helmets provided by manufacturers for noise investigations. As such, the make and model are covered by a confidentiality agreement.

For comparison with laboratory data additional measurements were conducted under real driving conditions. A test loop consisting of a stretch of dual carriageway between two roundabouts was used. The motorcycle used was a 2008 Suzuki GSXF-650 and the helmet a Shoei Raid II. A GPS unit was used to record data on motorcycle position and speed over the course of the test. The unit was mounted on the motorcycle dashboard and used by the rider to maintain the test speed of 110km/h along the stretches of dual carriageway. Measurements of the sound pressure level were acquired using a Edirol R-09 stereo digital recorder and miniature Knowles microphones mounted at the rider's ear. The microphones were calibrated with a Larson Davis CAL200 calibrator. A support vehicle was located in an isolated car park off the stretch of dual carriageway. Pure tone audiometry was conducted in the support vehicle using the Kamplex KS-8 screening audiometer before and after the test run.

# 3 System calibration and noise characteristics

An individual system calibration was required for each of the frequencies to be presented in the loudness matching task. The system was designed so that sound pressure levels from 40–90dB could be presented at-ear for every frequency to be tested. System volume was controlled by the software volume level and a calibration curve for each test frequency was produced using the PCB microphone system and the mannequin head which was mounted at head height for the participants.

Using the information from the system calibration, software-generated white noise could be pre-filtered to ensure the system genuinely produced noise with a flat frequency spectrum. A 30 minute sample of this white noise was generated and is referred to as the "white noise" test condition.For the second test condition used in the laboratory tests participants were asked to wear a motorcycle helmet while listening to the same white noise sample. The filtering characteristics of the helmet result in a strong change in the frequency content of the noise experienced by the listener. This test condition is referred to as "helmet noise". Additional work carried out by this group has involved detailed measurements of the noise experienced by the motorcyclist at known speeds under controlled conditions on a track [31]. Using data available from these measurements a third test condition of a 30 minute sample of motorcycle noise as experienced at steady 80km/h driving conditions was generated. This noise was pre-filtered using the same filter as the white noise sample. This noise allows listeners not wearing a helmet to be exposed to the acoustic environment experienced by a helmet-wearing motorcyclist. This test condition is referred to as "motorcycle noise".

Due to the very high low frequency sound pressure levels produced in this noise condition it was not possible to completely eliminate structural vibrations in the sound shelter between 100Hz and 200Hz. The dimensions of the booth mean that the participants can be considered to be in the near field when the wavelengths of the frequencies of interst and dimensions of the speaker are considered. The possibility of a standing wave being generated in the sound shelter is eliminated by the irregular and moving surfaces of the participants body during testing.

# 4 Test Procedures

## 4.1 Equal Loudness Matching

The most common method of loudness scaling is an estimation of loudness based on the matching of two tones of different frequency [26, 27]. A reference tone, traditionally 1kHz, is presented at a known sound pressure level and the listener adjusts a second tone of different frequency, so that its perceived loudness matches that of the reference tone. The loudness of tones of frequencies above and below the reference tone's are measured in this way. The measurements taken are psychophysical, that is, they are a psychological representation of the sound power, or loudness. Sounds perceived as being of the same loudness are assigned the same phon level. At 1kHz readings in dB and phons are by definition the same. At fixed phon level the sound pressure level measured in dB varies as a function of frequency.

Twelve participants took part in a free-field loudness matching procedure. None were payed for their time. In each trial a 1kHz reference tone was presented at 65dB. Eleven comparison tones (100Hz, 200Hz, 300Hz, 400Hz, 500Hz, 1kHz, 2kHz, 3kHz, 4kHz, 5kHz, and 7.5kHz) were each presented four times in random order, making a total of 44 trials, in two blocks of 22 with an enforced inter-block interval of 3 minutes. The initial level of each comparison tone presentation was chosen randomly within the range 50–80dB. All tones were 500ms in length and the participant could control their presentation with a keyboard from inside the sound cabin. A custom control interface allowed participants to repeat the presentation of the reference tone at will, and to raise and lower the level of the comparison tones by 2.5dB. Maximum and minimum levels of the comparison tones were limited to 90dB and 40dB. The interface provided feedback on trial number, and a warning in the event that comparison tone limits had been reached. Once happy with the match made participants moved onto the next trial by indicating that they were ready to do so using the interface. Measurements were counterbalanced, with half of the participants providing data first with the helmet and then without. It should be noted here that the level of the reference tone was set at 65dB without the helmet; when the helmet was inserted into the system the level of the reference tone will have been lower at ear. This point is addressed further in the discussion.

## 4.2 Insertion loss

The question of the acoustic effects of motorcycle helmets, in particular their attenuation properties, has not received much attention in the past, although there have been studies on protective helmets used in other applications. To our knowledge, the earliest study on motorcycle helmets was that of Van Moorhem *et al.* [1], who were motivated by the possible effects of helmets on the detection of warning signals, an issue also considered by McKnight and McKnight [18]. More recently, a set of measurements of the insertion loss of motorcycle helmets was carried out by Młyński *et al.* [28] who measured the insertion loss of three types of helmet. The direct measurement of insertion loss was carried out using microphones placed near the right ear of the helmet wearer. A second set of tests was carried out by measuring the wearer's hearing threshold with and without the helmet. The difference between the two thresholds was taken as a measure of the helmet effect on loudness. It was found that the two procedures gave comparable results, that is, the physical insertion loss measurements and the loudness results were very similar. A result shown in Figure 5 of this study [28], though not much remarked upon by the authors, was a gain in noise of about 5dB around 250Hz, i.e. an "insertion gain".

The insertion loss of the motorcycle helmet was measured using the same speaker, microphone and mannequin head set up as for the calibration. In order to produce pure white noise through the speaker the frequency response function of the system was measured. Once this had been calculated the inverse of the response function was used to pre-filter software generated white noise. This was then played through the system and measured to ensure that white noise had been produced. This allowed an identical software generated white noise signal to be repeatedly produced by the speaker system. The mannequin head was set at a fixed location directly below the speaker. A 30 second white noise burst was played over the speaker system and triggered the NI acquisition system. Data were acquired using the two at-ear microphones and by a third reference microphone within the IAC booth. This procedure was carried out for two test cases: firstly a baseline without the helmet and then with the helmet used in the participant testing. The insertion loss measurements were calculated by subtracting the resulting baseline at-ear spectrum from the at-ear spectra of the helmet case. The reference microphone was used to quantify how the addition of the helmets to the sound proof booth altered the acoustic field from the speaker. The difference was found to be negligible within the frequency range used and we assume that the helmet had a negligible effect on the incident acoustic field.

## 4.3 Threshold shift measurements

Due to the nature of the threshold shift measurements it was decided that one participant who agreed to be repeatedly exposed to the various noise conditions over a period of several weeks would be used. This participant was exposed to each noise condition, i.e. white noise, helmet noise and motorcycle noise, a total of 4 times per condition. Their baseline threshold was re-measured prior to each exposure. The tests were conducted early on each testing morning and the participant was asked to ensure they were not exposed to any significant noise levels on their journey to the testing facility. This participant was a non-motorcyclist in the 25 to 30 year age bracket.

In parallel to the participant testing in the laboratory testing was conducted under real world conditions. A second motorcycling participant was recruited for testing both inside and outside the laboratory. This participant had been a regular motorcyclist for a number of years and therefore had the possibility of some existing hearing impairment. The motorcycling particpant was in the 35 to 40 year age bracket.

The situation for this participant was different as in addition to the on road measurement this participant came into the lab for a single session of each type of noise exposure. For the laboratory sessions the motorcycling particpant was also asked to insure they avoided any significant noise exposure during their journey to the laboratory, in particular that they did not arrive by motorcycle.

In condition 1, the white noise was presented at 100dB for a period of 30 minutes. In condition 2, referred to as helmet noise, the listener was exposed to the same white noise at the same level while wearing the motorcycle helmet. In condition 3 referred to as motorcycle noise, listeners were exposed to the realistic motorcycling noise again for a period of 30 minutes. Post-exposure audiometry was carried out immediately after the 30 minute listening period. Sensitivities to 11 frequencies were measured on each occasion.

Threshold recovery time was assessed in a single session of each exposure type. The procedure was identical to the threshold shift measurements. Those frequencies that showed a threshold shift were tested repeatedly until the threshold returned to baseline levels. Testing intervals were 0, 5, 10, 15 and 30 minutes after noise exposure which was sufficient for all frequencies to return to baseline levels for each test condition.

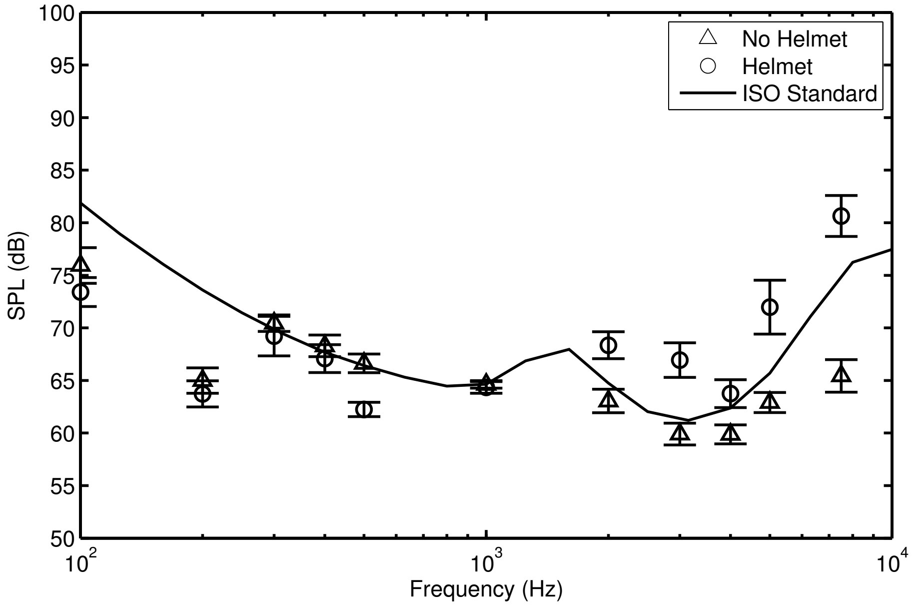

Figure 2: Equiloudness data - mean and standard error

# 5 Results

## 5.1 Equiloudness Matching

Equiloudness measurements for the 12 participants are shown in Figure 2. Measurements made with and without a helmet are shown in comparison with the international standard equiloudness contour for 65dB (ISO226).

## 5.2 Insertion Loss

The insertion loss measurement for the helmet is given in Figure 3. The measurement given is limited to the range of frequencies used in the loudness-matching task. Data above the 0dB line represent an amplification of the sound, that is an “insertion gain”.

## 5.3 Threshold Shift

Figure 4 shows a comparison of the spectral content of each noise type as experienced at ear by participants during the temporary hearing threshold tests. The low frequency components of the realistic motorcycling sound, below 500Hz, are of a much larger amplitude than experienced during either white noise test. The amplification of the lower frequency components by the helmet can be seen in the range of 100Hz to 250Hz.

Figure 5 shows the variation of riding speed and noise exposure levels experienced by the rider during the on road test.

Figure 6 gives baseline threshold and threshold shift data from one listener. Manural air conduction audiometry was used to measure the acuity of hearing

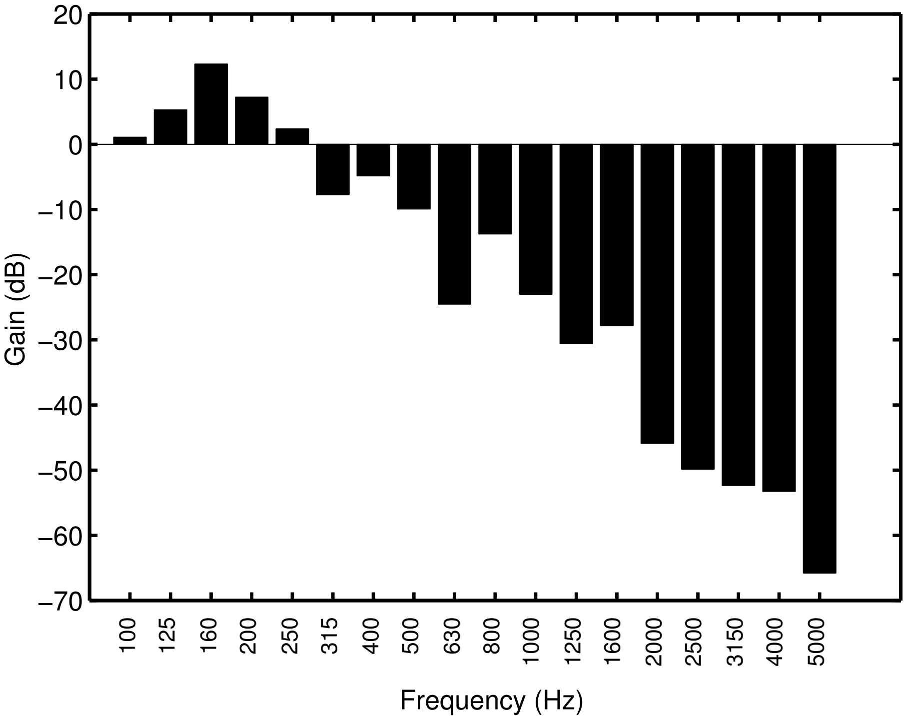

Figure 3: Insertion loss measurement of the helmet

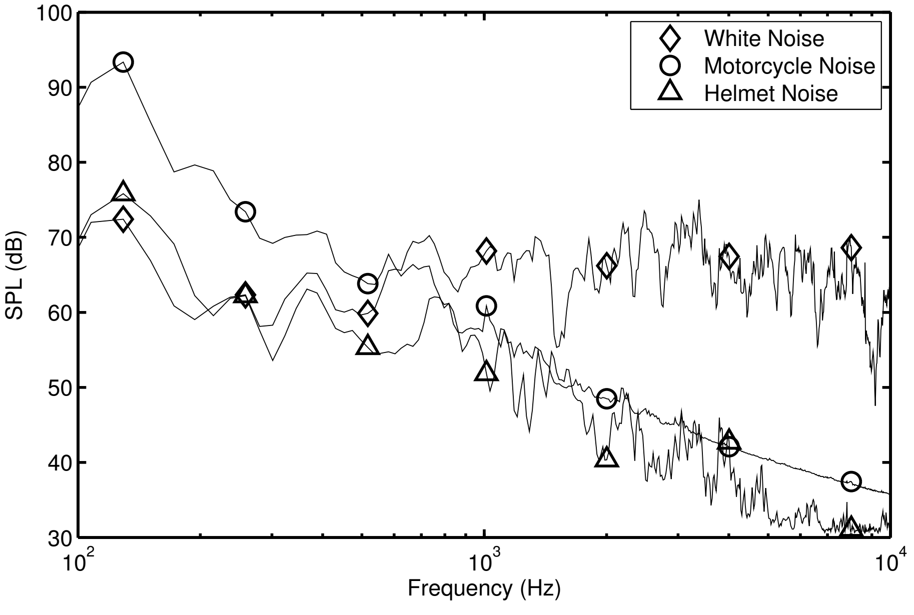

Figure 4: Noise spectra

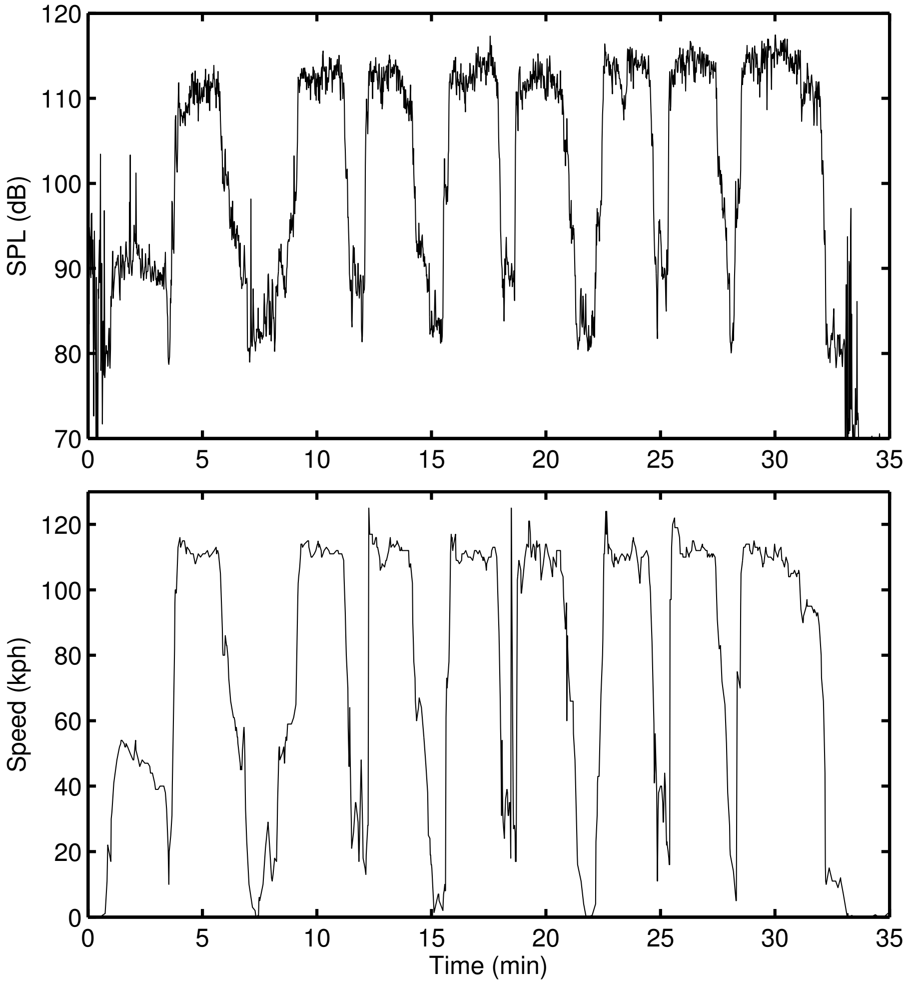

Figure 5: SPL and speed

Table 3: White noise recovery time (dB shift from baseline)

| $f$/kHz | 0.125 | 0.25 | 0.5 | 0.75 | 1.0 | 1.5 | 2.0 | 3.0 | 4.0 | 6.0 | 8.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0min | -10 | 0 | -5 | 0 | -5 | 0 | -5 | 0 | -15 | -15 | -10 |
| 5 mins | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -15 | -10 | -5 |
| 10min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -10 | -10 | -5 |
| 15min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -5 | -5 | -5 |
| 30min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

for this participant. This procedure consists of tone bursts over a series of frequencies presented to a subject using the Kamplex KS-8 screening audiometer. The participant raised a finger to indicate that they could hear a signal.

If after noise exposure the subject requires a different sound level to hear the sound e.g. the sound level has to be increased above the value on this threshold curve then the subject is said to have experienced a threshold shift. In the usual scenario the subject will require a higher sound level indicating a reduction is hearing sensitivity.

This listener completed each test condition three times for a total of nine separate sessions on non-consecutive days over a series of weeks. Figure 6 (a) shows the mean baseline hearing threshold assessed with pure tone audiometry at the audiometry facility. Figures 6 (b), (c), and (d) identify deviations from the thresholds taken before each test for each condition. Since each condition was tested three times these figures show the mean and standard deviation of the threshold shift for each condition.

Data points above the zero reference line indicate an increase in sensitivity, those below the line indicate a decreased sensitivity. Notable from these data are the decreased sensitivity at frequencies above 3kHz in the white noise condition, and the increased sensitivity for the same frequencies after exposure to noise while wearing a helmet and to a lesser extent after exposure to motorcycle noise. This is an unusual result which will be discussed in light of the helmet characteristics.

Tables 3, 4 and 5 give recovery time for each of the three conditions. Since the recovery time was only measured for one session for each noise condition, due to the time requirements for this measurement, there are no error bars associated with these tables.

Notable are the recovery times of up to 15 minutes following white noise exposure with and without a helmet in tables 3 and 4. Notable also is the direction of the change in threshold, given here as positive for increased sensitivity, and negative for decreased sensitivity.

Figure 7 gives data from twelve baseline threshold measurements from the second motorcycling particpant taken before exposure to different noises in four experimental conditions: exposure to white noise, helmet noise, motorcycle noise and the noise experienced while riding under real conditions on road, here described as road noise. Comparing figure 7 to the baseline measurements taken for the first participant, shown in figure 6 (a), there is some clear evidence of high frequency hearing impairment due to a combination of increased age and potentially motorcycling over a period of a number of years.

Figure 8 gives shifts from the baseline threshold measure for the motorcycling

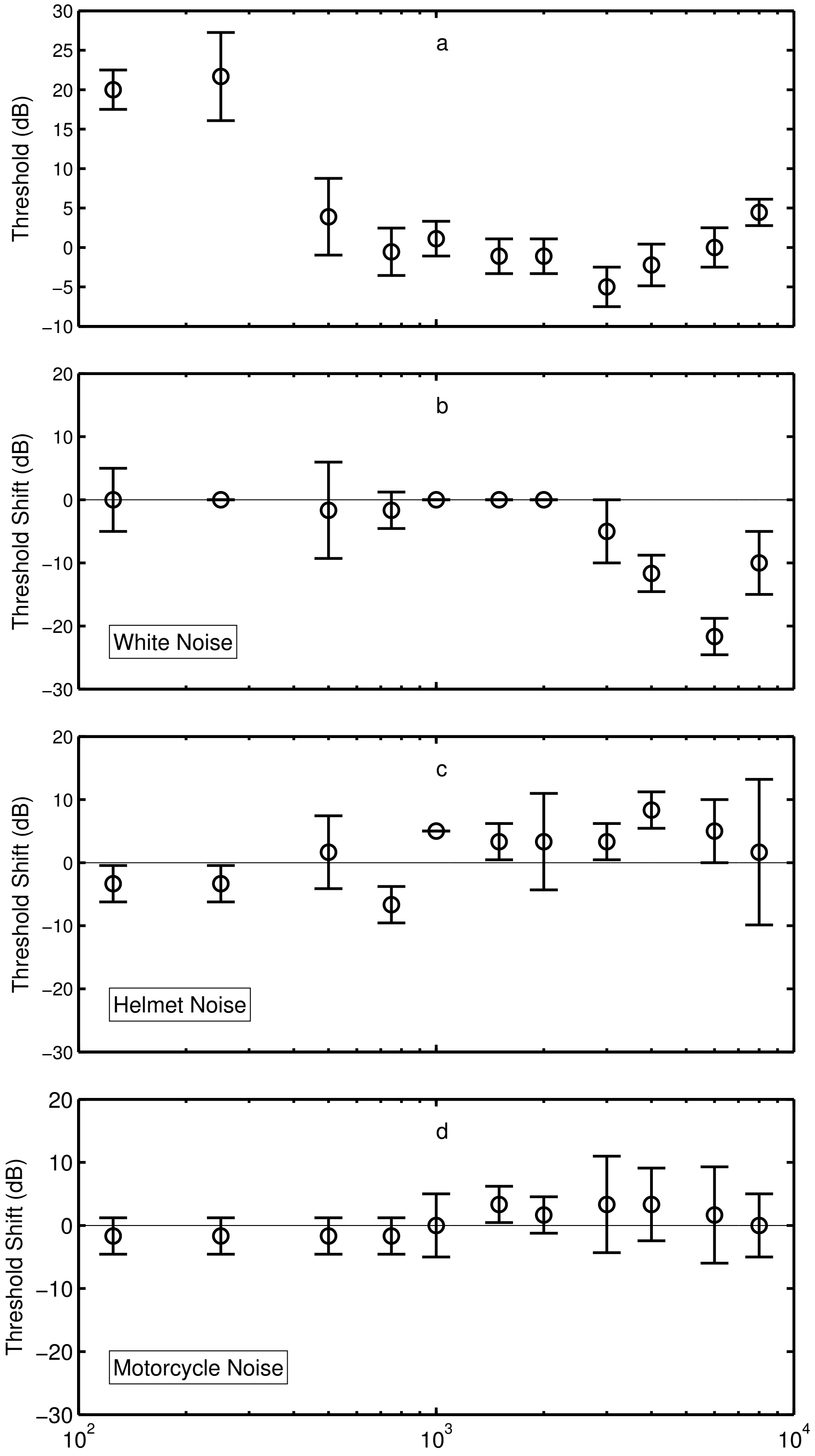

Figure 6: Mean baseline and threshold shift measurements with standard deviation : Non-motorcycling participant

Table 4: Helmet noise recovery time (dB shift from baseline)

| $f$/kHz | 0.125 | 0.25 | 0.5 | 0.75 | 1.0 | 1.5 | 2.0 | 3.0 | 4.0 | 6.0 | 8.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0min | -5 | 0 | -10 | 5 | 10 | 5 | 0 | 0 | 5 | 5 | 5 |
| 5min | 0 | 0 | -5 | 0 | 10 | 5 | 0 | 0 | 5 | 5 | 5 |
| 10min | 0 | 0 | -5 | 0 | 5 | 5 | 0 | 0 | 5 | 0 | 5 |
| 15min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 5 |
| 30min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 5: Motorcycle noise recovery time (dB shift from baseline)

| $f$/kHz | 0.125 | 0.25 | 0.5 | 0.75 | 1.0 | 1.5 | 2.0 | 3.0 | 4.0 | 6.0 | 8.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0min | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 5 | 0 | 5 | 0 |
| 5min | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 5 | 0 | 0 | 0 |
| 10min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30min | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

particpant. Notable in these data are their similarity to those in Figure 6 for the non-motorcycling particpant despite the differences in the baseline hearing sesnsitivity. Figure 8 (d) gives changes in threshold following the period of riding detailed in section 2.

# 6 Discussion

Mean data for the equiloudness measurements without the helmet follow a contour close to that given by ISO226 for a 65dB equiloudness contour supporting the efficacy of the techniques used here in measuring equiloudness. Any deviation from the standard at higher frequencies may be partly due to the age group of the cohort and may also be due to the position of the sound source. Listeners providing data in this task were undergraduate students with an average age of 22 years. The sensitivity to higher frequencies of this age group is greater than it would be for an older cohort. In addition to this, measurements in the ISO standard were made with the sound source directly in front of the listener. In our measurements, the sound source was directly above the listener, which may be relevant in the propagation of higher frequency sounds to the ear.

The insertion loss measurements of the helmet showed large attenuation of sound above 1kHz. In the case of the upper frequency used in the loudness-matching task this attenuation was as much as 25dB. The helmet showed the unusual property of amplifying certain frequencies below 1kHz. As noted above, this effect has been observed elsewhere [28]. The mechanism of this increase is likely structural resonance but this is not easily assessed. The helmet can be considered to be a hollow sphere with a large cavity. Analytical solutions to the resonance properties of sphere of this nature are not available in literature. Additionally the structure of a motorcycle helmet consists of layers of shock absorbing material with high damping and potentially non-linear vibrational

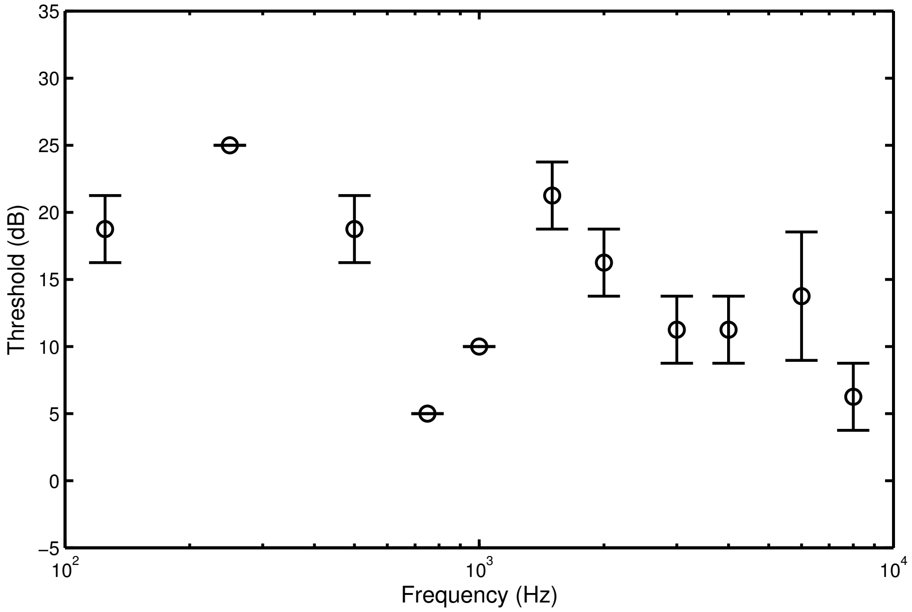

Figure 7: Baseline threshold : Motorcycling participant

behaviour. It is possible that the broadband increase shown by the measurements is due to damped structural resonances in this frequency range. When the helmet interacts with the human head the resulting vibrational system is even more complex. It is interesting to note that the human head is reported to have resonance frequencies in this range i.e. 350Hz to 900Hz [11].

Helmet 1 was used in the equiloudness measurements. Figure 2 shows that the character of the equiloudness curves was strongly influenced by the addition of the helmet for all participants. Above 1kHz, participants consistently chose higher levels for the comparison tones than they did when not wearing the helmet. At 7.5kHz the mean difference was 15dB, and while this is a considerable difference in sound pressure level, it is less than might be expected when the insertion loss curve is considered. From the shape of the insertion loss measurements we can correctly predict the general trend in the equiloudness curves as modified by the helmet. The discrepancy between the equiloudness and insertion loss measurements at 7.5kHz is in the region of 10dB.

This considerable difference could potentially be explained by the absence of alternative transmission paths in the insertion loss measurement procedure such as body and bone conduction. These transmission paths may not be affected in the same way as the air conduction paths by the insertion of a helmet into the system.

The insertion loss data do not include the performance of the human listener. To address this, an insertion loss type figure can be calculated using the equiloudness data. This can be done by looking at the change in the mean equiloudness contours for the cases with and without the helmet. While the same reference tone was used in both cases the addition of the helmet to the head slightly changes the level of the reference tone as experienced by the lis-

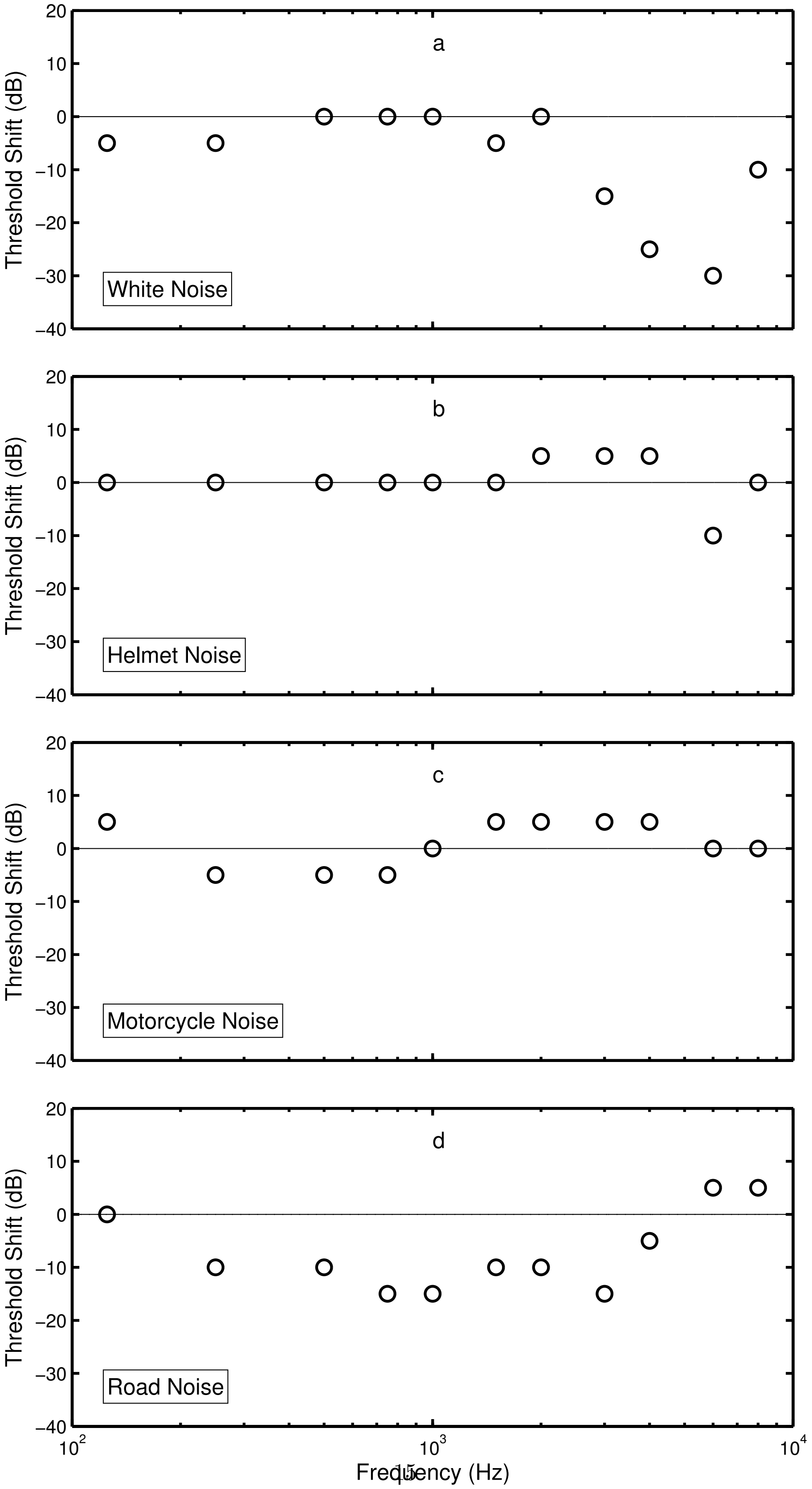

Figure 8: Threshold shift : Motorcycling participant

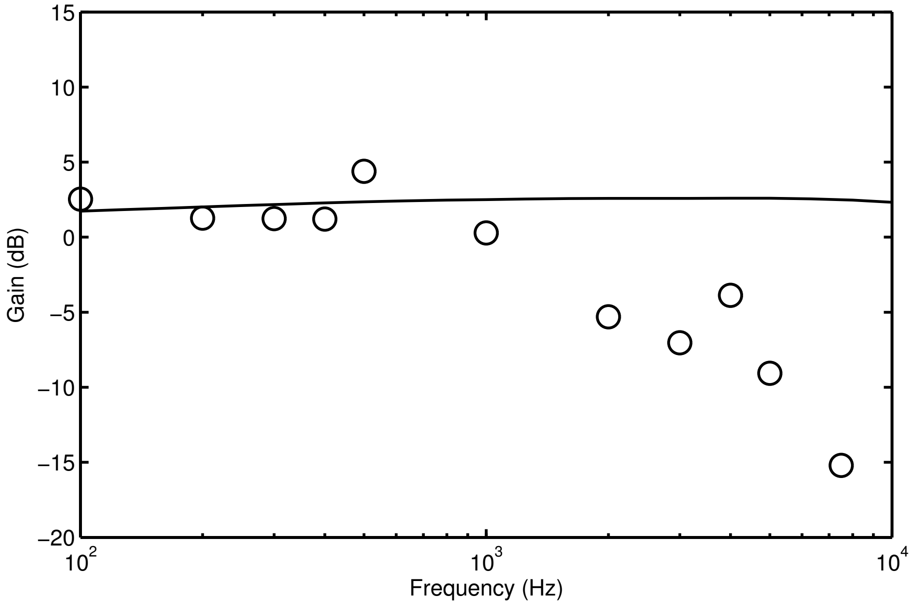

Figure 9: Change in loudness

tener. Data from the insertion loss measurements indicate that the level of the reference tone with the helmet is 62.5dB, 2.5dB lower than the 65dB reference tone experienced without the helmet and therefore on a different phon level. Comparisons of equiloudness measures at different phon levels is non trivial since each phon level follows a slightly different contour. In order to accurately compare a change in the equiloudness contours at two different phon levels the existing difference in contour shape must also be taken into account.

Figure 9 shows this insertion loss type measure for the equiloudness data. The reference line plotted in the figure gives the difference in sound pressure levels that would be required for loudness judgments to be unaffected moving from a 65dB to a 62.5dB reference tone. Any deviation from this line represents a change in the perception of equiloudness due to the addition of the helmet. The data show that the psychophysical effect of the helmet is to increase some judgments of loudness relative to the reference tone for sounds of frequency less than 1kHz and to decrease the judgment of loudness relative to the reference tone above 1kHz.

In addition to this, threshold recovery time following noise exposure is monitored. The results in Figures 6 and 8 show how the threshold profile changes following exposure to the different noises. A reduction in sensitivity following exposure may be predicted, but enhanced sensitivities at higher frequencies following exposure are shown where a helmet is used, or where the noise is shaped as a function of the spectral filtering characteristics of the helmet.

The white noise conditions both show a reduction in sensitivity at the higher frequencies. This temporary hearing threshold shift (THTS) is shown to decline and fall back towards the baseline hearing threshold. Reductions in sensitivity of as much as 15dB took up to 30 minutes to return to pre-exposure levels. Compare this with the motorcycle, helmet and road noise conditions in Figures 6 and 8. Here the increased sensitivity is reflected in the recovery times in Tables 4 and 5. It is notable that the recovery from both increased and decreased sensitivity is comparable, taking at most 30 minutes for this listener.

The mechanism(s) behind the measured increase in sensitivity reported here are unclear and it is suggested that they merit further investigation both psychophysically and in audiology. The effect, though temporary, is perhaps most accurately described in terms of an impermanent loudness recruitment. Whereas we do not propose, as in loudness recruitment itself, that there is cochlear damage resulting in the increased perception of loudness [35, 36], there are some similarities here. Loudness itself is a subjective phenomenon, and so an increased perception of loudness does not represent an increased sensitivity to sound, only the subjective judgement of its loudness. It is the pre-exposure to the louder sound dose has clearly resulted in a growth in the perception of loudness that cannot be explained in terms of cochlear damage, as judgements return to 'normal' with time. There is also a strong frequency dependence to this phenomenon relating to the frequency content of the nois exposure and so we present it here as worthy of further investigation in a number of fields.

It should be noted that the exposure here was relatively short in all cases, at 30 minutes, and at 100dB in all cases. Should either of these vary, changes in threshold will be different and recovery times may also vary. These data suggest that the magnitude and direction of the change has no bearing on the speed of recovery, with a full return to pre-exposure levels taking 30 minutes in each noise condition. It is possible that the measurements of threshold change are conservative. The resolution of the audiometer used was 5dB at all frequencies and so changes may have been up to 4dB more in each case. The severity of any THTS indicated in these data is then likely to be an underestimate.

Table 5 shows recovery time after exposure to motorcycle noise. The spectrum of this noise is shown in Figure 4. Notable here is that it includes at least the same amount of energy at the majority of frequencies as helmet noise, and more energy at frequencies below 400Hz than either of the other noises used. Despite this, after exposure to this noise at 100dB for 30 minutes no reduction in sensitivity at any frequencies was shown. Little change was seen at all in this condition. The changes that were seen were small with relatively temporary increases in sensitivity in some frequencies above 1kHz.

Figure 5 and Figure 8 (d) provide relevant data from on-road tests. A comparison of data in panel (d) with the lab test data for exposure to helmet noise and motorcycle noise, shown in panels (b) and (c), reveals some differences between the deviation-from-threshold profiles in this listener. This is despite the noise being either an approximation of that heard while wearing a helmet, or the noise actually heard while wearing a helmet. The reductions in sensitivity to frequencies below 6kHz while riding are not found in the laboratory. Similarly, the increases in sensitivity found at 2, 3 and 4 kHz in the laboratory are seen at the higher frequencies of 6 and 8kHz while riding. These differences can be attributed to the additional signals in the auditory environment experienced on the road. Figure 5 shows that the noise experienced on the road was not constant as it was in the laboratory. Periods of noise in excess of 100dB are separated by relatively quieter periods of approximately 82dB. These are directly related to the speed on the road, shown in panel (b). The higher speeds correspond to the periods of most significant noise exposure. Previous data [31] have shown that turbulent noise due to flow across the helmet is a significant component of the noise experienced in motorcycling, and this noise can change with head and windshield angle. The noises associated with the motorcycle itself and the complexities of riding, including gear changes, acceleration, deceleration, and head movements when riding will combine to form a different auditory-environment to that presented in the laboratory which most closely resembled a period of riding at constant speed along a straight section of road.

Significant low frequency threshold shifts were not measured in the subjects. Due to the inherent resilience of the human auditory system to low frequency sound it is not surprising that only a small threshold shift of approximately 5dB was experienced by the participants despite the amplification of the low frequency content by the helmet. The testing time of 30 minutes is likely insufficient to cause low frequency threshold shifts. It is an interesting open question as to what is the frequency dependence of short term hearing threshold shifts. This work highlights some of the complications which exist when dealing with broadband noise exposure which is not equally distributed across all frequencies.

## 7 Conclusions

The action of the motorcycle helmet as a spectral filter is to amplify certain frequency ranges and attenuate others. The amplification of low frequency sound by as much as 15dB and the resulting increase in perceived loudness of those sounds has implications for those concerned with the design of hearing protection technologies for riders. We can conclude that existing passive methods of hearing protection, such as ear plugs, are insufficient. Methods such as these are designed as barriers to the air transmission path and they do not consider paths such as bone and body conduction, where low frequencies are likely to dominante.

The attenuation of high frequency sound by the helmet serves to effectively remove a large portion of the acoustic environment. Acoustic feedback from the riding environment is vitally important for rider safety and forms an important part of the riding experience. Those concerned with the design of warning signals such as sirens should also be aware of the filtering characteristics of the helmet.

The THTS measurements allow us to conclude that the effects on hearing threshold of the noise experienced whilst riding and when the noise is correspondingly shaped with reference to a helmet spectrum are quantifiably different to those experienced due to white noise exposure. The data also show that it is possible to reproduce the patterns of threshold shift found on the road in a controlled laboratory setting. Notable also are increases in hearing sensitivity at frequencies higher than 1kHz after exposure to motorcycle, helmet and on-road noise. In addition to this, the reduced sensitivity experienced during the on-road tests was shown here to be greater than expected from the laboratory results.

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