Acta Acustica 2025, **9**, 28

https://doi.org/10.1051/aacus/2025013

Available online at:
https://acta-acustica.edpsciences.org

Technical & Applied Article

Open Access

Measurement of insertion loss and gain in variable hear-through and noise cancellation modes of true wireless earbuds

Jay Harrison[1]*, Alan W. Archer-Boyd[2], and Damian T. Murphy[1]

[1]Audiolab, School of Physics, Engineering and Technology, University of York, Genesis 6, Church Lane, Innovation Way, Heslington, York, YO10 5DQ North Yorkshire, United Kingdom

[2]BBC Research and Development, The Lighthouse, White City Place, 201 Wood Lane, London, W12 7TQ Greater London, United Kingdom

Received 28 November 2024, Accepted 4 March 2025

Abstract – This paper presents the results of objective tests to assess the insertion loss and gain performance of three true wireless earbuds that featured both active noise cancellation (ANC) and hear-through functionality. An acoustic test fixture (ATF) was used to examine the earbuds' attenuation and boosting of broadband noise, linearity of performance for different presentation levels, and consistency of performance over time. The results show that devices are capable of a wide range of both attenuation and boosting, with hear-through modes providing significant levels of boosting in frequencies that are considered important to the intelligibility of speech. Furthermore, none of the hear-through modes tested were found to provide responses that suggested the devices were capable of providing full acoustic transparency. The results may also be useful for those seeking to produce models that replicate key aspects of insertion loss and gain performance in contemporary true wireless earbuds.

Keywords: Variable Hear-through, Active Noise Cancellation, Acoustic Transparency, Insertion Loss, Insertion Gain, True Wireless Earbuds, Hearables

1 Introduction

True wireless earbuds are headphone devices that are worn inside the ear canal or at the canal entrance, with placement similar to half-shell or in-the-canal (ITC) hearing aids. True wireless earbuds typically feature silicone or foam tips which fully occlude the entrance to the canal. They also employ wireless technology protocols such as Bluetooth to receive audio data from external hardware devices and are not physically connected between left and right earbuds. They are now amongst the most popular devices used to listen to media with a smartphone, with a 2022 global consumer behaviours report finding that 41% of smartphone users owned a pair of true wireless earbuds and a further 20% intended to purchase a pair in the next year [1]. One of the main drivers in the rise in popularity of true wireless earbuds is the trend of consumers spending more time listening to audio content in a typical day. Shrinking form factors and improvements in battery life performance mean consumers are able to comfortably listen for longer periods of time. As an extension of a user's smartphone device true wireless earbuds are frequently used for much more than just listening to music. They are also used to play video games, watch visual media, take video/voice calls, and track user fitness/health, with listeners typically spending at least an hour a day engaging in each activity [1]. Listeners are also using active noise cancellation (ANC) [2, 3] in true wireless earbuds to control the extent to which they are able to perceive their surrounding external soundscape, with 68% of consumers stating that this feature would influence their next purchase, and 16% of listeners specifically using earbuds to improve their hearing in noisy environments, doing so for an average of 1.4 h per day [1]. ANC is now an established feature that can be found in a wide array of domestic and industrial headphone, headset, and hearing protection devices, with its main purpose being to lower the perceptible affects of any disturbing or dangerous environmental noise that the listener may be exposed to. Many studies have suggested that exposure to excessive environmental noise can lead to a range of impairments in an individual's cognitive performance [4–6] and general wellbeing [7–9]. While there have been some studies showing the positive effects of passive hearing protection devices can have on wellbeing [10], mosts research in this area has focused on the positive effects of passive hearing protection on speech intelligibility and recognition [11–13]. There have been comparatively fewer studies [14–16] investigating similar effects for ANC devices.

*Corresponding author: jay.harrison@york.ac.uk

Many true wireless earbud devices now also feature one or more hear-through modes [17], which use microphones mounted on the outer shell of either earbud to boost parts of the frequency spectrum of the external noise, allowing the listener to consume media while maintaining an increased awareness of elements of their surrounding soundscape. The origins of hear-through technology are most closely associated with the development of spatialized audio for augmented reality [18] and audio augmented reality (AAR) experiences more widely [19], where the optimum hear-through performance would be to provide the listener with a sense of full acoustic transparency, allowing them to perceive their surroundings alongside the AAR media. Acoustic transparency is defined as hear-through performance in a device that is perceived by a listener as being equivalent to that of open ear listening [20, 21], i.e. where the listener does not perceive any part of the frequency spectrum to be attenuated or boosted compared to open ear listening.

However, the primary applications for hear-through functionality in contemporary true wireless earbuds are more closely aligned with addressing issues relating to users' regular day-to-day listening requirements, such as increasing users' sense of personal safety in public spaces or acting as an assistive listening device in noisy environments. Respondents to a survey on mobile media consumption reported choosing not to consume media while wearing headphones, or not wearing headphones at all, when walking in isolated public spaces at night or in hazardous urban environments such as construction zones or areas of traffic [22, 23]. There has been a significant body of research aimed at quantifying the noise attenuation performance of both passive [24–26] and active noise reduction devices [27–29] under a variety of different test conditions. In contrast, there has been much less research carried out to quantify the performance of hear-through modes in commercially available devices, where measurement of both insertion loss [30] and gain [20] is potentially required.

In 2020 Gupta et al. [31] reviewed the challenges and techniques employed in developing hear-through systems for use in AAR. In 2020 Denk et al. [20] conducted a technical evaluation investigating the acoustic transparency of hear-through modes in seven hearables [17] and two bespoke research devices. Several different kinds of artefacts were identified including deviations of frequency response, comb filtering artefacts, and destruction of spatial cues. Schlieper et al. [32] measured the transfer functions of active noise cancellation and hear-through functionality in headphone devices that contain both features. However, this study only presented results of exponential sweep measurements to evaluate direction-dependent performance. There are no known studies that have used diffuse sound field noise to evaluate active noise cancellation and hear-through performance in devices that feature both modes.

The aim of the present study was therefore to quantify both the insertion loss [30] and insertion gain [20] provided by ANC and hear-through modes in commercially available true wireless earbuds that include both features. This study represents a set of case studies of devices that include this dual functionality, with the results expected to be useful for researchers seeking to model the noise attenuation and boosting performance of leading contemporary true wireless earbud devices. In the present study, Section 2 details the devices, device modes, and measurement apparatus that were used to produce the results. The method and results for the measurement of insertion loss and gain are described in Section 3. Section 4 provides a discussion of the results and Section 5 concludes.

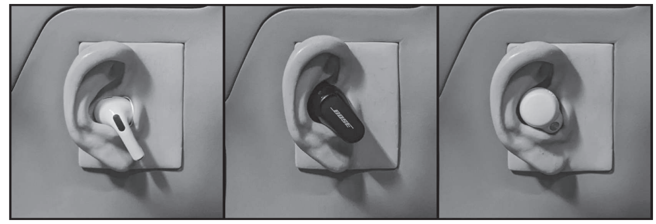

Figure 1. Photographs of the devices inserted in KEMAR. From left to right: Apple Airpods Pro (2nd gen.), Bose QuietComfort Earbuds II, and Sony LinkBuds S.

2 Material and methods

2.1 Devices tested

A review of commercially available true wireless earbud devices was undertaken according to the following criteria; devices should have been released within the year 2023 and offer a noise cancellation mode, plus a variable hear-through mode providing different levels of hear-through functionality. This review identified several potentially suitable devices, from which a final three were selected based on positive industry reviews [33–35] of noise cancellation and hear-through performance. These devices were the Apple Airpods Pro (2nd gen.) (firmware 5B58), Bose QuietComfort Earbuds II (firmware 1.3.26+g1226f68), and Sony LinkBuds S (firmware 2.1.3). Photographs of these devices are shown in Figure 1. All devices were new and purchased for use in this study. The devices' firmware and accompanying control apps were updated to the most current releases as of 20/03/23. Default settings were used for all devices.

2.2 Device modes tested

The device modes measured in the study are shown in Table 1. The Airpods featured a *"Noise cancellation"* mode, *"Off"* mode, and variable "Ambient noise reduction" (ANR) hear-through mode comprising of 101 levels, with ANR 100 providing the most reduction and ANR 0 the least. The LinkBuds provided a "*Noise canceling*" mode, "*Off*" mode, and variable "*Ambient sound* (AS) hear-through mode consisting of 20 levels with AS 1 providing the most reduction and AS 20 the least. In

Table 1. The modes tested in each device and study nomenclature used to describe equivalent modes.

Study nomenclature used to describe equivalent modes	Apple Airpods Pro 2 (2nd gen.) modes	Bose QuietComfort Earbuds II modes	Sony LinkBuds S modes
Hear-through mode (*HTM*)	Ambient noise reduction (*ANR*)	Noise cancellation (*NC*)	Ambient sound (*AS*)
– *HTM 1* (Greater awareness)	– *ANR 0*	– *NC 1* (Aware mode)	– *AS 20*
– *HTM 2*	– *ANR 20*	– *NC 2*	– *AS 16*
– *HTM 3*	– *ANR 40*	– *NC 4*	– *AS 12*
– *HTM 4*	– *ANR 60*	– *NC 6*	– *AS 9*
– *HTM 5*	– *ANR 80*	– *NC 8*	– *AS 5*
– *HTM 6* (Lesser awareness)	– *ANR 100*	– *NC 10* (Quiet mode)*	– *AS 1*
Noise cancellation mode (*NCM*)	Noise cancellation (*NC*)	Noise cancellation (*NC*)*	Noise cancelling (*NC*)
– *NCM* (Least awareness)	– *NC*	– *NC 10 (Quiet mode)**	– *NC*
Off Mode	Off	Battery depleted (Off)**	Off
– *Off*	– *Off*	– *Battery depleted (Off)***	– *Off*

*The results for Bose *NC 10* mode were used to represent both the *Noise Cancellation Mode* (*NCM*) and *Hear-Through Mode 6* (*HTM 6*) for comparative analysis with the other devices. **As the Bose earbuds did not feature a selectable *Off* mode, the passive Off Mode measurements were recorded after the battery had depleted.

contrast, the QuietComforts featured a "*Quiet mode*", "*Aware mode*", and a variable "*Noise cancellation* (NC) mode comprising of 10 levels, with NC 10 providing the most attenuation and NC 1 the least. Subsequent measurements carried out in pilot testing, and personal communications with the manufacturer, established that the performance of the "*Quiet mode*" was identical to "*Noise cancellation 10*" and the "*Aware mode*" was identical to "*Noise cancellation 1*".

To investigate the entire range of each device's performance, measurements were taken for the *Off* mode, noise cancellation mode, and 6 equivalent levels of the variable hear-through modes in the Airpods and LinkBuds. As the QuietComforts did not offer separate separate noise cancellation and variable hear-through modes, measurements of this device were taken for the "*Off*" mode and 6 levels of the variable "*Noise cancellation*" mode. The results for "*Noise cancellation 10*" were then used to represent both the Noise Cancellation Mode and Hear-Through 6 Mode for comparative analysis with the other devices. In the remainder of the paper the devices are anonymized and referred to as Devices A to C.

2.3 Acoustic test fixture

Rudzyn and Fisher [27] suggested the two main physical measurement methods, of Microphone In Real Ear (MIRE) and Acoustic Test Fixture (ATF), are preferable to the Real Ear Attenuation at Threshold (REAT) method for measurement of the attenuation provided by ANC devices. The MIRE method is most frequently used to measure the performance of hearing aid devices and while it does offer the advantage of accounting for variation of fit within a sample of participants, the ATF method is more suitable for the measurement of ANC devices. As the ATF method does not require any human subjects it is possible to test the devices up to the limits of their performance, with no risk of injury to participants from exposure to potentially dangerous sound pressure levels. It is also much easier to maintain tight control of test conditions, enabling a higher level of consistency between measurements, thus providing a higher level of accuracy when analysing the performance of different devices. ATF methods have shown to be equally applicable for the measurement of both insertion loss and gain across a range of devices and applications [20, 30, 36].

It should be stated however that as ATFs are not able to perfectly replicate all characteristics of the human head and auditory system, aspects of performance such as bone-conduction sound transmission are not accounted for, and as a result the level of attenuation measured using an ATF will be exaggerated compared to what is experienced by real listeners. Despite this, the ATF method was still considered the best of the available options and was therefore selected for use in the present study.

3 Spectral modification of broadband noise

The term spectral modification is used in this study to describe any attenuation or boosting of external noise introduced by the devices under test. *Passive Spectral Modification* (PSM) is used to describe both the attenuation and resonant peaks caused by the physical occlusion of the devices in *Off Mode*, *Total Spectral Modification* (TSM) describes the insertion loss and gain provided by the combination of passive occlusion and active noise cancellation/hear-through modes, and *Active Spectral Modification* (ASM) is used to describe both the attenuation and boosting that is provided by the active electronics of the noise cancellation/hear-through modes in isolation, without the additional attenuation/resonant peaks from the passive occlusion.

3.1 Spectral modification of broadband noise method

The following method for measuring the spectral modification of broadband noise provided by the passive and active modes in the devices was adapted from a methodology proposed by Rudzyn and Fisher [27]. The resulting methodology largely adheres to ETSI TS 103 640 [37], however, limitations with the available materials resulted in some unavoidable deviations. Known deviations include exceeding the specified noisefloor by 15 dB, the use of a larger loudspeaker array, and the use of the 30 s analysis duration specified in [27]. It is not thought that these points significantly affected the accuracy of the results. The method in the present study comprised of the following steps:

(a) Generate a diffuse sound field in a listening room using uncorrelated pink noise signals (see below for more details).
(b) Record 35 s of the open ear (OE) response of a GRAS 45BC KEMAR ATF in the diffuse field at broadband levels of 65, 70, 80, 90, 100, and 105 dB sound pressure level (SPL).
(c) Fit earbuds in the pinna of KEMAR and record passive response (PR) with *Off* mode selected (same recording process as used in step (b)).
(d) Record total response (TR) of the device for each active mode listed in Table 1 (same recording process as used in step (b)).
(e) Remove the earbuds from KEMAR and repeat steps (c)–(e) for a total of five iterations.
(f) Analyse recordings to determine the measurement iteration with the best fit (see below for more details).
(g) Linearly average over the selected measurement from 5 to 35 s to attain stable third-octave root mean square (RMS) levels [38, 39] of the open ear, passive, and total responses for all modes for that iteration.
(h) Calculate broadband noise spectral modification from third-octave RMS level results for all device modes listed in Table 1:
    (1) Passive spectral modification [dB] = OE[dB] − PR[dB]
    (2) Total spectral modification [dB] = OE[dB] − TR[dB]
    (3) Active spectral modification [dB] = PR[dB] − TR[dB]
(i) Repeat steps (c)–(h) for all devices being tested.

The broadband noise signal was generated in Matlab as a 50 channel, 35 s stem of uncorrelated pink noise. This was then fed to a 50 point Lebedev grid loudspeaker array using Reaper v6.75 running on a PC (Windows 10 Enterprise, Intel i9-13900k, 32GB RAM) and two Ferrofish A32 AD/DA converters, located in the listening room (128.7 m^3) at the Audiolab, University of York. The noisefloor was measured at 30 dBA SPL and the A-weighted T30 reverberation time was 96.7 ms. The array comprised of 40 Genelec 8030A and 10 Genelec 8040A active loudspeakers. An NTi XL2 Analyzer and M4260 measurement microphone were used to calibrate the broadband noise (LAeq) at the centre of the grid for the different presentation levels. The spectrum was found to be flat within ±5 dB for all bands of interest. This was considered an adequate approximation of diffuse field conditions for the purposes of the present study, in accordance with measurement procedures from past studies [20, 28, 40]. The signal was measured with left and right prepolarized ear simulators (RA0045-S1) fitted in a GRAS 45BC KEMAR ATF, the KEMAR was equipped with large (VA-Style) pinnae [41]. The output from each simulator was then passed through a Presonus DigiMax DP88 analog-to-digital converter and recorded using Reaper. The frequency range of the measurements was limited to 63–20,000 Hz due to the frequency responses of the loudspeakers.

3.1.1 Earbud fit

Denk et al. [20] and Struck [28] highlighted the importance of conducting multiple iterations of measurements to ensure a tight physical fit and achieve optimal passive attenuation performance. Each device featured a built-in app-based tool designed to check the quality of physical fit for either earbud. These tools were not used in the present study as they were found to provide unreliable measures of the quality of fit in KEMAR. Therefore the medium earbud tips/stability bands (Apple: "Medium" silicone tips, Bose: "M" silicone tips and stability band 2, Sony: "M" silicone tips) were used for all devices. Figure 1 shows the earbuds inserted in KEMAR. Measurements were repeated for a total of five iterations with the earbuds removed and reinserted between each iteration. The method for determining the measurement iteration with the best fit involved attaining the third-octave RMS levels of the passive responses (*Off* mode) from both ears for each iteration, and then performing an analysis to identify the iteration that demonstrated the broadest and most consistent range of attenuation and boosting of diffuse broadband noise for both ears [20].

3.2 Spectral modification of broadband noise results

Figure 2 shows the PSM for the *Off* modes of the measurement iterations that were selected for further analysis in Section 3.2. These results illustrate that a broadly similar physical fit and level of passive attenuation was achieved for both left and right ears in all devices, however, there were a few instances where ASM results for the right ear were not consistent with the left ear. It was thought this was due to general inconsistencies in the performance of the devices and differences in the quality of earbud fit between KEMAR's left and right pinna. As such these results were not considered representative of typical TSM performance in the devices and therefore all of the forthcoming results in this paper were derived from left ear device measurements only unless stated otherwise.

Figures 3 and 4 show the TSM and ASM provided by the devices when subject to 80 dB SPL pink noise in an approximated diffuse field. The results attained from the 80 dB SPL measurements are highlighted in the forthcoming analysis as they demonstrated the broadest range of both attenuation and boosting across all of the device modes.

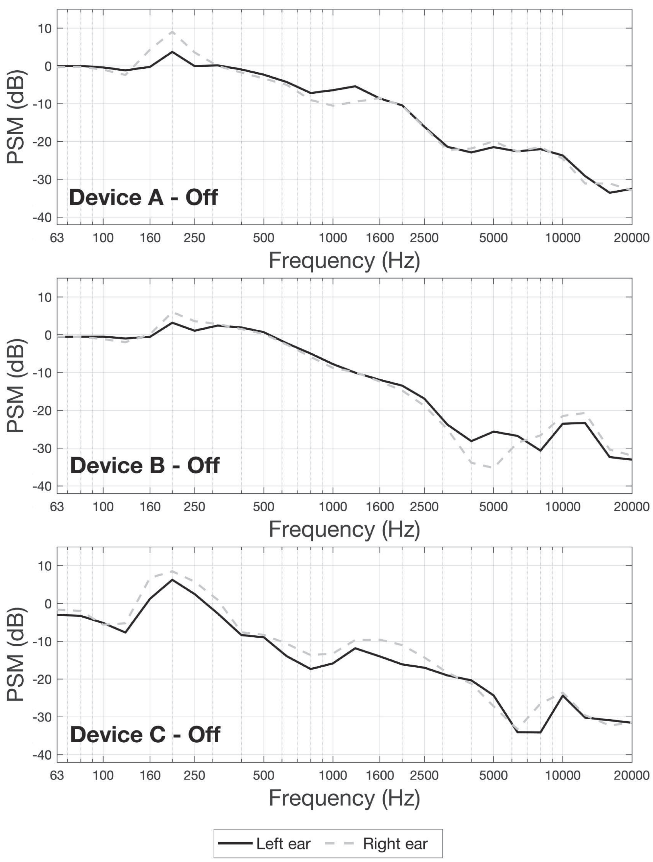

Figure 2. Passive spectral modification of diffuse pink noise at 80 dB SPL for *Off* modes for all devices.

This section will first consider the PSM results to analyse and compare differences in the insertion loss due to the passive occlusion of the devices. The TSM results will then be analysed to establish the nature of the spectral modification as it would be perceived at the ear by a real listener. The ASM results will also be presented to quantify and differentiate between the spectral modification provided by the passive occlusion of the devices and the active electronics in the noise cancellation and variable hear-through modes. No effort was made to speculate on the nature of the active electronics or processing contained within each device as this was not considered relevant to the aims of the study.

An additional spectral modification properties analysis was also performed on the PSM, TSM, and ASM results presented in Figures 2–4. The methodology for this analysis was based on criteria defined in a study by Rudzyn and Fisher [27]. Results for this analysis can be found in Tables A.1–A.3 of the supplementary information, accessible via online repository [42].

3.2.1 Passive spectral modification results

PSM results: off modes. Figure 2 shows the PSM provided by the passive occlusion of the devices at 80 dB SPL in third-octave bands. The results of the accompanying PSM properties analysis are presented in Table A.1 of the supplementary information [42]. The results for all three devices showed a notable boosting of frequencies centred around the 200 Hz band. This was the most pronounced in Device C with a boost of 6.27 dB, followed by Device A (3.73 dB), and Device B (3.19 dB). For all devices these regions of boosting only spanned the single band of 200 Hz, according to the analysis criteria of boosting breadth ≥3 dB adapted from Rudzyn and Fisher [27]. This boosting can be attributed to passive resonances created by the insertion of the devices in the ear canal(s) of the ATF, with the size and position of the passive resonant peak being dictated by the amount of acoustic leakage, volume of the cavity created, and the absorptivity of the earbud tip materials [43].

There were similar consistencies between the devices observed in the nature of attenuation across the rest of the frequency spectrum. All devices displayed similar attenuation characteristics whereby the cutoff frequencies of the main attenuation shelves began in the region of 400–800 Hz. The shelves then followed a broadly similar trend with the level of attenuation increasing for successively higher frequency bands, with the exceptions of slight peaks around 1250 Hz in devices A and C. Similarly minimal peaks can be observed at 5 kHz in devices A and B, and more pronounced peaks around 10 kHz in devices B and C. All devices also registered similar maximum levels of passive attenuation, however, the frequency bands at which these occurred differed, with Device C providing −34.12 dB at 8 kHz, Device A −33.57 dB at 16 kHz, and Device B −33.03 dB at 20 kHz.

3.2.2 Total spectral modification results

The plots in Figure 3 show the insertion loss and gain provided by the noise cancellation and hear-through modes of the devices. The results of the accompanying TSM properties analysis are presented in Table A.2 of the supplementary information [42].

TSM results: Noise cancellation modes. For frequencies above 5 kHz the TSM remained broadly unchanged from the underlying PSM for each device described in Section 3.2.1. This was with the exception of slight peaks at 8 kHz and 20 kHz in Device A, and 6350 Hz in Devices B and C. The maximum level of attenuation achieved in a single frequency band was −34.90 dB at 125 Hz in Device B. This compared with −32.37 dB at 8 kHz in Device C and −31.46 dB at 160 Hz in Device A.

TSM results: Hear-through modes. All six hear-through modes in Device A had singular regions of boosting ranging from a maximum amount of 14.37 dB for *HTM 1* to 8.54 dB for *HTM 6*, with all boosting regions centered around 2500 Hz and ranging from approximately 2000 to 4000 Hz for *HTM 1–3* and 2000 to 3150 Hz for *HTM 4–6*. This was contrasted by Device B where only the first four hear-through modes *(HTM 1–4)* featured any boosting, ranging from a maxima of 13.77 dB for *HTM 1* to 3.12 dB for *HTM 4*. All regions were centred around 2 kHz, however, the boosting region

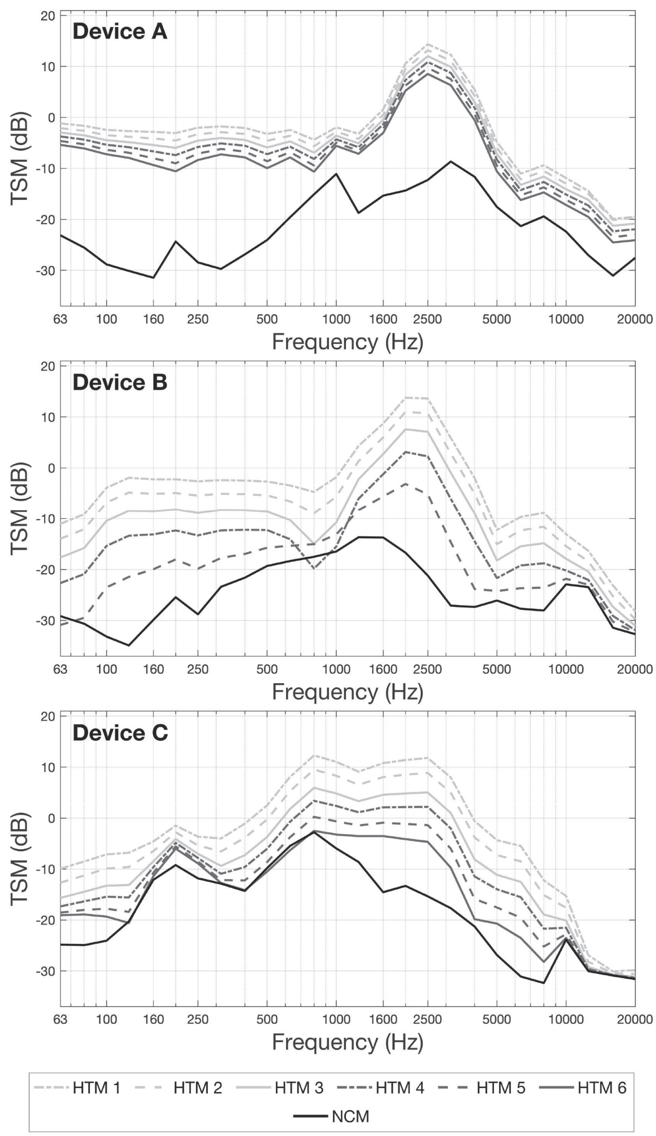

Figure 3. Total spectral modification of diffuse pink noise at 80 dB SPL for noise cancellation and hear-through modes for all devices. NCM and HTM 6 were identical for Device B.

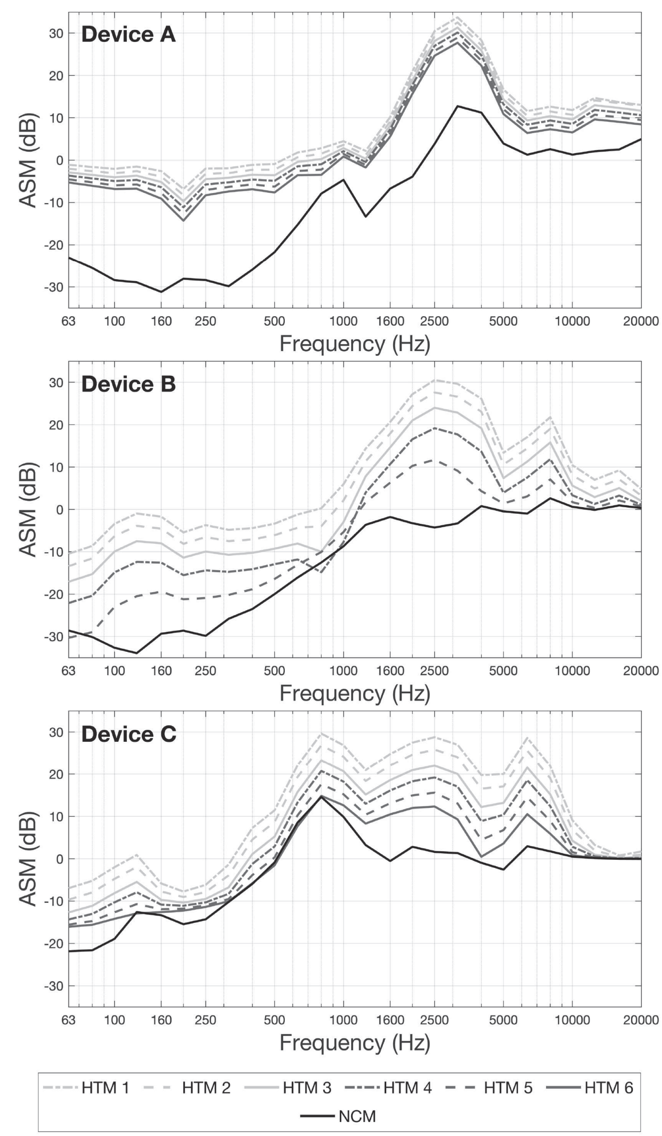

Figure 4. Active spectral modification of diffuse pink noise at 80 dB SPL for noise cancellation and hear-through modes for all devices. NCM and HTM 6 were identical for Device B.

was successively smaller for each mode, ranging from 1250 to 3150 Hz for *HTM 1*, compared with just a single band at 2 kHz for *HTM 4*. The hear-through modes in Device C also featured singular regions of boosting, however, they were much wider, ranging from 630 to 3150 Hz for *HTM 1* and centred around two main peaks at 800 and 2500 Hz for *HTM 1-5* with slight dips in the mainly flat plateau between the peaks at 1250 Hz. At 800 Hz this ranged from maximum amounts of 12.28 dB for *HTM 1* to 0.24 dB in *HTM 5*, while the boosting of the peaks centered around 2500 Hz ranged from 11.78 dB for *HTM 1* to 2.20 dB for *HTM 4*.

In the frequencies below the singular regions of boosting for the hear-through modes the boosting from the passive resonant peaks at 200 Hz is countered by broadly equal and opposite amounts of attenuation from the active electronics. This is visible in the PSM *Off* mode plots in Figure 2 and the ASM noise cancellation and hear-through plots in Figure 4. Consequently the regions from 63 to 1250 Hz in Device A, 125–1000 Hz in Device B, and 160–400 Hz in Device C maintain a relatively flat TSM response for *HTM 1* modes, with the largest attenuation deviations from 0 dB for each device being −4.72 dB and −4.36 dB at 800 Hz in devices B and A respectively, and −4.58 at 160 Hz for Device C. For the frequencies below these regions in devices B and C attenuation then increases with each successively lower frequency band, arriving at 63 Hz with a local minima of −11.03 dB for Device B and −9.92 dB for Device C.

TSM in the frequencies above the singular regions of boosting in the hear-through modes followed a broadly similar pattern for all devices, with the level of attenuation increasing for each successively higher frequency band. The only exceptions to this were slight peaks at 8 kHz for all hear-through modes in Device A and *HTM 1-4* for Device B, and at 10 kHz in *HTM 5* of Device B and *HTM 5* and *6* of Device C. The increases in attenuation then plateau for the *HTM 1* in devices A and C from 16 to 20 kHz at approximately −20 dB and −30 dB respectively. Device B's hear-through maintained the increase in attenuation for the remainder of the spectrum before reaching a maxima of −28.24 dB at 20 kHz in *HTM 1*.

The general shape of the TSM remained very consistent for all of the hear-through modes in devices A and C, with the only exceptions being a slight widening between the levels of attenuation provided by each mode from 160 to 800 Hz for Device A, and narrowing between the TSM for the hear-through modes in Device C from 63 to 100 Hz, 160 to 250 Hz, and 10 to 20 kHz. There was an average difference of approximately 1 dB between each hear-through mode in Device A, contrasted by an average difference of 2 dB for the hear-through modes in Device C.

Device B demonstrated a larger degree of variation in the shape of TSM between the hear-through modes. *HTM 1-4* maintained a broadly consistent shape, with the exception of a narrowing between modes from 8 to 20 kHz, and an average difference of approximately 3 dB. The shape of TSM for *HTM 5* was also broadly consistent with *HTM 1-4* from 63 to 400 Hz and 1250 to 20,000 Hz, however, from 400 to 1250 Hz it deviated, staying much closer to the shape observed in *HTM 6/NCM*, and consequently crossing over with *HTM 4* such that *HTM 4* exhibited 4 dB more attenuation than *HTM 5* at 800 Hz. Moreover the crossover observed in the *HTM 4* measurement at 800 Hz was to such an extent that it also registered 1 dB more attenuation than the *HTM 6/NCM* mode at 800 Hz. However, inspection of the equivalent ASM results in the Device B plot of Figure 4 might suggest that this crossover phenomenon was due to deviations in the shape of attenuation in *HTM 3* and *4*, manifested as two almost identical notches of increased attenuation at 800 Hz. Similar behaviour was also observed at 800 Hz in the results of Device B's *HTM 1* TSM performance for 105 dB SPL, this is shown in Figure 7 and discussed in Section 3.3.1.

3.2.3 Active spectral modification results

The plots in Figure 4 show the attenuation and boosting provided by the active electronics in the noise cancellation and hear-through modes of the devices. The accompanying results of the ASM properties analysis are presented in Table A.3 of the supplementary information [42].

3.3 Presentation level linearity

Studies that have measured noise cancellation [27] and hear-through [20] performance in headphone devices have conducted measurements using signals at a range of different presentation levels. One of the main reasons for this is to assess how well devices are able to attenuate noise in excess of 80 dB SPL, where prolonged exposure could potentially cause hearing damage [44]. However, as the results in Section 3.2.2 of the present study showed that all devices tested provided substantial amounts of both insertion loss and gain relative to the open ear at 80 dB SPL, it is considered especially important to measure how the spectral modification performance might differ depending on the presentation level of the noise source.

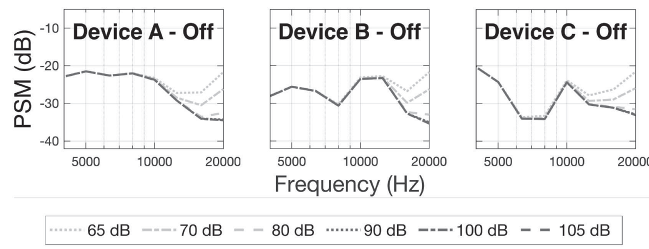

Figure 5. Passive spectral modification of diffuse pink noise at presentation levels of 65 to 105 dB SPL for *Off* modes for all devices. Results for 90, 100 and 105 dB were almost identical.

3.3.1 Presentation level linearity results

Figure 5 shows the PSM of diffuse pink noise for *Off* modes in all devices at presentation levels of 65–105 dB SPL, while Figures 6 and 7 show the TSM of diffuse pink noise for Noise Cancellation and Hear-Through 1 modes in all devices across the same range of presentation levels. As the results in Section 3.2.2 showed that the general shape of TSM remained broadly consistent for all of the hear-through modes tested in the devices it was decided that analysis of the linearity results for *HTM 1* alone would be sufficient to assess the presentation level dependency of all hear-through modes in the devices.

Linearity results: Off mode. The results presented in Figure 5 show that the PSM remains consistent for all presentation levels tested from 63 to 10,000 Hz in devices A and C, and from 63 to 12,500 Hz for Device B. In frequencies above these regions the level of attenuation appeared to increase with higher presentation levels. This behaviour was found to be similar for all devices across the full range of presentation levels tested. Maximum levels of attenuation were achieved for presentation levels of 90–105 dB SPL, with all the devices demonstrating consistent attenuation from 63 to 20,000 Hz. At 80 dB SPL the devices provided approximately 2 dB less attenuation at 20 kHz, while at presentation levels of 75 and 65 dB SPL devices A and C both provided successively lower levels of attenuation from 12,500 to 20,000 Hz, with Device B demonstrating similar performance for 16–20 kHz. While these results could be indicative of a form of intentional level dependent behaviour [26] where higher frequency noise is subject to greater attenuation at higher levels, it is also possible that they could be a symptom of device self-noise.

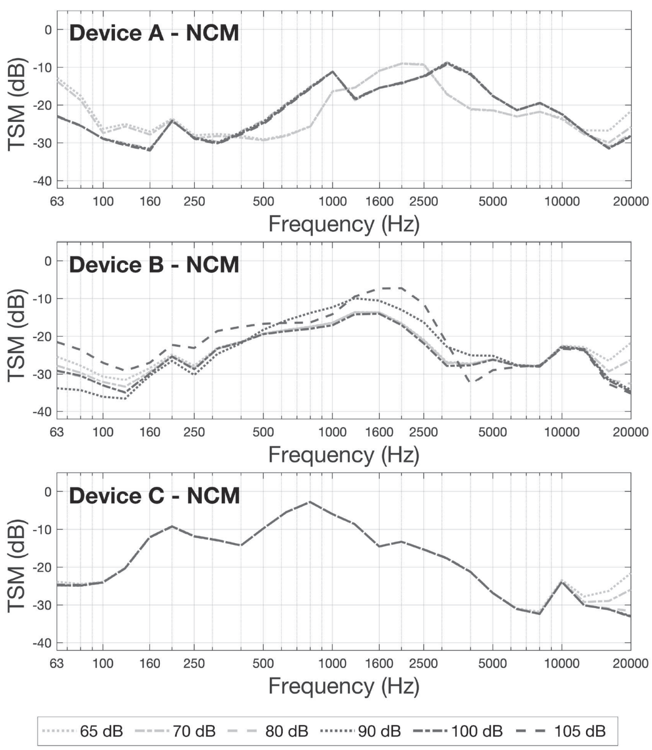

Figure 6. Total spectral modification of diffuse pink noise at presentation levels of 65–105 dB SPL for Noise cancellation modes for all devices.

Linearity results: NCM. The plots in Figure 6 shows TSM performance was dependent on presentation level for the *NCM* in all devices to varying degrees. Aside from the level dependent PSM behaviour between 12,500 and 20,000 Hz, the TSM provided by Device C's *NCM* remained consistent across all presentation levels tested. This was contrasted by Device A's *NCM* where the TSM provided two distinctly different shapes of TSM depending on the presentation level.

For presentation levels of 65 and 70 dB SPL the attenuation in the TSM of Device A's *NCM* followed a very similar shape and featured a singular main peak at 2 kHz, around which there was a region from 1 to 4 kHz where attenuation was smallest. This was contrasted by the results for presentation levels of 80 to 105 dB SPL where there were two separate regions where attenuation was least prominent centered around peaks at 1000 and 3150 Hz. The other main difference between the TSM in Device A's *NCM* for presentation levels from 65–70 to 80–105 dB SPL was in the attenuation of frequencies below 200 Hz. In this region, attenuation levels were the highest for the presentation levels of 80–105 dB SPL, while attenuation levels were successively lower for 70 and 65 dB SPL, mirroring the level dependent behaviour observed in the higher frequencies for the PSM and TSM results.

The TSM in the *NCM* of Device B also exhibited level dependent behaviour, however this did not follow the same trend of greater attenuation for higher presentation levels observed in devices A and C, and therefore may be more likely due to overload rather than by design. The TSM attenuation was consistent for all presentation levels between 6350 and 10,000 Hz and for frequencies above this followed broadly the same level dependent behaviour as observed in the PSM results. From 200 to 6350 Hz TSM results in Device B also remained largely consistent for presentation levels of 65 to 80 and 100 dB SPL, and for frequencies below this, demonstrated similar behaviour to the other devices with more attenuation for higher presentation levels. However, the 90 and 105 dB SPL results exhibited significant differences from 63 to 6150 Hz that were indicative of two different kinds of inconsistency in their performance.

The fact that the results for the 100 dB SPL Device B *NCM* TSM measurement remained broadly consistent with the equivalent results for 65–80 dB, yet the shape of the 90 dB TSM results featured significant deviations, is potentially indicative of inconsistencies in the performance of the device. However, it is more likely that the inconsistencies observed in the 105 dB SPL TSM results were due to Device B's *NCM* reaching its overload limit [27]. This interpretation is supported by a spectrogram analysis of the raw pink noise recordings for the *NCM* in Device B, which found temporal discontinuities in both left and right ear devices at 105 dB SPL. This is shown in Figure B.1 of the supplementary information [42]. Further spectrogram analysis of the raw recordings of *NCM* responses for all devices at all presentation levels found no evidence of similar discontinuities that would be potentially indicative of overload performance.

Linearity results: HTM 1. The plots in Figure 7 shows that the TSM for the hear-through 1 modes in all devices exhibited level dependent behaviour. In Device A's *HTM 1* the TSM was consistent from 63 to 16,000 Hz for presentation levels of 65–100 dB SPL.

At 20 kHz, level dependent behaviour consistent with the PSM results was observed for the lower presentation levels, with successively higher levels of attenuation from 65 to 80 dB SPL, before remaining consistent from 80 to 100 dB SPL. For Device A's *HTM 1* response at 105 dB SPL the shape of the TSM remained broadly consistent with the 80 to 100 dB SPL results, but provided between 2 and 3 dB more attenuation across all frequency bands. This is potentially indicative of a form of limiting functionality where noise signals above 100 dB SPL are subject to greater levels of attenuation in an attempt to protect the listener from dangerous environmental noise levels. However, it is also possible that this level dependent behaviour could be a symptom of Device A's *HTM 1* reaching their overload limit at 105 dB SPL, as spectrogram analysis of the raw pink noise recordings revealed temporal discontinuities occurring at intervals of every 6–8 s in both left- and right-ear device responses. This is shown in Figure 8.

Further spectrogram analysis of the raw recordings of *HTM 1* responses for all devices at all presentation levels tested found no evidence of similar irregularities that

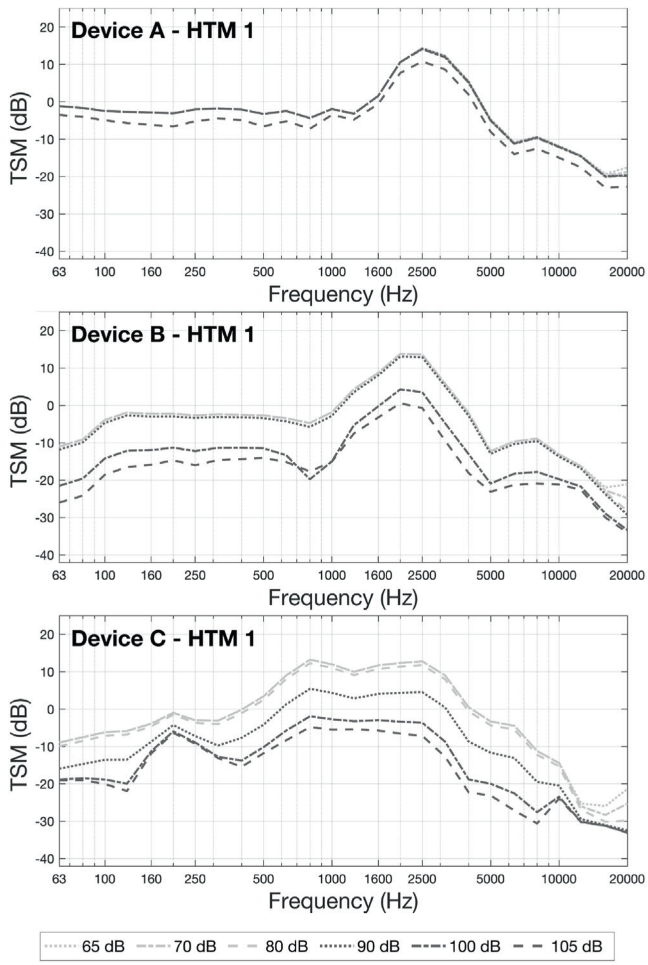

Figure 7. Total spectral modification of diffuse pink noise at presentation levels of 65 to 105 dB SPL for Hear-through 1 modes for all devices.

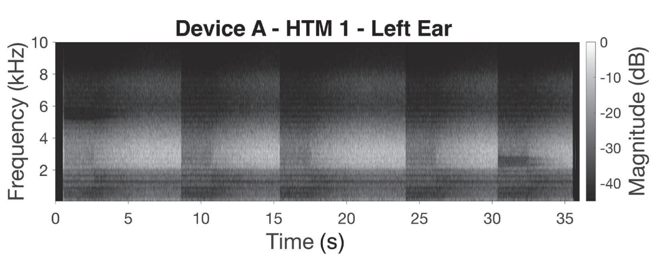

Figure 8. Spectrogram showing temporal discontinuities in the spectral modification of 105 dB SPL diffuse pink noise for the Device A's HTM 1. Discontinuities are visible approximately every 6–8 s.

would be potentially indicative of overload performance. These results show that even when subjected to potentially dangerous noise levels of 105 dB SPL Device A's *HTM 1* still applies as much as 10 dB of boosting relative to the open ear, such that a 105 dB SPL noise signal is translated to 115 dB at 2500 Hz.

The TSM performance of Device B's *HTM 1* was also found to be level dependent, with a wider range of variation between the results for different presentation levels compared to Device A. The TSM was perfectly consistent for presentation levels of 65–80 dB SPL between 63 and 12,500 Hz, with level dependent behaviour observed in the 16 and 20 kHz frequency bands broadly consistent with the PSM results discussed in Section 3.3.1. At 90 dB SPL the shape of the TSM was identical to the 65–80 dB results from 63 to 12,500 Hz, above this exhibiting similar level dependent behaviour with successive increases in attenuation for 16 and 20 kHz bands, while there was an increase in attenuation of approximately 1 dB across all frequencies compared to the 65–80 dB SPL results.

The shape of the TSM for the 100 dB SPL presentation level was broadly consistent with the results for 80 and 90 dB, however, there was approximately a 10 dB increase in attenuation from 63 to 8000 Hz compared to the 90 dB SPL TSM, with the difference in attenuation decreasing slightly for frequencies above this region. The TSM for the 105 dB SPL presentation level also exhibited similar level dependent performance with approximately a 3–5 dB further increase in attenuation for most frequency bands compared to the 100 dB SPL results. However, there were two notable deviations from this observed. Firstly, the difference in attenuation between 100 and 105 dB SPL narrowed to approximately 1–2 dB from 10 to 20 kHz, and then the TSM levels for 100 and 105 dB SPL were also found to have crossed over around the 630–1000 Hz region, such that the 100 dB SPL measurement provided approximately 3 dB more attenuation than the 105 dB SPL at 800 Hz. Similar behaviour was also observed at 800 Hz in the results of Device B's *HTM 3* and *HTM 4* TSM and ASM performance for 80 dB SPL, this is shown in Figures 3 and 4 and discussed in Section 3.2.2. These results show that even when presented with potentially dangerous noise levels of 100 dB SPL, Device B's *HTM 1* still applies as much as 4 dB of boosting relative to the open ear, meaning a 100 dB SPL noise signal is received at the ear as 104 dB at 2 kHz. It is only then at a presentation level of 105 dB SPL that the noise is attenuated such that the peak of TSM at 2 kHz is equal to the level that would be received by the unoccluded open ear.

The TSM performance of the *HTM 1* in Device C was also found to be level dependent and exhibited the widest range of difference in TSM across the presentation levels that were tested. The results for the 65–80 dB SPL measurements exhibited consistent shapes of TSM from 63 to 12,500 Hz and above this featured the same level dependent behaviour as observed in the higher frequencies of the PSM and *HTM 1* TSM results for the other devices. The TSM for the 80 dB SPL also exhibited approximately 1 dB more attenuation from 63 to 12,500 Hz compared to the 65 and 70 dB results. At presentation levels of 90–105 dB SPL the TSM in Device C's *HTM 1* exhibited similar level dependent behaviour as observed for 100 and 105 dB SPL results in Device B's *HTM 1*, where the amount of attenuation for noise at presentation levels above 80 dB SPL was broadly equal to the relative increase in presentation level. Despite this the 90 dB SPL was still boosted by as much as 6 dB at 800 Hz and 5 dB at 2500 Hz, and it was only then at presentation levels of 100 and 105 dB SPL that there were no instances of boosting observed in any of the frequency bands for Device C's *HTM 1*.

3.4 Spectrotemporal performance

Previous studies that have investigated the noise cancellation [28] and hear-through [20] performance of headphone devices have also sought to measure how this performance varies over time. This is carried out to assess both the consistency of performance over time and the nature of the onset of spectral modification following the initial attack of the external noise stimuli. Investigations of the onset and consistency of spectral modification performance in noise cancellation modes are especially important to understand how quickly and reliably devices are able to protect users from potentially dangerous levels of new and ongoing environmental noise. In the present study both of these elements of time domain performance were assessed via spectrogram analysis of the raw diffuse pink noise recordings from the measurement session described in Section 3.1. There were no measurements made to assess the tracking performance of the devices when subject to noise sources exhibiting instationary behaviour, such as rapid spatial movement or changes in spectra. For the time domain measurements that were conducted, the given device mode under test was set using the devices' control app before the commencement of each measurement recording. The results therefore describe how the already selected and active device modes responded to the consequent onset of the diffuse pink noise signal, rather than the responses of the device modes to being activated during an ongoing signal. Analysis was conducted for all device modes, however only select results for Device A merited more detailed discussion.

Figure 9 shows the onset of spectral modification for *HTM 5* in Device A at a presentation level of 80 dB SPL. The equivalent onset performance for *HTM 1* responses at 105 dB SPL in devices B and C is shown in Figure C.1 of the supplementary information [42]. These specific hear-through modes and presentation level measurements give the best visual representations of the onset performance of TSM in hear-through modes for each device. These onset responses were found to be consistent across all hear-through modes and presentation levels for each device with the exception of Device A's hear-through mode responses at 105 dB SPL, where suspected limiting/overload behaviour was observed. This is shown in Figure 8 and discussed further in Section 3.3.1.

Inspection of the spectrogram analysis results revealed differences between the onset performance of the hear-through modes in each device. The onset of spectral modification in Device A's hear-through modes exhibited an initial delay of approximately 2 s before the spectral modification was applied between 2 and 3 s after the initial onset of the noise signal. This behaviour was found

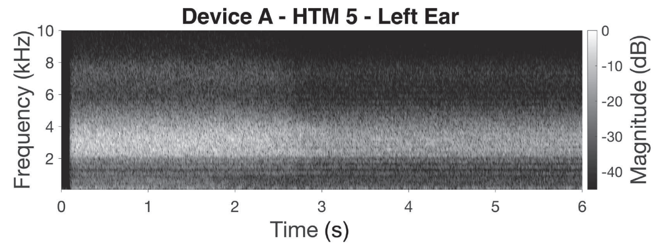

Figure 9. Spectrogram showing the onset of spectral modification of 80 dB SPL diffuse pink noise for Device A's HTM 5. This onset is visible from 2 to 3 s and most prominent in the frequencies either side of the 2 to 4 kHz region.

to be clearly audible when auditioning the measurement recordings during analysis. This was contrasted by the onset performance observed in the hear-through modes of devices B and C where the onset of spectral modification appeared to be almost instantaneous, occurring within a matter of milliseconds. This onset period was found to be audibly imperceptible during the informal auditioning of the measurement recordings and was only detected through visual analysis of the spectrograms. The onset of spectral modification for the noise cancellation modes in all devices also appeared to be instantaneous as visual and audible inspection of the *NCM* response raw recordings failed to reveal any evidence indicating the onset duration.

Further spectrogram analysis of the entire 35 s diffuse pink noise raw recordings found that TSM performance remained consistent and stable over time for all device modes and presentation levels with the exception of Device A's hear-through modes and Device B's *NCM* at 105 dB SPL where discontinuities from suspected limiting/overload were observed. This can be seen in Figure 8 of the paper and Figure B.1 of the supplementary information [42]. While only the results for the left ear devices are presented in this section, all results discussed were found to be consistent in both left and right ear device recordings.

4 Discussion

Analysis of the results shows that all three devices are capable of providing a wide range of both attenuation and boosting of broadband noise signals. The performance of the spectral modification in the devices was found to be highly dependent on the quality of the earbuds' physical fit in the ear canal. Excess acoustic leakage was found to be especially detrimental to the performance of the noise cancellation modes for all devices. The TSM of the noise cancellation modes in all devices was found to provide considerable levels of attenuation across all measured frequency bands, and while the general shape of attenuation varied between devices there were some commonalities observed. For instance, with the least attenuation prominent peaks centred around the lower mid-range region

(800–1600 Hz) were observed, with the greatest attenuation being observed in the regions above 8000 and below 250 Hz.

The general shape of the TSM provided by the hear-through modes remained broadly consistent between the different levels of hear-through for all devices. However, there was a greater degree of variation observed in the TSM shape of the hear-through functionality between the different devices. This is reflected in differences between how the hear-through modes were described in the devices' accompanying app-based control interfaces.

In Device A's hear-through modes there was considerable attenuation of noise for frequency bands above 4 kHz. However, below 1600 Hz there was no greater than 3 dB of attenuation observed for *HTM 1*, only increasing to a maximum of 10 dB attenuation in this region for *HTM 6*. In fact 1600–4000 Hz was actually subject to a significant amount of boosting by all of Device A's hear-through modes. It is therefore the case that and lessening of ambient noise perceived by users of Device A's hear-through modes would most likely be due to the relative difference between the boosting in the frequencies most important to speech intelligibility (1600–4000 Hz), and the minimal levels of attenuation in frequencies below this region. In contrast, the variable hear-through modes in Device C exhibited much less attenuation and more boosting of frequency bands associated with environmental noise compared to Device A. This was evidenced by much wider regions of boosting observed in four of the six hear-through modes tested in Device C.

Results found that the TSM in Device B's *HTM 1* was very similar to the equivalent measurement in Device A, with the exception of Device B featuring wider breadths of boosting in *HTM 1* and *HTM 2* (1–4 kHz), thus providing a similar hear-through experience to Device A where the singular region of boosting was focused solely around the frequencies that are important for speech intelligibility [45], with frequencies outside of this region attenuated. However, the main difference between the hear-through functionality in Device B and the other devices was the range of attenuation observed in the TSM performance across the different levels of hear-through. Device B also featured by far the highest levels of attenuation for frequency bands either side of the mid-range in any of the hear-through modes tested across all devices.

The measurement of intermediate levels of hear-through modes in the devices also revealed the extent of differences in the ranges of spectral modification available to the user. Device B provided the largest range of spectral modification, with a span of approximately 15–20 dB from *HTM 1* to *HTM 5* for most of the frequency spectrum. Device C featured a range of approximately 10–15 dB from *HTM 1* to *HTM 6* across the majority of the spectrum. However, Device A provided a much smaller range of approximately 5 dB between *HTM 1* and *HTM 6*. This ability to select a specific level of hear-through allows the user a degree of control over the ease with which they are able to perceive their acoustic surroundings. This therefore allows the user to adjust the volume of the media they are consuming while maintaining the same level of awareness of their surroundings, relative to the media. These results illustrate differences in the extent to which users would be able to adjust the desired volume of media on each device, while still maintaining the same relative awareness of their surroundings.

Overall, the results indicate that there is considerable variation in the nature and intended use cases of insertion loss and gain in contemporary true wireless earbuds, and that these extend far beyond the existing rudimentary definitions of noise cancellation and acoustic transparency. Despite this there were still many commonalities observed in the results.

The results of the linearity analysis revealed that the TSM performance in the devices was highly dependent on the presentation level of the noise signal. This was especially apparent for the performance of the hear-through modes at higher presentation levels where the amount of boosting was curtailed in all devices to some degree to limit the potentially damaging effects of sustained exposure to high noise levels. However, the nature of this behaviour varied greatly between devices with Device A's *HTM 1* still providing 10 dB of boosting to diffuse sound field noise at presentation levels of up to 100 dB SPL. The results also revealed evidence of temporal discontinuities observed in the results of Device A's *HTM 1* and Device B's *NCM* at 105 dB SPL. These were found to be potentially indicative of overload performance in the devices, however, further measurements at higher presentation levels would be required to fully determine this. Otherwise the TSM performance of the noise cancellation modes in all devices was found to be largely independent of presentation level.

The onset performance of TSM was found to be instantaneous for all device modes tested with the exception of the hear-through modes in Device A where the spectral modification only began to take effect between 2 and 3 s after the initial onset of the noise signal.

There were also two specific instances of potentially irregular behaviour observed in the performance of Device B's hear-through modes. These occurred at 800 Hz where the level of attenuation was seen to cross over between modes and presentation level measurements counter intuitively to performance found in all other results. It is possible that this performance is representative of the usual behaviour expected in Device B, however, it is also possible that these irregularities were a symptom of issues in the quality of the physical fit of the earbuds in the ATF's ear canal.

The results presented in this paper are subject to the following limitations:

- The evaluation of a limited number of devices restricts the generalisation of the results.
- Only one pair of each device was tested, meaning it is possible that aspects of the devices' measured behaviour could have been representative of faults rather than normal performance.

- The results are only based on how the devices responded to steady-state broadband noise.
- Measurements were only produced for the default modes of performance in each device.
- These measurements could have been influenced by any inconsistencies in performance specific to the firmware installed on the devices.
- The relatively low number of measurement iterations conducted increases the likelihood that the results may have been influenced by issues with the quality of physical fit.
- The presentation levels used to assess the linearity of performance in the devices were insufficiently high to assess the overload performance of all devices.
- Various limitations relating to the use of the ATF were also discussed in Section 2.3.

5 Conclusion

The evaluation of the performance of the true wireless earbud device modes tested in this study sought to quantify the extent and nature of insertion loss and gain provided by the devices when subjected to diffuse pink noise, and also measured how the performance of the devices changed with respect to different presentation levels. An analysis of the devices' performance over time was also conducted. Several limitations of the study were also identified and the results and conclusions presented are conditional on these limitations.

The results represent the first of their kind to measure the spectral modification of diffuse sound field noise for noise cancellation and hear-through modes in commercially available devices that feature both modes of functionality. In doing so the results reveal that the hear-through modes in the devices tested exhibited significant amounts of boosting relative to the open ear in frequencies that are considered important to the intelligibility of speech. This result indicates that none of the devices appeared to be attempting to achieve complete acoustic transparency in their hear-through mode functionality. Instead, the levels of boosting around frequencies important for speech intelligibility potentially indicate that some devices are being designed to encourage their continual use throughout the day, allowing verbal communication to occur contemporaneously with the ongoing consumption of media. The boosting behaviour identified in this study is also potentially indicative of the growing convergence between commercial earbuds and hearing-aid devices. This is supported by a recent announcement from Apple that a new hearing health experience update for the Airpod Pro 2 will include a clinical-grade hearing aid feature [46].

The noise cancellation modes in each device were all found to be capable of providing significant amounts of attenuation across the entire frequency spectrum measured. Further work should take the form of perceptual sound quality evaluations of the noise cancellation and hear-through mode performance in the devices tested. Further technical investigation of these and other similar devices should also be carried to investigate the spectral modification performance when presented with different kinds of environmental noise and instationary noise signals, including noise sources that exhibit rapid spatial movement or changes in spectra.

Acknowledgments

The authors would like to thank Andrew Chadwick for his assistance in conducting the measurements in this study and Frank Stevens for his support and guidance.

Funding

This research was funded in part by the UK's Arts and Humanities Research Council (XR Stories project, Grant No. AH/S002839/1) and in part by the University of York, in partnership with BBC Research and Development.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to this article.

Data availability statement

Additional materials are available online through Zenodo repository: https://doi.org/10.5281/zenodo.14938030 [42]. The dataset analysed during the current study is available from the corresponding author on reasonable request.

Author contribution statement

JH: conducted measurements, performed the data analysis, and wrote the original draft of the manuscript. All authors contributed to the conceptualization of the study and the review and editing of the submitted version of the manuscript.

Glossary

AAR: Audio augmented reality; ANC: Active noise cancellation; ASM: Active spectral modification; ATF: Acoustic test fixture; HTM: Hear-through mode; MIRE: Microphone in real ear; NC: Noise cancellation; OE: Open ear; PR: Passive response; PSM: Passive spectral modification; REAT: Real ear attenuation at threshold; RMS: Root mean square; SPL: Sound pressure level; TR: Total response; TSM: Total spectral modification.

References

1. Qualcomm, SAR Insight & Consulting: The State of Sound Report 2022 A global analysis of audio consumer behaviors and desires, Qualcomm and SAR Insight & Consulting, 2022.
2. L. Lu, K.L. Yin, R.C. de Lamare, Z. Zheng, Y. Yu, X. Yang, B. Chen: A survey on active noise control in the past decade – part I: linear systems. Signal Processing 183 (2021) 108039. https://doi.org/10.1016/j.sigpro.2021.108039.
3. L. Lu, K.L. Yin, R.C. de Lamare, Z. Zheng, Y. Yu, X. Yang, B. Chen: A survey on active noise control in the past decade – part II: nonlinear systems. Signal Processing 181 (2021) 107929. https://doi.org/10.1016/j.sigpro.2020.107929.
4. M. Klatte, K. Bergström, T. Lachmann: Does noise affect learning? A short review on noise effects on cognitive performance in children. Frontiers in Psychology 4 (2013) 578. https://doi.org/10.3389/fpsyg.2013.00578.

5. M.J. Jafari, R. Khosrowabadi, S. Khodakarim, F. Mohammadian, The effect of noise exposure on cognitive performance and brain activity patterns. Open Access Macedonian Journal of Medical Sciences 7 (2019) 2924–2931. https://doi.org/10.3889/oamjms.2019.742.
6. R. Thompson, R.B. Smith, Y. Bou Karim, C. Shen, K. Drummond, C. Teng, M.B. Toledano: Noise pollution and human cognition: an updated systematic review and meta-analysis of recent evidence. Environment International 158 (2022) 106905. https://doi.org/10.1016/j.envint.2021.106905.
7. W.K. Persson, R. Rylander, S. Benton, H. G. Leventhall: Effects on performance and work quality due to low frequency ventilation noise. Journal of Sound and Vibration 205 (1997) 467–474. https://doi.org/10.1006/jsvi.1997.1013.
8. World Health Organization: Burden of disease from environmental noise: quantification of healthy life years lost in Europe. World Health Organization, 2011.
9. T. Münzel, T. Gori, W. Babisch, M. Basner: Cardiovascular effects of environmental noise exposure. European Heart Journal 35 (2014) 829–836. https://doi.org/10.1093/eurheartj/ehu030.
10. R. Leung, M.M. Cook, M.F. Capra, K.R. Johnstone: The contribution of respiratory and hearing protection use to psychological distress in the workplace: a scoping review. International Archives of Occupational and Environmental Health 95 (2022) 1647–1659. https://doi.org/10.1007/s00420-022-01863-7.
11. J.C. Fernandes: Effects of hearing protector devices on speech intelligibility. Applied Acoustics 64 (2003) 581–590. https://doi.org/10.1016/S0003-682X(02)00141-X.
12. M. Hashimoto, M. Kumashiro, S. Miyake: Speech perception in noise when wearing hearing protectors with little low-frequency attenuation. International Journal of Industrial Ergonomics 18 (1996) 121–126. https://doi.org/10.1016/0169-8141(95)00074-7.
13. E. Pekkarinen, V. Viljanen, A. Salmivalli, J. Suonpää: Recognition of low-pass filtered words in a noisy and reverberant environment with and without earmuffs. Scandinavian Audiology 19 (1990) 223–227. https://doi.org/10.3109/01050399009070776.
14. B.J. Mueller, A. Liebl, N. Herget, D. Kohler, P. Leistner: Using active noise-cancelling headphones in open-plan offices: no influence on cognitive performance but improvement of perceived privacy and acoustic environment. Frontiers in Built Environment 8 (2022) 1–15. https://doi.org/10.3389/fbuil.2022.962462.
15. F. Niu, X. Qiu, D. Zhang: Effects of active noise cancelling headphones on speech recognition. Applied Acoustics 165 (2020) 107335. https://doi.org/10.1016/j.apacoust.2020.107335.
16. Y. Kim, Y. Park: Effect of active noise control and masking sound on speech intelligibility. Applied Acoustics 123 (2017) 152–157. https://doi.org/10.1016/j.apacoust.2017.02.021.
17. F. Rumsey: Headphone technology Hear-through, bone conduction, noise canceling. Journal of the Audio Engineering Society 67 (2019) 914–919.
18. R.W. Lindeman, H. Noma, P.G. De Barros: Hear-through and mic-through augmented reality: using bone conduction to display spatialized audio, in: 2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality, ISMAR, Nara, 2007, pp. 173–176. https://doi.org/10.1109/ISMAR.2007.4538843.
19. A. Härmä, J. Jakka, M. Tikander, M. Karjalainen, T. Lokki, J. Hiipakka, G. Lorho: Augmented reality audio for mobile and wearable appliances. Journal of the Audio Engineering Society 52 (2004) 618–639.
20. F. Denk, H. Schepker, S. Doclo, B. Kollmeier: Acoustic transparency in hearables-technical evaluation. Journal of the Audio Engineering Society 68 (2020) 508–521. https://doi.org/10.17743/jaes.2020.0042.
21. H. Schepker, F. Denk, B. Kollmeier, S. Doclo: Acoustic transparency in hearables – perceptual sound quality evaluations. Journal of the Audio Engineering Society 68 (2020) 495–507.
22. J. Hardley: Embodied perceptions of darkness: multistable experiences of mobile media in the urban night. M/C Journal 24 (2021) 2. https://doi.org/10.5204/mcj.2756.
23. C.S. De Silva: Private sound environments in urban public space: headphone use in parks in New York, in: K.A. Franck, T.-S. Huang, Eds, Routledge handbook of urban public space: use, design, and management, Taylor & Francis, New York, 2023, pp. 142–159.
24. H. Yu, J. Filloon, D.N. Ramsey, K.K. Ahuja, L.N. Sankar: Modelling and testing sound leakage in ill-fitting earplugs. AIAA SCITECH 2022 Forum, San Diego, CA and Virtual, 3–7 January, 2022. https://doi.org/10.2514/6.2022-2562.
25. A.G. Samelli, R.F. Gomes, T.V. Chammas, B.G. Silva, R.R. Moreira, A.C. Fiorini: The study of attenuation levels and the comfort of earplugs. Noise & Health 20 (2018) 112–119. https://doi.org/10.4103/nah.NAH_50_17.
26. E.H. Berger, P. Hamery: Empirical evaluation using impulse noise of the level-dependency of various passive earplug designs. Journal of the Acoustical Society of America 123 (2008) 3528–3528.
27. B. Rudzyn, M. Fisher: Performance of personal active noise reduction devices. Applied Acoustics 73 (2012) 1159–1167. https://doi.org/10.1016/j.apacoust.2012.05.013.
28. C.J. Struck: Objective measurements of headphone active noise cancelation performance, in: 2019 AES International Conference on Headphone Technology, San Francisco, CA, USA, 27–29 August, 2019.
29. H.Y. Seol, S.H. Kim, G.Y. Kim, M. Jo, Y.S. Cho, S.H. Hong, I.J. Moon: Influence of the noise-canceling technology on how we hear sounds. Healthcare (Switzerland) 10 (2022) 1–8. https://doi.org/10.3390/healthcare10081449.
30. J. Cui, A. Behar, W. Wong, H. Kunov: Insertion loss testing of active noise reduction headsets using acoustic fixture. Applied Acoustics 64 (2003) 1011–1031. https://doi.org/10.1016/S0003-682X(03)00067-7.
31. R. Gupta, R. Ranjan, J. He, G.W. Seng, S. Peksi: Acoustic transparency in hearables for augmented reality audio: hear-through techniques review and challenges, in: Proceedings of the 3rd AES International Conference on Audio for Virtual and Augmented Reality, Online, 17–19 August, 2020. https://doi.org/10.1016/s0967-2109(98)00021-0.
32. R. Schlieper, S. Preihs, J. Peissig: An open dataset of measured HRTFs perturbed by headphones, in: Audio Engineering Society – 152nd Convention, In-Person and Online, May, 2022. (The Hague).

33. rtings: Apple AirPods Pro (2nd generation) headphones review (Online), 2022. Available at: https://www.rtings.com/headphones/reviews/apple/airpods-pro-2nd-generation-truly-wireless (Accessed 19/12/2022).
34. rtings: Bose QuietComfort Earbuds II truly wireless headphones review (Online), 2022. Available at: https://www.rtings.com/headphones/reviews/bose/quietcomfort-earbuds-ii-truly-wireless (Accessed 19/12/2022).
35. rtings; Sony LinkBuds S truly wireless headphones review (Online), 2022. Available at: https://www.rtings.com/headphones/reviews/sony/linkbuds-s-truly-wireless (Accessed 19/12/2022).
36. R.B. Crabtree, A. Behar: Measurement of hearing protector insertion loss at ultrasonic frequencies. Applied Acoustics 59 (2000) 287–299. https://doi.org/10.1016/S0003-682X(99)00003-1.
37. European Telecommunications Standards Institute: ETSI TS 103 640 speech and multimedia transmission quality (STQ); Test methods and performance requirements for active noise cancellation headsets and other earphones (Online), 2022. Available at: https://www.etsi.org/deliver/etsi_ts/103600_103699/103640/01.02.01_60/ts_103640v010201p.pdf (Accessed 22/11/2024).
38. C. Couvreur, I.C. Couvreur: Implementation of a one-third-octave filter bank in Matlab. Applied Acoustics 1997, 0–12.
39. J.J. Jamil: One-third-octave filter bank, including additional inputs and outputs (Online). MATLAB Central File Exchange, 2011. Available at: https://www.mathworks.com/matlabcentral/fileexchange/30942-one-third-octave-filter-bank-including-additional-inputs-and-outputs (Accessed 22/11/2024).
40. I. Veit, H. Sander: Production of spatially limited “diffuse” sound field in an anechoic room. Journal of the Audio Engineering Society 35 (1987) 138–143.
41. International Electrotechnical Commission: BS EN IEC 60318-7:2022 Electroacoustics Simulators of human head and ear, 2022. Available at: https://knowledge.bsigroup.com/products/electroacousticssimulators-of-human-head-and-ear-head-and-torso-simulator-for-themeasurement-of-sound-sources-close-to-the-ear (Accessed 27/11/2024).
42. J.A. Harrison, A.W. Archer-Boyd, D.T. Murphy: Supplementary information for the journal paper measurement of insertion loss and gain in variable hear-through and noise cancellation modes of true wireless earbuds. Zenodo, 2025, https://doi.org/10.5281/zenodo.14938030.
43. M.R. Paurobally, J. Pan: The mechanisms of passive ear defenders. Applied Acoustics 60 (2000) 293–311. https://doi.org/10.1016/S0003-682X(99)00045-6.
44. A. Lie, M. Skogstad, H.A. Johannessen, T. Tynes, I.S. Mehlum, K.C. Nordby, B. Engdahl, K. Tambs: Occupational noise exposure and hearing: a systematic review. International Archives of Occupational and Environmental Health 89 (2016) 351–372. https://doi.org/10.1007/s00420-015-1083-5.
45. K. D. Kryter: Methods for the calculation and use of the articulation index. Journal of the Acoustical Society of America 34 (1962) 1689–1697.
46. Apple: Apple introduces AirPods 4 and the world’s first all-in-one hearing health experience with AirPods Pro 2 (Online), 2011. Available at: https://www.apple.com/uk/newsroom/2024/09/apple-introduces-airpods-4-and-a-hearing-health-experience-with-airpods-pro-2/ (Accessed 22/11/2024).

Cite this article as: Harrison J. Archer-Boyd A.W. & Murphy D.T. 2025 Measurement of insertion loss and gain in variable hear-through and noise cancellation modes of true wireless earbuds. Acta Acustica **9**, 28. https://doi.org/10.1051/aacus/2025013.