Large-Scale Optimization of Perceptual Headphone Sound Quality Target Curves

PEQdB Inc., Stanford, CA, 94305, USA

Saurav Chala et al.

support@peqdb.com

ABSTRACT

Everyday listeners helped develop the PEQdB over-ear, in-ear, and generic headphone target curves to discover the optimum tonality for headphones. Many in the scientific audio community consider the Harman over-ear 2018 and Harman in-ear 2019 target curves the most well-established headphone target curves. These target curves consist of many methodological issues that aim to be addressed by the PEQdB headphone target curves. We will discuss the methodological pitfalls of the Harman headphone target curves and the technology behind the PEQdB target curves in detail. The PEQdB target curves leverage the power of diverse data collection and modern machine learning algorithms to identify the optimal headphone target curves for the average person.

1 INTRODUCTION

1.1 Harman Flat In-Room Target Curves

To understand the issues with the Harman headphone target curves, we have to review their literature, beginning with their 2013 paper, *Listener Preferences for In-Room Loudspeaker and Headphone Target Responses* [1]. In the paper, the authors tasked listeners to adjust the bass and treble of loudspeakers and headphones to their subjective preference. The Harman Flat In-Room loudspeaker target curve was created by equalizing a pair of Revel Performa Three F208 loudspeakers to have a flat steady-state measurement from ~23 Hz to 20 kHz when measured with an array of flat omnidirectional microphones at the prime listening position in a typically reflective listening room.

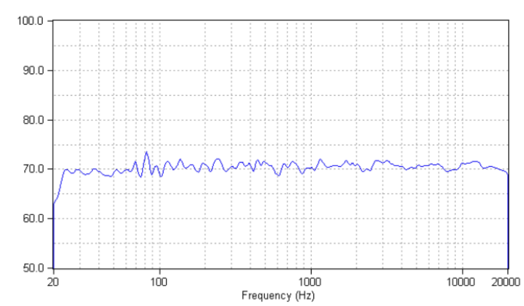

Figure 1. After equalization to flat target response, the average in-room amplitude response of the left and right loudspeakers.

The Harman flat in-room headphone target or head-related-transfer-function (HRTF) had an ambiguous conception. Dr. Olive stated that “the amplitude response of the headphone was first flattened and then equalized to match the in-room target response of the loudspeaker measured at the DRP" (Drum Reference Point) [1]. Assuming the GRAS 45CA, which the authors used to measure the headphones in the study, was also used to calculate the flat in-room HRTF, this is a perplexing choice since the GRAS 45CA is a flat-plate headphone measuring device with no human-like anatomical features beyond its anthropometric pinna [2].

Figure 2. GRAS 45CA [2].

Sound incidence with headphones is independent of direction since the volume of space sound occupies while wearing a headphone is uniformly pressurized by the diaphragm. For this reason, a diffuse-field head-related transfer function (HRTF) should be used as a baseline in perceptual headphone listening tests to make further adjustments. Sound arrives equally from all directions in a diffuse field acoustic environment, resulting in a uniform energy distribution. In headphone calibration, when measured with a flat omnidirectional microphone, a diffuse-field target assumes a flat frequency response under such conditions. A diffuse-field HRTF is measured or modeled under diffuse-field conditions, representing how sound from all directions is filtered by the subject's anatomy, most commonly measured either at the blocked entrance of the ear canal or the eardrum. Since the authors designed the room to derive the Harman flat in-room headphone target to represent a typically reflective room [3], ad hoc spatial averaging would be needed to approximate a diffuse-field HRTF. Below is a comparison of the Harman flat in-room HRTF versus the average eardrum (DRP) diffuse-field HRTF of 47 individuals outlined in *Determination of Noise Immission From Sound Sources Close to the Ears* [4], adhering to ISO 11904-1:2002 [5].

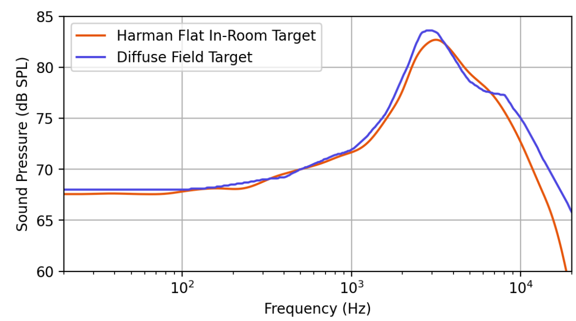

Figure 3. Comparison of Harman flat in-room HRTF versus the average DRP diffuse-field HRTF of 47 individuals.

The Harman flat in-room HRTF has the ear resonance peak at too high of a frequency, too much energy at 5 kHz, and a marked treble roll-off compared to the average diffuse-field HRTF of the 47 subjects tested.

1.2 Harman Over-Ear Target Curves

For the method of adjustment in the loudspeaker and headphone listening tests in [1], listeners were only allowed to modify two variable parameters distributed across two filters: the gain in decibels (dB) of a low-shelf filter centered at 105 Hz and a high-shelf filter centered at 2.5 kHz of an equalized Sennheiser HD 800 headphone. Note that the authors did not disclose the Q-factors of the filters in the paper, so the approximations below are from equalizing the flat in-room target curve to the identified average preference. A low-shelf filter at 105 Hz with a gain of 5.2 dB and a Q-factor of 0.65 was used with a high-shelf filter at 2500 Hz with a gain of -3.9 dB and a Q-factor of 0.49 to achieve the target curve in green.

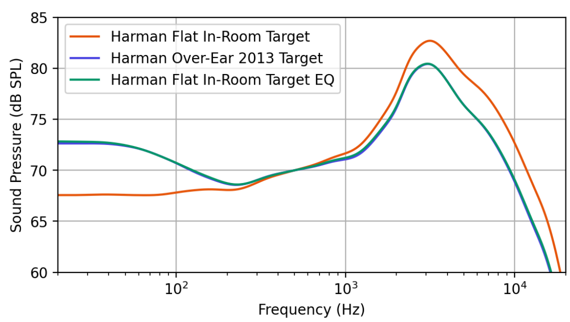

Figure 4. The Harman flat in-room headphone target equalized to the Harman over-ear 2013 headphone target [1].

The author of [1], Dr. Sean Olive, claims he chose the 105 Hz low-shelf frequency because "the majority of subwoofers are crossed over to the main speaker near (or slightly below) this frequency," "variations in bass level due to acoustical interactions between loudspeakers and rooms occur near and below near this frequency." Most notably, "informal investigations by the authors found that extending the bass shelf frequency to above 105 Hz hurt the timbre of vocals and other instruments whose fundamental pitches fall within this frequency region." Over time, informal listener feedback on the Harman over-ear headphone targets has occasionally highlighted a thin character to the sound due to the sudden increase in low-frequency energy near the low-shelf center frequency of 105 Hz. From *The Measurement and Calibration of Sound Reproducing Systems* [6] by Dr. Floyd Toole, it is evident that highly rated loudspeakers placed in a typically reflective room gradually increase in their low-frequency energy beginning below about 1-2 kHz as opposed to the abrupt rise beginning around 170 Hz in the subjectively-preferred steady-state room curves from [1] resulting from the filter parameters.

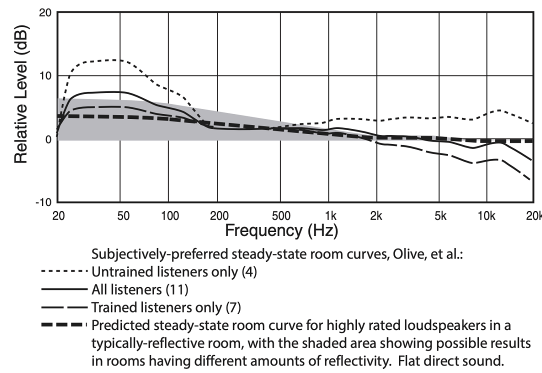

Figure 5. Subjectively preferred steady-state room curve targets in a typical domestic listening room [1] and a prediction of the range of steady-state room curves that might occur in a typically reflective room by Dr. Toole [6].

Dr. Olive also states that the "treble filter frequency of 2.5 kHz was chosen because this is a common midrange-tweeter crossover frequency where the directivity of the loudspeaker begins to increase, and the in-room response of the loudspeaker begins to fall downwards" and that "the exact amount of high-frequency drop will depend on directivity of the loudspeaker, the ratio of direct-reflected sounds at the listening seat, and the absorption characteristics of the room." In *Factors that Influence Listeners' Preferred Bass and Treble Balance in Headphones* [7], the same method of adjustment procedure in [1] was replicated with 249 listeners over an equalized Sennheiser HD518 headphone to create the Harman 2015 over-ear headphone target. We saw the latest published modifications to the over-ear target in *A Statistical Model that Predicts Listeners' Preference Ratings of Around-Ear and On-Ear Headphones* [8], primarily reducing the energy near the 3 kHz ear-gain resonance peak from their flat in-room headphone target [1].

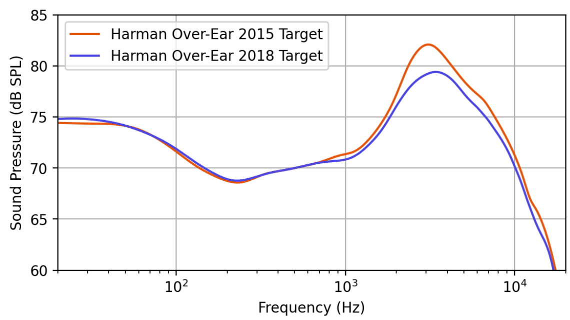

Figure 6. Comparison of Harman 2015 and 2018 over-ear headphone target curves

When directly asked about the rationale behind the adjustment on x.com, Dr. Olive stated, “It was largely driven by feedback from trained listeners who felt it was too hot in that area. Subsequent tests confirmed this adjustment was preferred” [9]. In the listening tests, participants rated the subjective sound quality of an AKG K712 headphone equalized to the magnitude frequency response of various headphone models and the Harman over-ear 2018 target curve on a 100-point scale.

1.3 Harman In-Ear Target Curves

In 2016, in *The Preferred Low Frequency Response of In-Ear Headphones* [10], ten Harman employees took part in a listening test where they could modify the center frequency and gain of a low-shelf filter over Sennheiser Momentum in-ear headphones. The earphones were equalized to the Harman over-ear 2013 headphone target [1] without a bass boost, albeit with less energy past 10 kHz due to the insufficient treble extension of the earphones used.

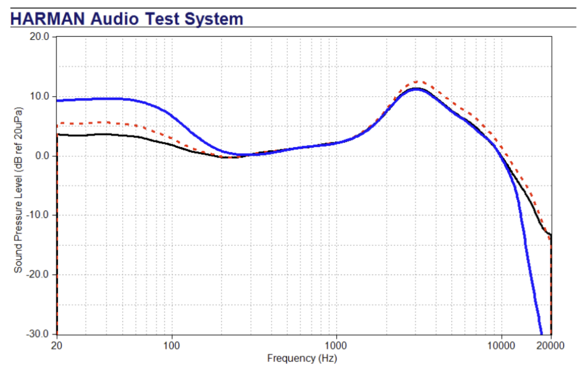

Figure 7. Blue is the Harman In-Ear 2016 headphone target; red is the Harman 2015 over-ear target, and black is the Harman 2013 over-ear target.

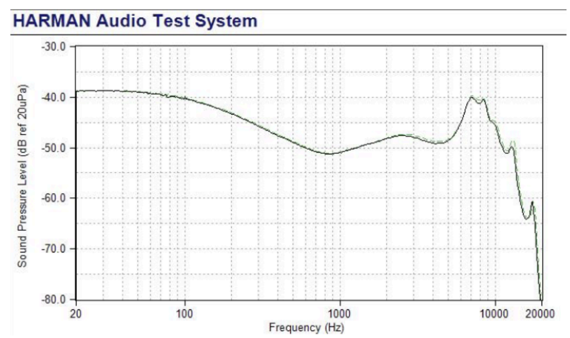

Figure 8. The magnitude frequency response of the Sennheiser Momentum in-ear headphones used for the listening tests (GRAS RA0045).

Equalization from the Harman over-ear 2013 target without bass to the Harman in-ear 2016 target can be approximated with a low shelf filter center frequency of 120 Hz, gain of 10 dB, and Q-factor of 0.7.

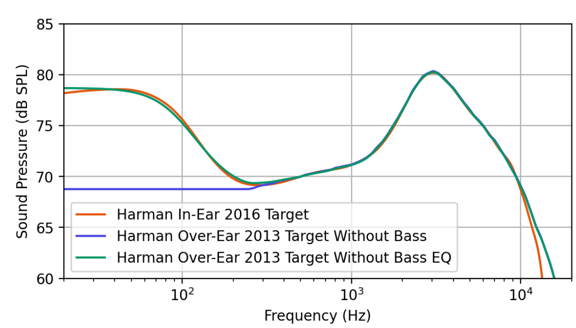

Figure 9. Harman over-ear 2013 headphone target without bass equalized to the Harman in-ear 2016 headphone target.

In 2017, the Harman in-ear target was updated in the paper, *The Influence of Program Material on Sound Quality Ratings of In-Ear Headphones* [11]. The authors claim that the new target was validated in an unpublished study where an unknown number of listeners adjusted the bass and treble of the target curve, and the authors made final adjustments. They also state that the new target was compared to the Harman in-ear 2016 target and that the Harman in-ear 2017 target curves were rated the highest by their listeners. In the study, participants rated the subjective sound quality of Sennheiser Momentum in-ear headphones equalized to the magnitude frequency responses of various earphones and two Harman in-ear 2017 target curves on a 100-point scale across ten songs.

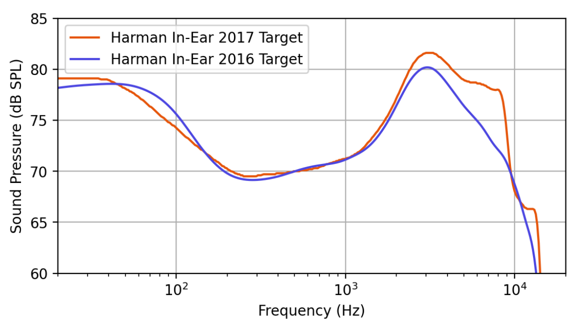

Figure 10. Harman In-Ear 2016 and 2017v1 target curves comparison.

Across the different program materials, the relative ranking of the target curves remained relatively constant, with an analysis of variance (ANOVA) test that revealed no significant differences related to the different programs, as shown in Figure 11.

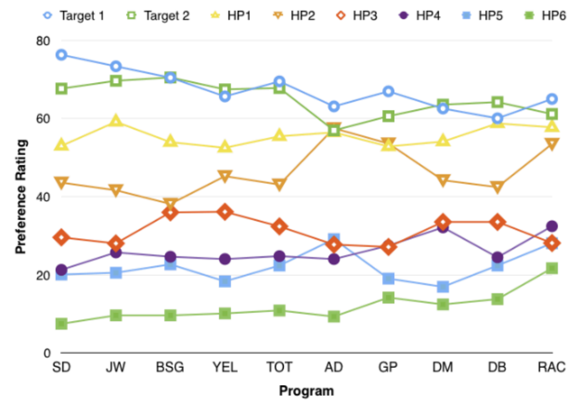

Figure 11. Mean preference ratings for virtualized headphones and target curves across different programs [11].

The final revision to the Harman In-Ear target came in 2019, in collaboration with Listen, Inc., to automate predicted preference ratings for in-ear headphones [12]. This revision primarily smoothed and extended the high-frequency magnitude response.

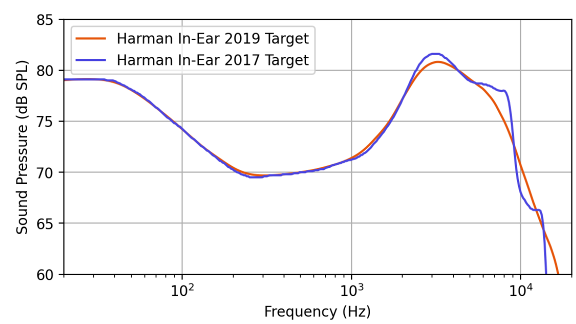

Figure 12. Harman In-Ear 2017 and 2019 target curves comparison.

Over the years, common informal criticisms of the Harman In-Ear 2019 target have been that it is too sub-bassy, thin/anemic, shouty/brittle, and veiled in the highs.

2 METHOD

2.1 Baseline HRTF

As discussed earlier, a diffuse-field head-related transfer function is the appropriate baseline for headphone target curve conception. Adhering to

ISO 11904-1:2002 [5], the average eardrum (DRP) diffuse-field HRTF of 47 individuals outlined in *Determination of Noise Immission From Sound Sources Close to the Ears* [4] is used as a baseline in all logged listening tests. Using a baseline HRTF derived from humans rather than a mannequin allows us to have a baseline HRTF free of unwanted resonances agnostic to different measurement test fixtures. It sets the standard for what head and torso simulators should aim to achieve. After a user selects their headphone, the system uses an automatic EQ algorithm [13] that generates 12 filters to compensate for the headphone's magnitude response relative to the diffuse-field HRTF before the preference optimization.

	Count	Frequency	Q-factor
Low-shelf filter	1	105 Hz	0.71
Peaking filter	10	Up to 7500 Hz	0.1 to 4.0
High-shelf filter	1	10000 Hz	0.71

Table 1. Categorization of twelve filters used to compensate for headphone magnitude response relative to the diffuse-field HRTF.

2.2 Parameter Range

Nine variable parameters distributed across three filters are simultaneously tested versus the baseline HRTF: a low-shelf filter, an ear-gain peaking filter, and a high-shelf filter. Each filter has variable frequency, Q-factor, and gain (dB).

	Frequency	Q-factor	Gain
Low-shelf filter	80 to 220 Hz	0.5 to 0.75	-3 to 14 dB
Ear-gain peaking filter	2000 to 3500 Hz	1 to 2.5	-6 to 0 dB
High-shelf filter	1500 to 5000 Hz	0.3 to .6	-6 to 2 dB

Table 2. The parameter ranges for the filters used in the listening tests

We informally designed the filter parameter range and selection to allow for the broadest range of adjustments necessary with a minimal error rate when tested over 40 trials, optimizing using the Gaussian process and Probability of Improvement [14] as the acquisition function. The algorithm provides random parameter sets for the first five trials, and the acquisition function chooses parameter sets for the remaining 35 trials.

2.3 Program Selection

The song used for the listening tests is Inner Cell from the Polygondwanaland album by King Gizzard & the Lizard Wizard [15]. We chose it for its high bandwidth, spectral density, and dynamic range.

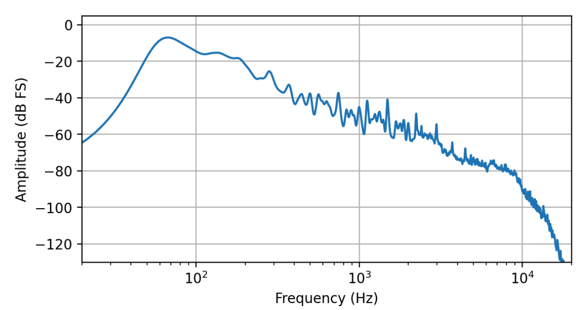

Figure 13. Frequency analysis of Inner Cell from the Polygondwanaland album by King Gizzard & the Lizard Wizard.

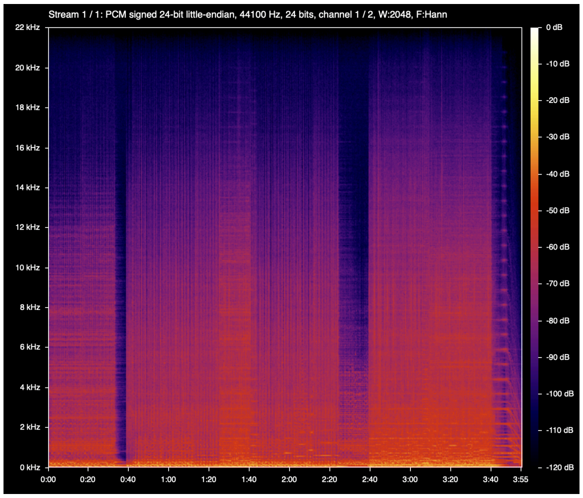

Figure 14. Spectrogram of Inner Cell from the Polygondwanaland album by King Gizzard & the Lizard Wizard.

2.4 Loudness Normalization

After applying the equalization filters, we initially normalized select high-energy samples from the Polygondwanaland album to -12 LUFS per ITU-R BS.1770-4 [16]. Later, we switched to using only Inner Cell with a fixed preamp set to the negative maximum gain that the generated filters could apply.

2.5 Listening Test Procedure

For each trial, participants rate the subjective sound quality of the modified sound sample on a slider with a range of -5 to +5, with 0 being the initial trial value. -5 indicates the worst possible perceived sound quality, +5 indicates the best-perceived sound quality, and 0 indicates average perceived sound quality.

2.6 Selection of Headphone Measurements

The accuracy of the measurement fixtures and measurements determined the priority order for the different measurement sources. The two highest priority over-ear magnitude response databases use GRAS 43AG [17] or 45BC [18] test fixtures with RA040x [19] couplers and KB5000 [20] and KB5001 [21] pinnae. The two highest priority in-ear measurements use clone IEC 60318-4 [22] couplers with minimal standard deviations between each and versus official manufacturer measurements.

	Over-Ear Headphones	In-Ear Headphones
1.	Hangout.Audio [23]	squig.link [25]
2.	Oratory1990 [24]	timmyv.squig.link [26]

Table 3. Priority list for first two highest priority magnitude response databases or over-ear and in-ear headphone measurement selection.

The following figures demonstrate the measurement accuracy of the two highest priority clone IEC 60318-4 couplers by first comparing squig.link's Softears VolumeS measurement to the official manufacturer measurement [27] and the second comparing timmyv.squig.link's Truthear Nova measurement to squig.link's. IEC 60318-4 tolerance [19] error bars are overlaid for the specified measurement accuracy from 100 Hz to 10 kHz. Both comparisons fall well within the tolerance bounds. Above 10 kHz, there is a discrepancy between the manufacturer Softears VolumeS measurement and squig.link's. The differences between timmyv.squig.link's and squig.link's measurements above 10 kHz are miniscule. Whether any differences are due to variations in the in-ear headphones or the couplers is unknown. Nevertheless, the minimal deviation signifies high accuracy and consistency, especially for measurements of separate units on inexpensive test equipment.

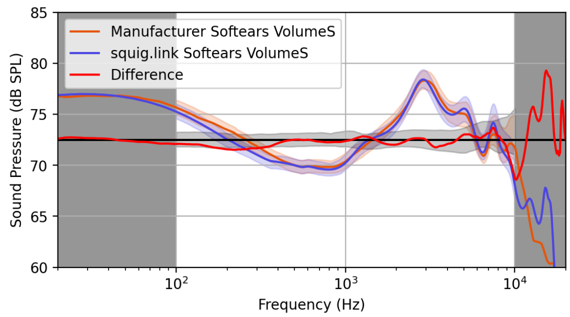

Figure 15. Softears VolumeS manufacturer measurement [27] versus squig.link measurement.

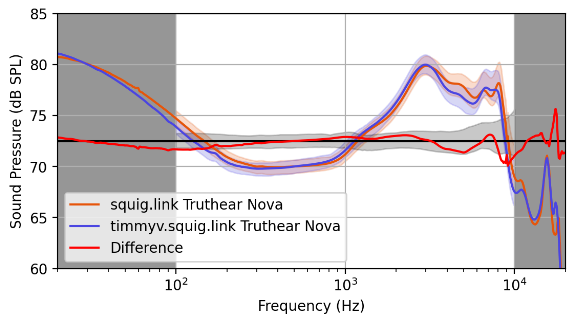

Figure 16. Truthear Nova squig.link and timmyv.squig.link measurement comparison.

3 RESULTS

The test was first carried out on a selected group of testers before being released to the public internet. This large-scale public data collection allowed us to collect data from users of 266 different models of headphones. We compare the average predicted optimal target magnitude response between the open and closed beta, users who use the default song, users who upload their own music, and users using in-ear and over-ear headphones. The difference between the resulting in-ear and over-ear targets is relatively small, so we compute the combined curve of all the tests as a general target curve [28]. We also compared results with ITU-R BS.1770-4 [16] loudness normalization to using a fixed preamp (no loudness normalization) and found no significant differences.

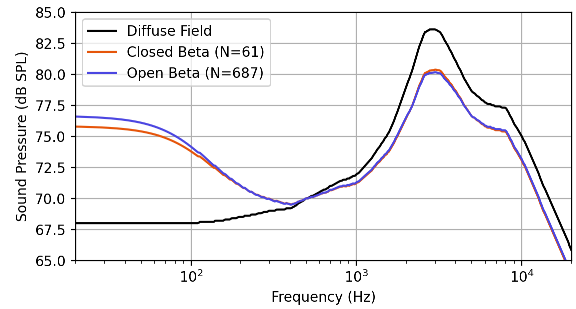

Figure 17. Closed beta versus open beta magnitude response preference.

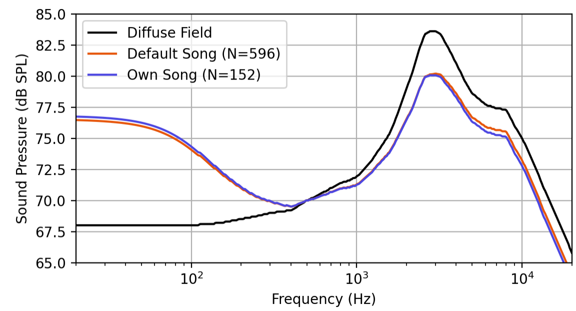

Figure 18. Default song versus own song magnitude response preference.

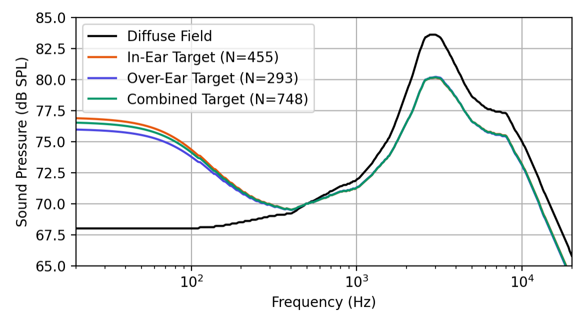

Figure 19. PEQdB in-ear, over-ear, and combined target magnitude response curves.

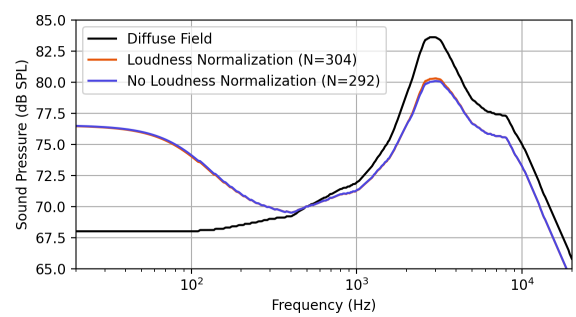

Figure 20. Comparison of results with and without loudness normalization.

4 DISCUSSION

4.1 Comparison versus Harman Targets

In a plot comparing the PEQdB in-ear and over-ear target curves to the Harman over-ear 2018 and in-ear 2019 target curves, our targets differ in key areas, improving perceived sound quality considerably. There is little difference in magnitude frequency response preference between in-ear and over-ear headphones from our testing, highlighting the pitfalls of the methodological inconsistencies in the Harman headphone studies.

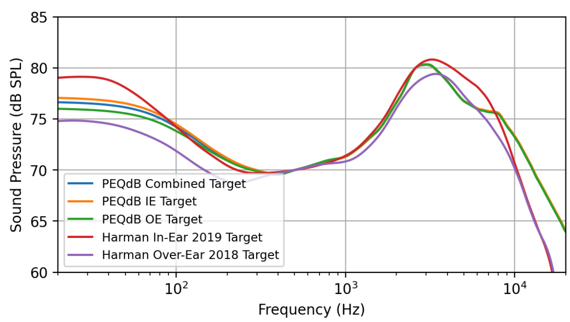

Figure 21. PEQdB in-ear and over-ear target curves compared to Harman over-ear 2018 and in-ear 2019 target curves.

The low-shelf filter frequency location of the Harman In-Ear 2019 target curve is closer to the low-shelf filter frequency location of the PEQdB target curves, likely due to letting users adjust the low-shelf filter frequency and gain in their initial in-ear listening tests. Informal complaints about the Harman over-ear 2018 target being thin in the bass are addressed, with the PEQdB over-ear target having a higher bass shelf frequency and increased gain, which is more representative of loudspeakers placed in a typically reflective listening room. When comparing a spatially averaged steady-state magnitude frequency response measurement captured by a Sennheiser MKH 8020 omnidirectional microphone [29] of a pair of anechoically flat Neumann KH120 II loudspeakers [30] located two meters from the listening position at +/- 30° angles of incidence in a typically reflective room to the diffuse-field HRTF-removed PEQdB over-ear headphone target curve without the ear gain adjustment, the low-frequency tracking is spectacular aside from resonances which should ideally be attenuated with corrective signal processing or acoustic treatment, demonstrating high realism in the PEQdB target bass profile. Compensating for the ~1.5 dB low-frequency elevation in the MKH 8020, as shown in Figure 22, would further improve the low-frequency tracking of the KH 120 II pair.

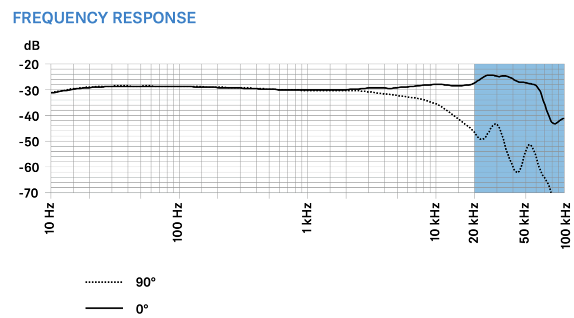

Figure 22. 0 and 90° angles of incidence magnitude response measurements of Sennheiser MKH 8020 omnidirectional microphone [29].

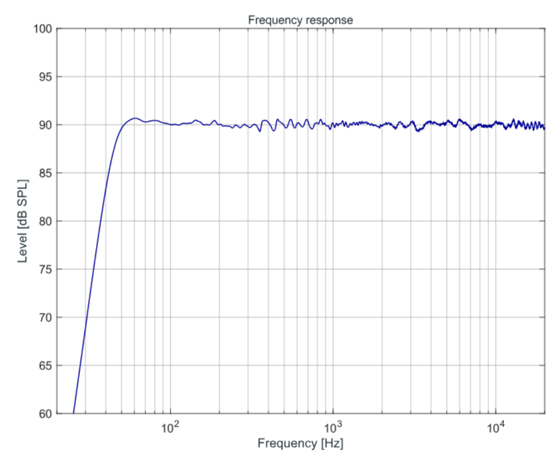

Figure 23. On-axis anechoic magnitude frequency response measurement of Neumann KH 120 II loudspeaker [30].

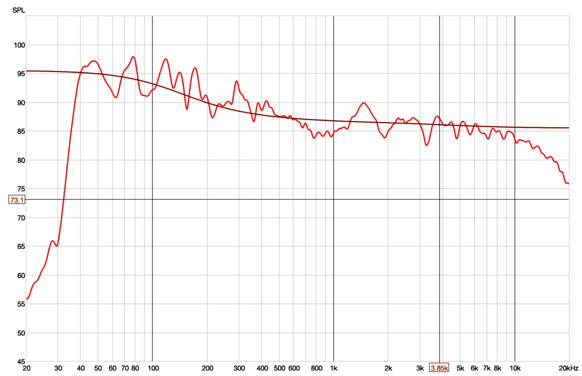

Figure 24. The spatial average of a pair of Neumann KH120 II loudspeakers measured in a typically reflective listening room compared to the PEQdB over-ear headphone target with the diffuse-field HRTF and ear gain adjustment subtracted from the response.

We addressed the informal complaints about the Harman over-ear and in-ear headphone target curves sounding veiled in the highs by using a more appropriate diffuse-field HRTF and filter selection in our listening tests. Finally, the informal criticisms of the Harman in-ear 2019 target curve sounding too shouty, thin, and sub-bass focused are addressed by the reduced 2-8 kHz region and more reserved sub-bass boost in the PEQdB in-ear target curve.

4.2 Effect of Program Material on Listener Preference

As demonstrated in [11], song choice has little effect on listener preference for headphone tonality. The concept of program material agnostic headphone preference is further validated by the minuscule difference in listener preference when users performed listening tests with their uploaded songs versus our default song, as shown in Figure 22.

4.3 Brüel & Kjær 5128 Measurements

We opted not to use B&K 5128 measurements for two reasons: the first is that the sample size of available headphone measurements is too small, and the second is the unnatural low-frequency resonances for in-ear headphone measurements caused by a rocking mode from the physical interaction between the in-ear headphone and the measurement device. When comparing the mean human ear canal impedance of 32 subjects versus an IEC 60318-4 compliant coupler below 1000 Hz, no difference falls outside one standard deviation of the tested subjects [25].

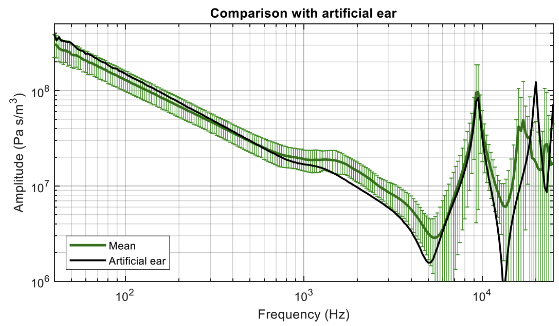

Figure 25. Mean human ear canal impedance of 32 subjects versus IEC 60318-4 compliant coupler [31].

When comparing in-ear headphone measurements between Hangout.Audio's IEC 60318-4 compliant coupler and their B&K Type 4620 ear simulator for the B&K Type 5128, several marked low-frequency discrepancies are seen, which are not represented in Figure 25. In the Moondrop Variations B&K Type 4620 measurement, there are resonances at about 110 and 400 Hz, which are absent in the IEC 60318-4 measurement.

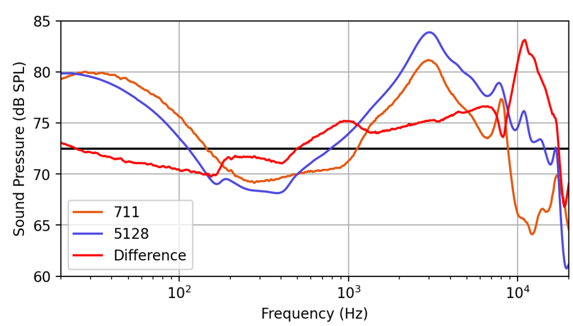

Figure 26. Moondrop Variations measurement on an IEC 60318-4 (711) compliant coupler versus a B&K Type 4620 ear simulator.

Resonances at about 80 and 400 Hz are present in the Moondrop Aria Type 4620 measurement but absent in the IEC 60318-4 measurement.

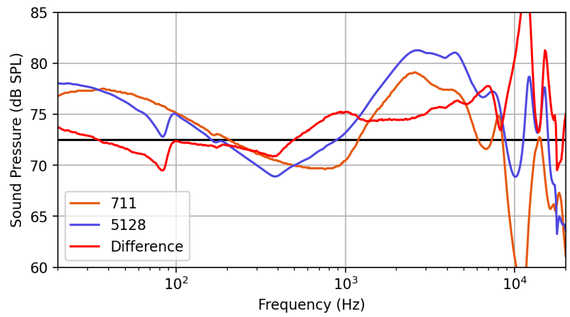

Figure 27. Moondrop Aria measurement on an IEC 60318-4 (711) compliant coupler versus a B&K Type 4620 ear simulator.

The delta's shape between the in-ear headphones changes considerably below 200 Hz, illuminating the low-frequency unreliability of in-ear headphone measurements on the B&K Type 4620 ear simulator. B&K 5128 to IEC 60318-4 in-ear headphone target translation curves, which include the ~400 Hz rocking mode that does not occur in humans, should be treated with caution, especially since such target curves have zero empirical backing.

4.4 Absolute Listening Level

Due to the nature of the listening experiments, we could not control absolute listening levels, and therefore, equal loudness contours [32] may come into play when evaluating target curves across listeners who took the listening tests at significantly different listening levels. On the other hand, not controlling for absolute listening level gives listeners the freedom to set the listening level to their individual preferences, resulting in the PEQdB target curves being optimized for the average preferred listening level.

5 CONCLUSION

The PEQdB over-ear, in-ear, and generic magnitude frequency response target curves are the most statistically optimal headphone target curves created and should be the industry standard for tonality.

6 REFERENCES

[1] Olive, S. E., Welti, T., & McMullin, E. (2013, October). *Listener Preferences for In-Room Loudspeaker and Headphone Target Responses* (Convention Paper 8994). Presented at the 135th Convention of the Audio Engineering Society, New York, NY, USA.

[2] GRAS Sound & Vibration. (n.d.). *GRAS 45CA Headphone/Hearing-Protector Test Fixture*. https://www.grasacoustics.com/products/test-fixtures/for-hearing-protector-test/product/734-45ca

[3] Olive, S. E. (2009, May). *A new reference listening room for consumer, professional and automotive audio research* (Convention Paper 7677). Presented at the 126th Convention of the Audio Engineering Society, Munich, Germany.

[4] Hammershøi, D., & Møller, H. (2008). *Determination of Noise Immission from Sound Sources Close to the Ears*. Acta Acustica united with Acustica, 94(1), 114–129. https://doi.org/10.3813/AAA.918014

[5] International Organization for Standardization. (2002). *ISO 11904-1:2002 Acoustics — Determination of sound immission from sound sources placed close to the ear — Part 1: Technique using a microphone in a real ear (MIRE technique)*. https://www.iso.org/standard/29053.html

[6] Toole, F. E. (2015). *The Measurement and Calibration of Sound Reproducing Systems*. Journal of the Audio Engineering Society, 63(7/8), 512–526. https://doi.org/10.17743/jaes.2015.0064

[7] Olive, S. E., & Welti, T. (2015, October). *Factors that Influence Listeners' Preferred Bass and Treble Balance in Headphones* (Convention Paper 9382). Presented at the 139th Convention of the Audio Engineering Society, New York, NY, USA.

[8] Olive, S. E., Welti, T., & Khonsaripour, O. (2018, May). *A Statistical Model that Predicts Listeners' Preference Ratings of Around-Ear and On-Ear Headphones* (Convention Paper 9919). Presented at the 144th Convention of the Audio Engineering Society, Milan, Italy.

[9] Olive, S. [@seanolive]. (2022, April 14). *It was largely driven by feedback from trained listeners who felt it was too hot in that area. Subsequent tests confirmed this adjustment was preferred* [Post]. X. https://x.com/seanolive/status/1514831235461181446

[10] Olive, S. E., Welti, T., & Khonsaripour, O. (2016, August). *The preferred low frequency response of in-ear headphones*. Paper presented at the AES Conference on Headphone Technology, Aalborg, Denmark. Audio Engineering Society. https://www.aes.org/e-lib/browse.cfm?elib=18562

[11] Olive, S. E., Welti, T., & Khonsaripour, O. (2017, May). *The Influence of Program Material on Sound Quality Ratings of In-Ear Headphones* (Convention Paper 9778). Presented at the 142nd Convention of the Audio Engineering Society, Berlin, Germany.

[12] Listen, Inc. (2019, August 12). *Prediction of listener preference of in-ear headphones using the Harman model*. https://www.listeninc.com/products/test-sequences/free/prediction-of-listener-preference-of-in-ear-headphones-using-the-harman-model/

[13] Pasanen, J. (n.d.). *AutoEq: Automatic headphone equalization from frequency responses*. GitHub. https://github.com/jaakkopasanen/AutoEq

[14] Garnett, R. (2023). *Bayesian optimization*. Cambridge University Press. https://bayesoptbook.com/

[15] King Gizzard & The Lizard Wizard. (n.d.). *Polygondwanaland*. https://kinggizzardandthelizardwizard.com/polygondwanaland

[16] International Telecommunication Union Radiocommunication Sector. (2015). *Recommendation ITU-R BS.1770-4: Algorithms to measure audio programme loudness and true-peak audio level*. https://assets.corusent.com/wp-content/uploads/2021/10/ITUR_BS_1770_4_Audio_Program_Loudness_En.pdf

[17] GRAS Sound & Vibration. (n.d.). *GRAS 43AG Ear & Cheek Simulator*. https://www.grasacoustics.com/products/ear-simulator-kit/constant-current-power-ccp-1/product/737-43ag

[18] GRAS Sound & Vibration. (n.d.). *GRAS 45BC KEMAR head & torso with mouth simulator, non-configured*. https://www.grasacoustics.com/products/head-torso-simulators-kemar/kemar-non-configured/product/749-45bc

[19] GRAS Sound & Vibration. (2019). *Improved ear simulators for headphone testing: IEC 60318-4 compliant/compatible ear simulators for testing of headphones, earphones and headsets up to 20/50 kHz* (Brochure No. LI0215_2019). GRAS Sound & Vibration. https://www.gras.dk

[20] GRAS Sound & Vibration. (n.d.). *GRAS KB5000 Right Anthropometric Pinna 35 Shore OO*. https://www.grasacoustics.com/products/accessories/for-artificial-ears-and-mouths/product/729-kb5000

[21] GRAS Sound & Vibration. (n.d.). *GRAS KB5001 Left Anthropometric Pinna 35 Shore OO*. https://www.grasacoustics.com/products/accessories/for-artificial-ears-and-mouths/product/730-kb5001

[22] AliExpress. (n.d.). *Precision Artificial Ear IEC711 Frequency Response Curve Tester Artificial Ear 318-4 Headphone Tester*. https://www.aliexpress.us/item/3256805222108700.html

[23] Hangout.Audio. (n.d.). *Crinacle's Headphone Graph Tool*. https://graph.hangout.audio/headphones/

[24] u/oratory1990. (n.d.). *r/oratory1990 Wiki: Headphone EQ Presets*. Reddit. Retrieved May 19, 2025, from https://www.reddit.com/r/oratory1990/wiki/index/list_of_presets/

[25] Super* Review. (n.d.). *Squiglink: IEM and headphone frequency response database*. https://squig.link/

[26] TimmyV. (n.d.). *Timmy's squig.link*. https://timmyv.squig.link/?share=Custom_Tilt&bass=6&tilt=-0.6&treble=0&ear=0

[27] Softears. (n.d.). *Softears VolumeS dual modes switchable in-ear hi-fi earphones*. https://softears.store/products/softears-volume-s-hifi-in-ear-hd-audiophile-headphones-two-levels-tuning-3-5-4-4

[28] PEQdB. (n.d.). *PEQdB Target, PEQdB IE Target, PEQdB OE Target – PEQdB Grapher*. Retrieved May 19, 2025, from https://peqdb.com/graphs/?share=PEQdB_Target,PEQdB_IE_Target,PEQdB_OE_Target

[29] Sennheiser. (n.d.). *Condenser microphone MKH 8020*. https://www.sennheiser.com/en-us/catalog/products/microphones/mkh-8020/mkh-8020-stereoset-506288

[30] Neumann. (n.d.). *KH 120 II*. https://www.neumann.com/en-us/products/monitors/kh-120-ii

[31] Jønsson, S., Schuhmacher, A., & Ingerslev, H. (2018). *Wideband impedance measurement in the human ear canal: In vivo study on 32 subjects* (arXiv preprint arXiv:1811.03389). arXiv. https://arxiv.org/abs/1811.03389

[32] International Organization for Standardization. (2023). *ISO 226:2023 – Acoustics — Normal equal-loudness-level contours*. https://www.iso.org/standard/83117.html