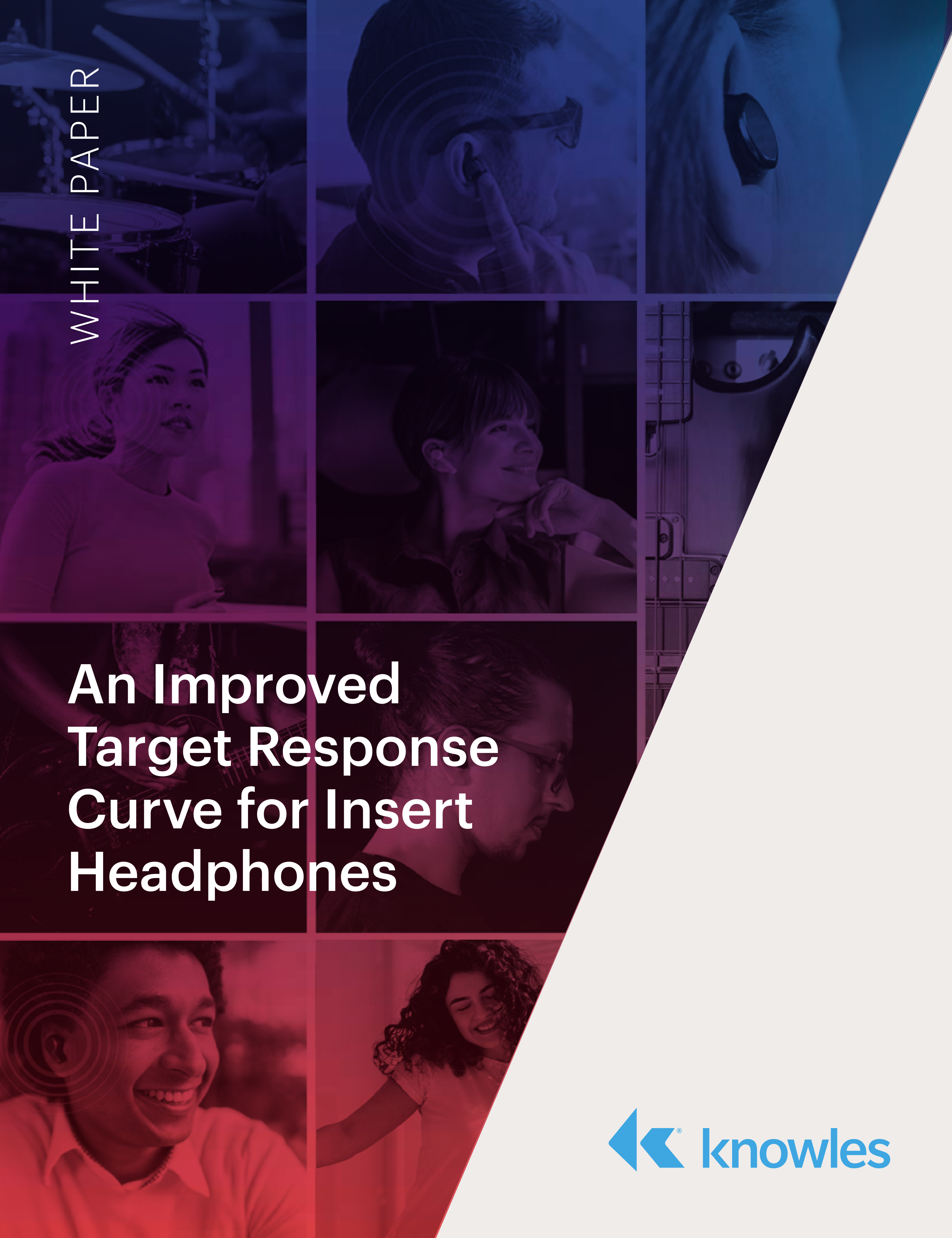
WHITE PAPER



An Improved Target Response Curve for Insert Headphones

knowles

Introduction (and synopsis)

The Harman earphone target response curve has been widely used to guide the design of earphones, yet the studies on which it was based did not properly cover the full audible spectrum. This curve, first proposed in 2013, was based on research by Sean Olive and his team to find the curve that listeners liked best. Headphones with a response curve similar to this target consistently received the highest ratings from listeners in carefully controlled listening tests. However, Olive stated that the results were really only valid below 10 kHz due to limitations of his test methods and available earphone test couplers[2].

Knowles has recently taken up the challenge of discovering what listeners would prefer in the 10 to 20 kHz region, taking advantage of its ability to create wide bandwidth earphones, and recent advances in test coupler technology. Extensive controlled-listening tests show that the high frequency response should be much flatter than the original Harman curve, an increase of 12 dB near 16 kHz (Figure 1). This requires additional high frequency output capability in earphones. Knowles recommends the use of balanced armature tweeters to enable meeting this curve without the need for strong electrical equalization that can cause electrical overloads.

While listeners agree on their preferred response curve at lower frequencies, at high frequencies older people prefer larger boost in the high frequency response. By measuring subjects' hearing response and comparing the result to the typical rate of age-related hearing decline, their equivalent hearing age could be determined. In general, listeners wanted an additional 3 dB of boost for each 10 years of additional equivalent hearing age.

This paper describes the development of a new preferred response curve for earphones, covering the test methods, the curves preferred by various hearing equivalent age groups, and provides suggestions for hardware to help meet the new preferred curve.

Preferred Response Curve for Earphones

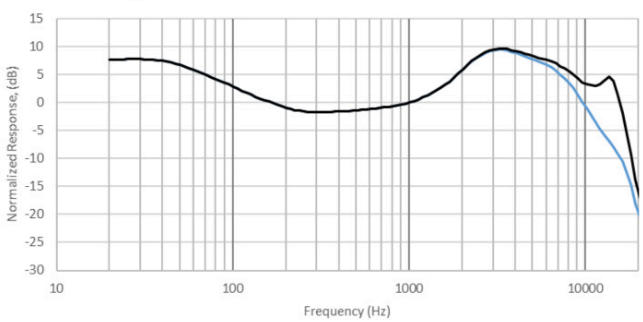


Figure 1. The Harman (blue) and Knowles (black) recommended response curves for earphones.

Test Method

Knowles used the MUSHRA protocol (Multiple Stimuli with Hidden Reference and Anchor), where listeners can instantly switch between several different recordings to compare them, and then enter their preference ratings for those recordings. We closely followed the method used by Sean Olive to develop the Harman curve. Listeners listened to excerpts of several songs over earphones, rating the quality of different earphone response curves.

The listeners were presented with 6 levels of high frequency boost, the original Harman curve, and an anchor curve where the high frequency energy above 8 kHz was removed. The loudness of the earphones was set to 80 dB SPL, using the ITU program loudness assessment method. The user interface is shown in Figure 3.

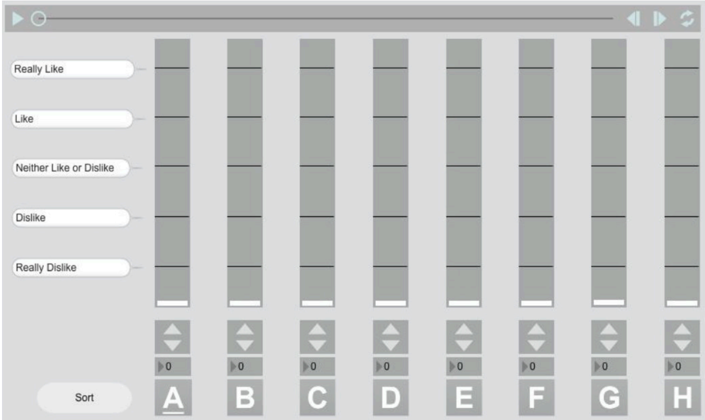


Figure 2. User interface for MUSHRA testing.

[1] *Listener Preference For Different Headphone Target Response Curves, Olive, Welti, McMullin, 134th AES Convention, May 2013*
[2] *Influence of Listeners' Experience, Age, and Culture on Headphone Sound Quality Preferences, Olive, Welti, McMullin, 137th AES Convention, October 2014*

The music was played through custom earphones made by Knowles (Figure 4). These use a 7 mm dynamic driver woofer and a Knowles WBFK tweeter. The smooth and extended high frequency response of this earphone enabled testing high frequency preferences. The earphones were first equalized flat (Figure 5), then equalized to take on the various response curves the listeners were to audition. The earphones were fitted with a MEMS microphone to check that earphones were properly sealed to the subjects' ears.

The headphones were measured using the GRAS RA0401 damped ear simulator with the supplied funnel-shaped coupler, with the ear tips deeply inserted into the coupler using small or medium size ear tips. This test method should be used to compare headphones against the recommended curves in this paper. Non-damped ear simulators can have very different shaped responses above 10 kHz, and different insertion depths will also change the response curves.

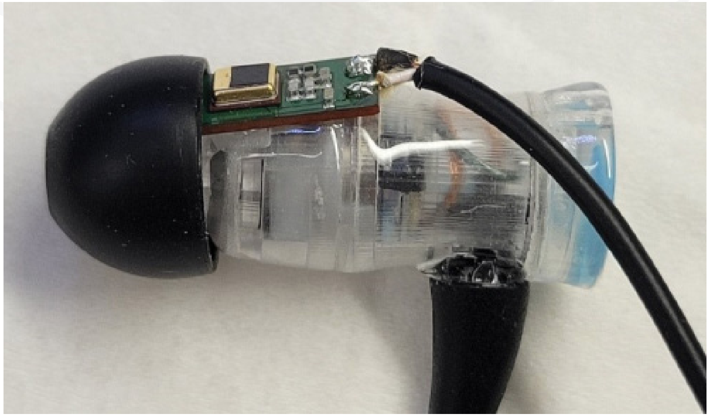


Figure 3. Knowles K-1 hybrid earphone, with MEMS mic attached to monitor the response.

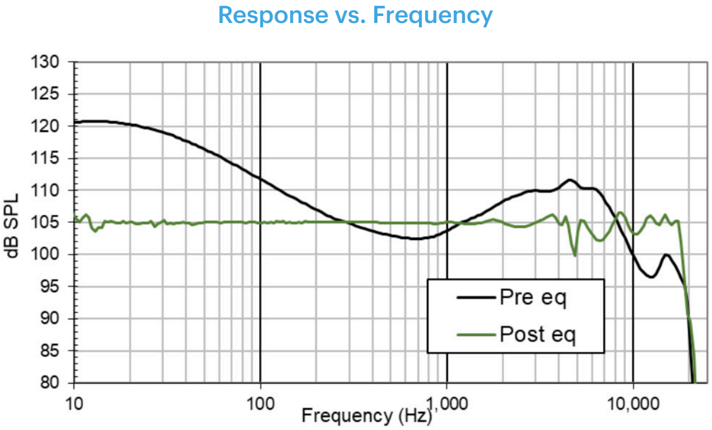


Figure 4. Knowles K-1 earphone before and after neutralizing equalization

The high frequency hearing abilities of the listeners were expected to shape their preferences for the earphone response. The hearing thresholds for people generally rise with age, making it more difficult to hear high frequencies, as shown in Figure 5. This graph shows normal age-related losses, and does not include individuals with abnormal losses due to disease or high noise exposure. The effect increases with frequency, with a rather sharp change above 10 kHz.

The hearing of all subjects was measured using a broadband audiometer. Subjects were assigned to one of 4 groups from figure 2 that best matched their high frequency hearing ability. In this way, we are able to extrapolate from our subjects' preferences to predict the headphone response preferences for the general population.

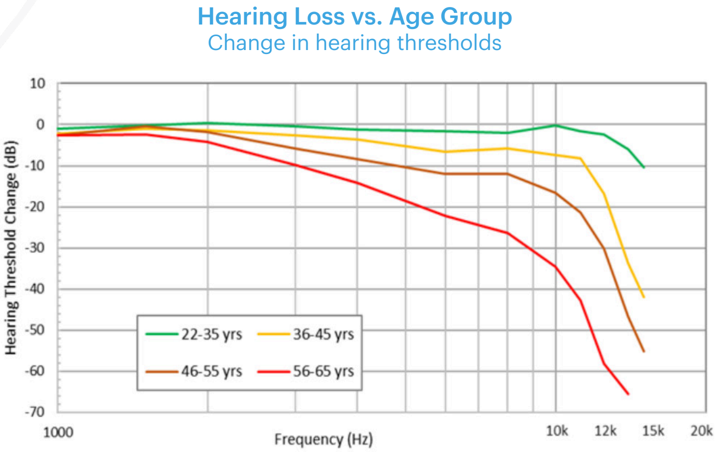


Figure 5. Typical change in hearing thresholds with age, with no noise-induced losses

The selection of music for the testing could have a large effect on listener preferences. We selected songs that had representative energy at high frequencies in order to get unbiased results. To learn what is a typical music spectrum, we analyzed 200 recordings chosen randomly from the last 10 years of the Billboard Top 100™. The top 100 list shows the most highly sold and streamed music, so it represents the majority of music that headphone wearers are likely to be listening to.

The average song spectrum is shown in Figure 6, with 95% of the music being within ±5 dB of this average curve. We selected 4 songs to use in the preference testing that had spectra similar to this average curve and contained acoustic instruments that are easy to judge the response of, such as vocals and cymbals[3].

[3] *Breathing by Ariana Grande, Break My Heart by Dua Lipa, Only Human by Jonas Brothers, Gives You Hell by All-American Rejects*

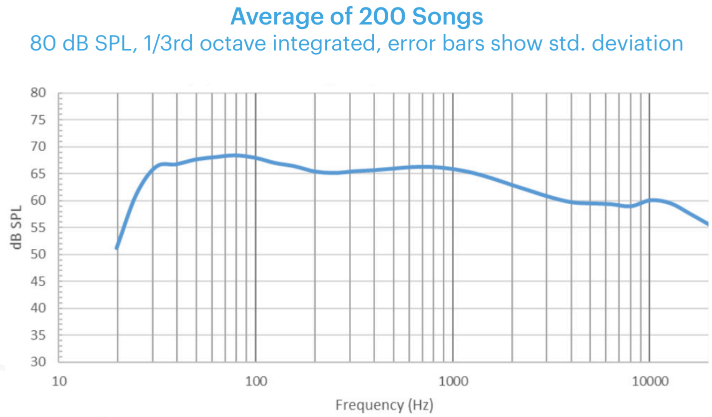


Figure 6. Average spectra of pop music.

We used listening tests using a small group to narrow down the possible equalizations to present to the large group. We started with the Harman curve, then added various high frequency equalization curves. The curves were chosen to preserve as much as possible the portion of the Harman curve that was below 10 kHz, since that was well established by Harman's research. The most popular filter turned out to be a filter centered at 16 kHz, with a Q of 4. Listeners felt that the greatest change to the Harman curve should be made at the highest frequencies. Listeners with greater hearing loss preferred greater boost. Therefore a different range of boosts was provided for each age group in the final testing. The range of curves tested are shown in Figure 8.

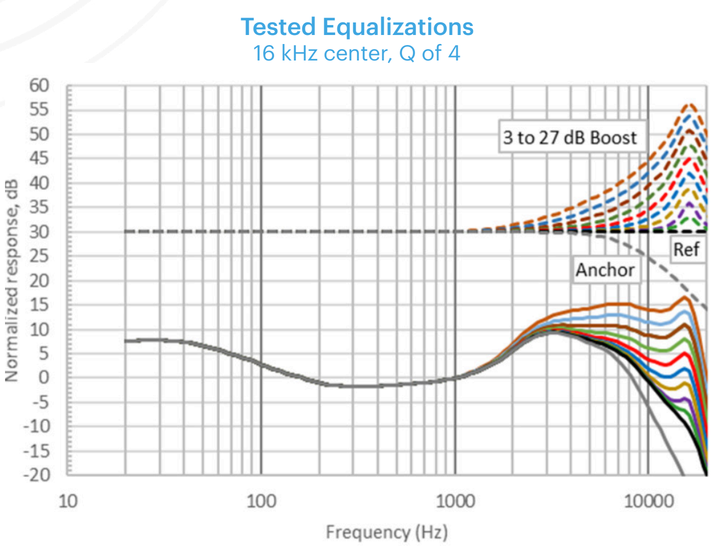


Figure 8. Curves used in final preference testing. Dashed line is equalization added to Harman curve, solid line is the combined effect.

Test Results

The listening test results are shown in Figure 9. The amount of boost is shown on the X axis, and listener sound quality ratings are on the Y axis. These are the ratings of nearly 70 listeners. For young listeners with no impairment, the preferred boost was 12 dB relative to the original Harman curve. Ratings remained high over a ±3 range of boost. For each 10 years of additional equivalent hearing age, listeners preferred to have an additional 3 dB of boost, with the oldest equivalent group wanting 21 dB more high frequency energy than the Harman curve. As shown in Figure 8, the oldest equivalent group preferred a headphone response curve that remains nearly flat for all frequencies above 3 kHz (brown curve).

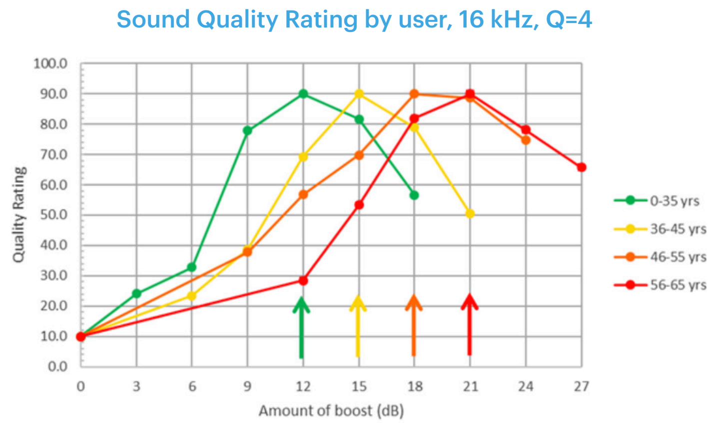


Figure 9. Listener quality ratings, normalized.

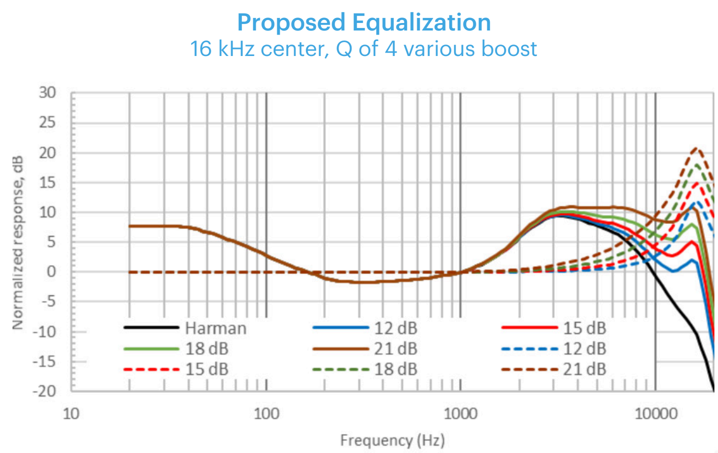


Figure 10. Preferred curves

The increase in preferred boost with age is much smaller than the change in hearing thresholds shown in Figure 5. Less boost is need for sounds well above hearing thresholds. The preferred response curve for older listeners is expected to be loudness dependent. Greater boost of high frequencies will be desired for volume settings used for background listening, which moves the music closer to the hearing thresholds.

Not all listeners wanted the same amount of boost. A regression analysis shows that 95% of listeners preferred a level within ±5 dB of the group average. Therefore, it would be useful to provide listeners with at least ±5 dB of adjustment over the 16 kHz boost, perhaps within a phone app for the headphones.

Tweeters

The high level of response past 16 kHz is not easy to achieve in a single driver earphone. Equalization can be used to raise the level of high frequency energy, but this greatly increases the risk of clipping the signal, either within the DSP or within the power amplifier. This can be avoided by dropping the maximum volume for the system, but then users may be disappointed with the impact of the headphone.

Adding a balanced armature tweeter can dramatically increase the high frequency sensitivity of the earphone, avoiding the need for strong equalization. The tweeter enables using dynamic drivers optimized for maximum low-frequency output required in noise-cancelling headphones. The tweeter not only avoids high frequency loss due to the larger, heavier cone, but also allows moving the dynamic further from the port opening without the risk of high frequency loss. This allows for more attractive and comfortable headphone housing shapes.

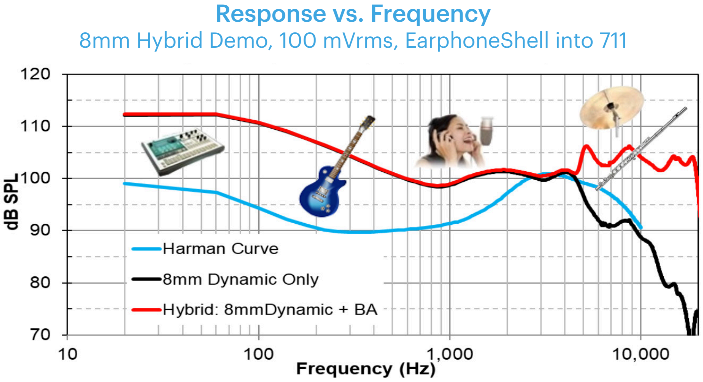


Figure 12. Response of 8 mm demonstration hybrid earphone, before equalization. Black is woofer, Red is woofer + tweeter, blue is Harman curve. Tweeter greatly reduces the need for equalization.

Wrap up

Careful blind testing of a wide variety of listeners shows that the Harman curve severely understates the amount of high frequency energy that listeners prefer with their earphones. Listeners want between 12 and 21 dB more treble, depending on the state of their hearing. Further boost is needed to accommodate variation between listeners, and listening at reduced music levels. Existing single-driver earphones will have difficulty providing this much high frequency signal in combination with high bass output for ANC. Adding a balanced armature tweeter reduces the amount of boost needed in the system equalizer (Figure 12). If a software control is provided for the user to adjust the headphone to their taste and their age, we recommend a control centered at a frequency higher than 12 kHz, ideally near 16 kHz. Listeners will want at least ±5 dB of adjustment beyond the average boost for their age group. An earphone that matches the above recommendations is expected to provide a highly satisfying experience for the end user, resulting in higher sound quality ratings.

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