

QUANTIFYING ACOUSTIC DISTORTIONS FROM HEARING AID GROUP DELAYS

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INTRODUCTION

In digital hearing aids, the input sound is processed in different frequency channels, where each channel is manipulated by various algorithms (such as compression, directional microphone, noise reduction, feedback cancellation, and frequency lowering). Processed signals from each channel are then added together to form the final output from the hearing aid. This processing is not instantaneous, but requires time, described by the group or processing delay of the device. Delay is typically not a concern when it is less than 10 ms (Stone and Moore, 1999, 2002) and the hearing aid is worn in a completely occluding mode, where no intentional (from vents) or unintentional leakage occurs. On the other hand, the amount of processing delay does matter when the hearing aid is worn in a non-occluding mode (such as with the use of open-fit or any type of instant-fit eartips), where there is opportunity for the direct unamplified sounds to leak through the vent and mix with the amplified sounds in the ear canal. This interaction between the amplified sound, which is delayed, and the unamplified sound results in a distortion to the combined signal.

These distortions have perceptual consequences. For example, Bramslow (2010) reported that delays of 10 ms led to poorer sound quality, characterized by metallic or hollow-sounding speech. Stone et al. (2008) reported an upper limit for delay of 5-6 ms for acceptable performance in an open fitting. However,

acceptable performance does not mean optimal performance. Balling et al. (2020) showed that the **Widex PureSound™** program with the 0.5 ms delay was overwhelmingly preferred (> 85%) by normal hearing and hearing-impaired listeners to the default universal program with a delay of 2.5 ms. Schepker et al. (2019, p. 9) defined “the processing delay of 6.5 ms causing comb-filtering effects” as “the main limiting factor for sound quality”. Clearly, a shorter delay is preferable to a longer delay, even when both the delays might be “acceptable”. Considering that over 82% of hearing aids dispensed today use instant-fit eartips (Strom 2019), and virtually all of these instant fit eartips are non-occluding (Balling et al., 2019), processing delay should be front and center as an issue for promoting hearing aid satisfaction and acceptance.

Hearing healthcare professionals are always interested in the behavioral benefits that hearing aid wearers get from using a particular type of processing. However, it is equally important to understand the physical/acoustic impact of that processing and how that may explain the behavioral (and perhaps neural) benefits. While a difference in the acoustic output of a hearing aid may not always have a neurological or behavioral consequence, the lack of an acoustic difference makes it difficult to suggest that neurological or behavioral differences could even be observed. Thus, measuring the acoustic effect of processing delay should be the first task in understanding its potential neurological

and behavioral consequences. To that end, this paper will describe the acoustic measures that are meaningful in estimating the behavioral/neural impact of group delay. We will use the PureSound™ program on the WIDEX MOMENT™ hearing aid, as well as premium hearing aids from two other hearing aid manufacturers that we compared in previous studies (Kuk et al., 2020; Slugocki et al., 2020) as examples. It is noteworthy that, in this demonstration, the competitors' hearing aids have been upgraded to their recently launched models.

HEARING AIDS

The PureSound™ program of the MOMENT™ hearing aid and the recently introduced premium hearing aids from manufacturer #1 and manufacturer #2 were used. All hearing aids were programmed for an N2 (max 40 dB) hearing loss profile (Bisgaard et al., 2010) according to the NAL-NL2 fitting rationale in their respective fitting software. Feedback tests were run on each hearing aid. Feature sets were programmed according to the manufacturers' defaults, with all adaptive features either "On" or "Off" to gauge the effect of these features on processing delay. Because the results measured with adaptive features "On" were identical to those with features "Off", we only report on the results of features "On" for all but the /da/ syllable measurement, because of its direct implication for the electroencephalographic (EEG) measures.

ACOUSTIC MEASURES OF GROUP DELAY

1. Delay time - Group delay measurement was conducted in a B&K acoustic test chamber (type 4222) with the test hearing aids connected to a closed 711 coupler. White noise was presented at 65 dB SPL. Output was recorded in the reference microphone and the coupler microphone, and a transfer function was computed to derive the group delay. The delay times were computed in 1/3 octave bands from 500 Hz to 8000 Hz.

Figure 1 shows that the group delay measured with PureSound™ (in blue) was around 0.5 ms across frequencies, while the delays of manufacturers #1 (in dark grey) and #2 (in green) were 8 ms and 6 ms respectively. PureSound™ and manufacturer #1's hearing aid showed a relatively stable delay across frequencies. It is unclear why manufacturer #2 showed

more fluctuations in delay across frequencies. Such fluctuations could lead to an increased perception of unnaturalness.

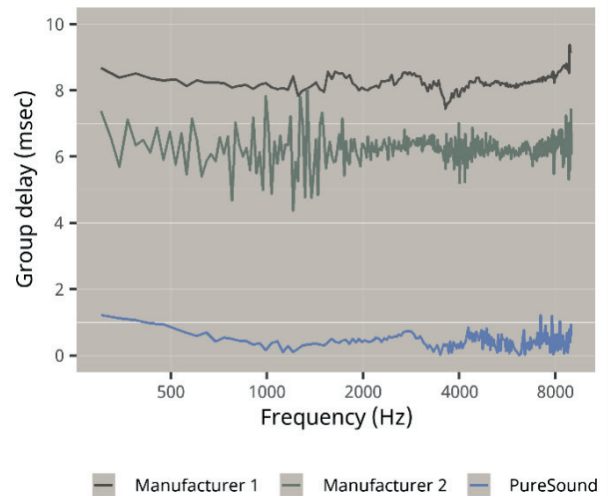


Figure 1: Comparison of group delays between PureSound™ and manufacturers #1 and #2.

2. Spectral distortion – Spectral distortion related to processing delay is commonly known as the comb-filter effect, due to the characteristic shape resembling the teeth of a comb. This comb-filtering was measured in a B&K acoustic test chamber (type 4222), with the test hearing aids connected to an open 711 coupler in order to include the combined effect of hearing aid amplified sound and direct sound on the frequency-gain response. A broadband white noise was used as the input stimulus. The gain function was derived from the difference between the two power spectral density estimates at the coupler and the reference microphone.

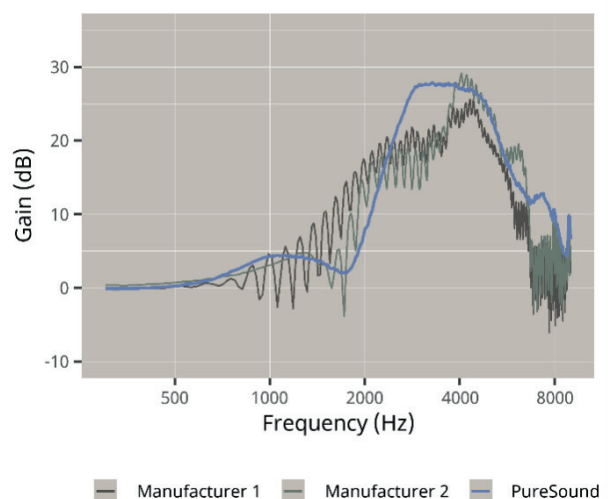


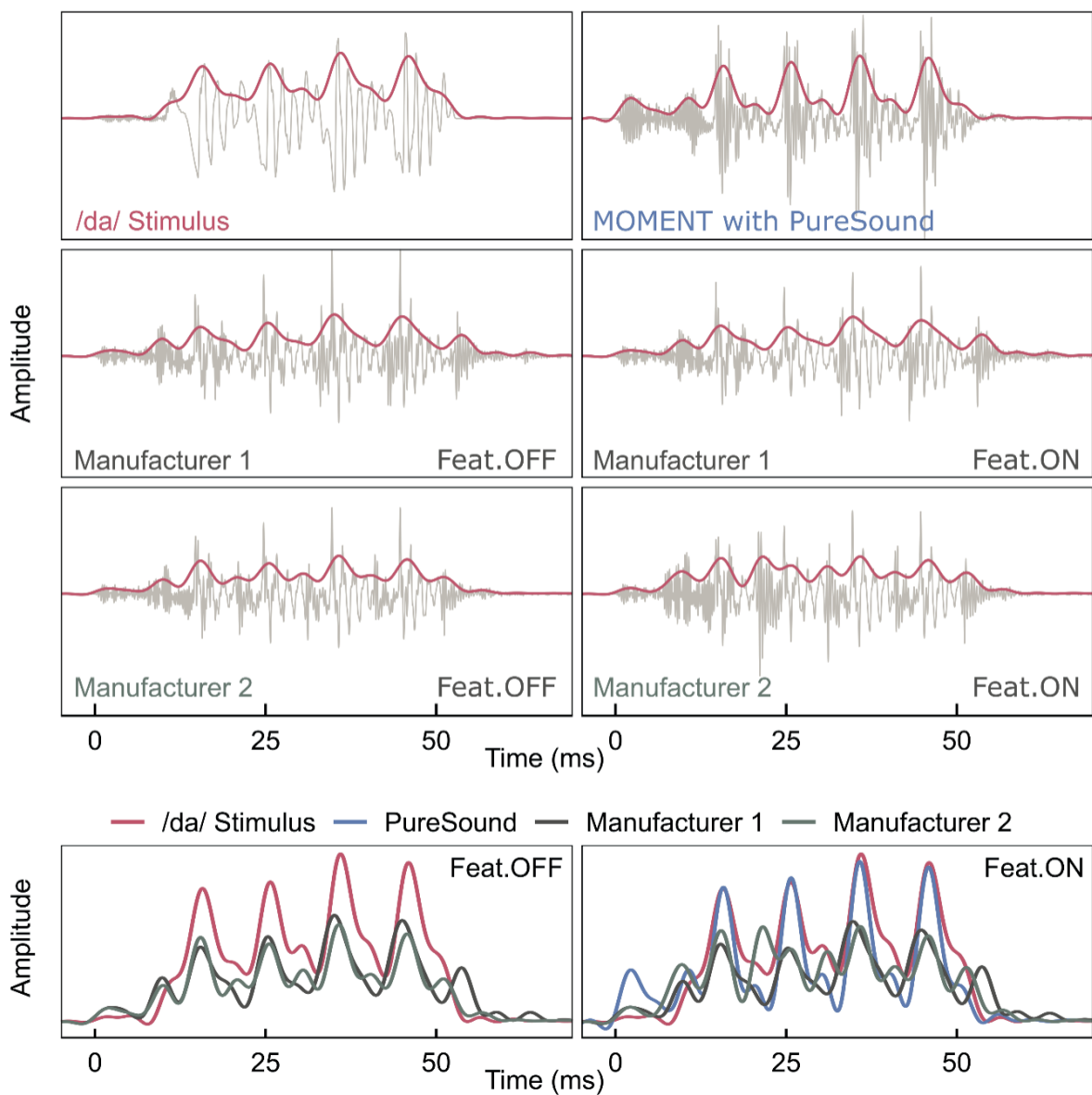
Figure 2: Spectral distortion (or comb-filtering effect) resulting from the different group delays of PureSound™, manufacturer #1 and manufacturer #2.

Figure 2 compares the frequency gain curves among the three hearing aids. Ideally, the curve should be smooth, without the peaks and dips (resonances/cancellations) that result when direct sound mixes with a delayed amplified version of itself in the ear canal. A resonance means the amplified and unamplified sounds are added in phase, while cancellation would suggest the two sounds are subtracted (or added out of phase). Note the smoothness of the gain curve obtained with the PureSound™ hearing aid. On the other hand, the gain curves from manufacturer #1 and manufacturer #2 showed significant peaks and dips.

Perceptually, sounds at the peaks will sound louder and sounds from the dips will sound softer than the amplified signal alone. This could give the perception of unnaturalness that wearers often report as a “hollow”, “echoic”, or “metallic” quality.

3. Distortion of fundamental frequency

(FO) in /da/ – The fundamental frequency (FO) of a talker is an important speech cue that aids auditory scene analysis (Bregman, 1990). Furthermore, the proper neural encoding of this cue has been demonstrated to correlate with listeners’ speech-in-noise abilities (Skoe and Kraus, 2010). Conceivably, mixing of the unamplified and delayed amplified



sounds could distort the temporal envelope and weaken the neural encoding of the F0. To verify that group delay would affect the F0, we used a synthesized /da/ syllable (duration = 50 ms; fs = 20 kHz) presented at 70 dB SPL to KEMAR, placed in an anechoic chamber in the unaided condition and the aided (PureSound™, manufacturers #1 and #2) condition using open eartips. As indicated before, the hearing aids from manufacturers #1 and #2 were tested in both adaptive features “On” and “Off” modes. The final /da/ presentation was selected as the most representative of each hearing aid’s stabilized processing state. The envelope of this final /da/ token was then derived from the recording signal using the Hilbert transform. Envelopes were compared among the different aided conditions.

Figure 3A shows the temporal envelope derived from the KEMAR-recorded responses between the unaided condition and the three different aided conditions in both features “On” and “Off” modes. The envelope, which represents the fundamental frequency, is shown in pink, while the actual waveform is shown in gray. The figure shows that the envelope of the PureSound™ program aligns with the original unaided sound nicely, while the envelopes of manufacturers #1 and #2 are smaller in amplitude and less well-aligned to the peaks of the unaided envelope. Figure 3B facilitates the comparison by superimposing all 4 envelopes onto one figure in both features “On” and “Off” modes. There is virtually no difference in the envelopes between features “On” (right) and “Off” (left).

DISCUSSION

These acoustic measurements confirm a difference in group delay between the PureSound™ program on the MOMENT™ hearing aid and the default programs of manufacturers #1 and #2. The delays range from 0.5 ms in the PureSound™ program to 8 ms in manufacturer #1’s premium device. This difference in delay leads to measurable acoustic differences in the spectrum of sounds (Figure 2). Additionally, it affects the envelope of the /da/ syllable, leading to poorer representation of the fundamental frequency cue (F0), an important cue during auditory scene analysis (Figure 3). The spectral distortion (resonance and cancellation of frequencies in the natural sound) from group delay may lead to poorer sound quality described by adjectives such as hollow, echoic, metallic, and unnatural.

Another important observation from the current study is that the amount of spectral and temporal distortion measured from manufacturers #1 and #2 remains the same, regardless of the activation of the adaptive features employed in the hearing aids (Figure 3B).

This suggests that the impact of the group delay will be the same, regardless of the state of the hearing aid. It further demonstrates that (in the 2 manufacturers that we compared) group delay is an inherent property of the hearing aids unaffected by adaptive processing. In other words, there is no mechanism or setting/state within the hearing aids of manufacturers #1 or #2 that would allow wearers to experience a different delay. Previously, we measured the acoustic effects of group delay in several premium hearing aids. These hearing aids were upgraded recently, with their manufacturers claiming more intelligent and sophisticated processing. A reasonable question to ask is whether such an improvement in processing could shorten the group delay and lead to a more “natural” sound as compared to previous models. When one compares Figures 1 and 2 to those reported by Balling et al. (2020) on the delay and spectral distortion, we obtain essentially the same findings.

Figure 4 compares the temporal envelopes of the unaided /da/ stimulus to that measured from the PureSound™ program (top panel) and those of manufacturers #1 (middle panel) and #2 (bottom panel), both with the earlier version (dotted line) and the more recently introduced (solid line) premium products. With minor exceptions, the acoustic envelopes of the /da/ syllable measured with the previous premium products are identical to the current upgraded product for manufacturers #1 and #2. This suggests that the newer processing does not change the group delay or how well the natural signal is preserved.

Slugocki et al. (2020) used the envelope following response (EFR) to compare the neural coding of a /da/ syllable in listeners when wearing the PureSound™ program relative to those wearing the last generation of premium hearing aids from manufacturers #1 and #2. Their data showed a stronger EFR with the PureSound™ program, followed by manufacturers #1 and #2. These results suggest stronger “phase locking” of the neural response to the speech envelope in the PureSound™ program compared to the other two hearing aids. The results also support a better neural representation of the F0 cue and potentially better speech-in-noise ability of listeners wearing

the PureSound™ program. Because the EFR is well-documented to track periodicities in the evoking audio signal (for a review, see Skoe & Kraus, 2010), we would expect to see similar results if we compare the EFR between the PureSound™ program and the more recently introduced premium products from manufacturers #1 and #2 measured in this report. In other words, the processing on the newer devices still does not preserve the naturalness of the input signals.

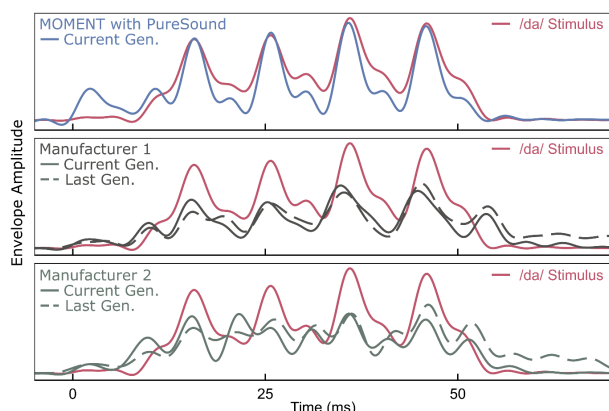


Figure 4: Envelope of the synthesized /da/ syllable measured from KEMAR under different hearing aid conditions. The pink line is the unaided response, and the different colors represent the different test hearing aids. The dotted lines are acoustic measurements of earlier versions of #1 and #2 reported in Slugocki et al. (2020), and the solid lines are current measurements.

CONCLUSION

These measurements show that group delay significantly alters the spectral-temporal aspects of amplified sounds (including speech) in open fittings at the wearer's ear canal, resulting in a less natural input for the brain to process. As a result, sound quality and speech understanding may suffer. The measurements further show that the newer versions of hearing aids from manufacturers #1 and #2 retain the same processing delay time as the previous models, with the same acoustic consequences. Because these acoustic measurements are similar to measurements made previously on the earlier models, it is anticipated that any behavioral and neural differences reported in earlier studies on the MOMENT™ hearing aids (Balling et al., 2020; Kuk et al., 2020; Slugocki et al., 2020) will remain with these newer models.

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