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Group Delay and Processing Delay in Hearing Aids
The Facts and the Fantasies

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Group Delay or Processing Delay

The terms Group Delay (GD) and Processing Delay (PD) have often been used interchangeably when referring to digital hearing aids. Group delay is the negative of the slope of the phase response at any frequency. It can have both positive and negative values and has peaks at each abrupt change in the amplitude frequency response curve (Kates 2005). The term Processing Delay has been proposed as the delay between input and output in a digital hearing aid. This is the same as GD in the case where GD is constant which is often not the case in hearing aids. It fails to account for other delays in the hearing aid which can contribute from 2 - 5 ms to the group delay (Kates 2005). "A manufacturer who only quotes the digital processing delay is misrepresenting the actual delay of the product." (Kates 2005)

The processing delay depends on the sampling rate and the algorithm being implemented. In general, the better the frequency resolution, the greater the group delay (Kates 2005). Henrickson (2004) reported processing delays between 1 and 11 ms for current digital instruments. Dillon reported group delays between 3 and 11 ms for 5 hearing aids and this group delay was reasonably constant with frequency. There is no question that delay occurs in digital hearing aids and there is no question that we can measure it and specify it. The critical question is "Do we need to?" Does digital processing delay provide information necessary for the safe and effective use of a digital hearing aid?

The clinical evidence that exists on this subject, from a number of studies, indicates that digital processing delays of the sort employed in current hearing aids have no impact on user performance or acceptance. A summary of 14 recent papers or presentations relating to the effects of time delay in hearing aids is attached. They may be grouped into two categories - those that speculate about the effects of time delay and those that attempt to measure its effect for normal or hearing impaired listeners.

The Speculations

Frye (2000) speculated that the fitting of a digital hearing aid to only one ear or with a non-occluding earmold would create "artificial echoes." Noting that "echoes and reverberation in a room adversely affect intelligibility," he concludes that "the same can be said of artificial echoes generated by delay in a hearing instrument." No proof is offered in support of these speculations. In this regard, it should be noted that delay through the processed path creates a single delayed version of the direct signal while room echoes consist of multiple delayed versions of the direct signal. Room echoes involve delays in excess of 10 milliseconds and early reflections in a room generally create a coloration of the sound, not an echo (Allen in Acoustical Factors Affecting Hearing Aid Performance, Studebaker & Hockberg, Ed. 2nd Ed, 1993, Ch 1). Stone & Moore (2003) speculate that, if a subject used a vented earmold, the resulting comb filtering would affect the timbre of sound but do not mention echo.

Schweitzer (2002) speculated that processing delay could cause problems in vented fittings for sloping losses, unilateral losses, drummers, conductive/mixed loss cases and cases where perception of frequency-modulated speech components is important. He provides an anecdotal report of a drummer who preferred an aid with a 1 ms delay over one with a 10 ms delay. It should be noted that the literature on delayed auditory feedback and drummers indicates that time delays less than about 40 ms have no effect on drummers' ability to maintain tempo (Dahl & Bresin, Proceedings of the COST G-6 Conference on Digital Audio Effects (DAFX-01), Limerick, Ireland, December 6-8, 2001).

Henrickson (2004) notes that "temporal cues are important for speech processing" and "temporal distortion affects perception by the hearing-impaired using amplification." He cites psychoacoustic evidence showing that ITDs of 0.1 - 0.7 ms disrupt localization while larger ITDs disrupt lateralization and speculates that asymmetric delays between ears may cause "clinical problems." He reports delays in analog aids of 0.3 - 0.7 ms with delays in digital aids between 1 and 11 ms. No evidence is offered to support the suggestion that the delays in digital aids cause, localization, speech processing or perception problems for hearing-impaired users. It should be noted that the delays reported for analog hearing aids are sufficient to cause complete disruption of localization. How can delays in digital aids make it worse?

Flamme (2002) expresses concern that delay time might not be bilaterally matched, either because of a unilateral fitting or mismatched delays in a bilateral fitting. However, citing 3 references, he states that, if mismatch in delay times does not change often, people adapt within a period of hours or days.

The Clinical Evidence

Stone and Moore published 4 papers between 1999 and 2005 in which they systematically examined the effect of processing delay on the disturbance effect listening to one's own voice, the ability to discriminate consonants in VCV nonsense syllables in background noise and on speech production. The general conclusions for hearing-impaired subjects were that:

1) For constant delay across frequency, the delay that is likely to be acceptable when speaking is around 23 ms for very mild losses, about 15 ms for losses around 35 dB and about 32 ms for losses around 55 dB. There was no effect on speech production rates.

2) For delay that decreases with frequency, low-frequency delays of 15 ms or more had a small but statistically-significant deleterious effect on the ability to identify VCV nonsense syllables while subjective ratings of the disturbance in listening to one's own voice indicated that delays of 9 ms or more had a significant deleterious effect. There was no significant effect of across-frequency delay on speech production rates, for across-frequency delays up to 24 ms.

3) For delays exceeding about 20 ms, listening to one's own voice, the associated percept is primarily of an echo. This echo is different from the echoes heard in everyday life. For delays less than about 10 ms, the associated percept is more of a subtle change in the timbre of the sound.

4) There appears to be acclimatization to the effects of the delay on the time scale of about 1 hour.

These studies involved occluding fittings and did not address the issue of unilateral or vented fittings.

Agnew and Thornton (2002) reported a mean JND of 4.08 ms and a mean objectionable delay of 14.32 ms for a normal-hearing group of hearing aid engineers listening to their own voice in an AB comparison. Fittings had a small slit leak.

Dillon et al (2003) reported on a study using both normal and impaired subjects listening to music, speech and their own voice through 5 digital hearing aids with processing delays ranging from 1.2 - 10 ms . Fittings were vented. The conclusions were that there was no overall significant differences among the devices and for impaired listeners, there was no significant correlation between device preference and processing delay.

Arehart and Kates (2004) reported on a study using both normal and hearing-impaired subjects listening monaurally through headphones to clicks, vowels and a sentence delayed by 2 - 25 ms in the low frequencies and decreasing to 4 ms at 4 kHz. Determined JND for normals to be about 4 - 10 ms and for hearing impaired to be about 5 - 25 ms depending on the stimulus. This is similar to Stone & Moore (2003) for frequency-dependent delay.

Discussion:

Given that there is a trade-off between group delay and frequency resolution, quantization noise and processing complexity (Kates 2005), any decision to select a hearing aid based on its group delay needs to be made on solid clinical evidence. Contrary to speculation by a few individuals, available clinical evidence indicates that the processing or group delay present in current digital hearing aids has no objectionable effects for hearing impaired listeners. It would be unfortunate if hearing aid wearers were denied the benefits of greater frequency resolution or smarter processing because clinicians were led to believe that processing delays of 2 ms were somehow better than processing delays of 10 ms. This is already happening! In a recent publication, Chung (2004) states that "In clinical practice, clinicians need to test the processing delay of digital hearing aids and choose hearing aids with a balance between the signal processing complexity and the amount of processing delay." There is no indication of how this balance is to be arrived at and the clinical evidence in the references cited indicate that no such balancing act is even necessary.

Conclusion:

Based on current knowledge, digital processing or group delay would appear to be irrelevant information when it comes to the selection and fitting of digital hearing aids. At a time when the field of audiology is attempting to embrace evidence-based practices, it appears premature and counter-productive to encourage the provision and use of technical data that the best available evidence indicates are irrelevant. To do so only increases the probability that the placebo effect will become part of the selection and fitting process.

Papers and Presentations on Group Delay

Publication	Date	Author(s)	Subjects	Comments and Conclusions
Tolerable Hearing-Aid Delays: I. Estimation of Limits Imposed by the Auditory Path Alone Using Simulated Hearing Losses Ear & Hearing	June 1999	Stone & Moore	10 male; 10 female; normal-hearing.	Subjects listened through 4 simulated hearing losses (with recruitment) to recordings made in the (mostly) occluded ear canal of talkers, mixed with signals through a simulated 4 channel WDRC fast (Ta=Tr=7ms) compression hearing aid. Simulations were very detailed. Minimum delay was 6 ms. CONCLUSIONS: "disturbing effects become significant for delays exceeding 20 ms."
Just Noticeable and Objectionable Group Delays in Digital Hearing Aids J. Am. Acad. Audiol.	June 2000	Agnew & Thornton	18 male hearing aid engineers; normal-hearing	Subjects wore an ITE hearing aid module with a small slit leak. Subjects listened to their own voice. Hearing aids had a flat, broad response; gain set for comfortable level. Subjects could instantly switch between delay and no delay for comparison. Authors expected lower acceptable delays with this method and these subjects than with hearing impaired subjects without a reference. CONCLUSIONS: The mean just noticeable delay was 4.08 ms and the mean objectionable delay was 14.32 ms.
Tolerable Hearing-Aid Delays: II. Estimation of Limits Imposed During Speech Production Ear & Hearing	Aug 2002	Stone & Moore	16 male; 16 female; normal-hearing.	Subjects listened to their own voice using wearable digital processing and head-level microphones in two acoustic environments. Receivers coupled with foam eartips. CONCLUSIONS: "Hearing aid designers who have an algorithm with a long processing delay that provides demonstrable benefit should not be afraid of using delays up to 15 msec: longer delays of up to 30 msec would require that the aid user is forewarned and counseled as to the potential side effects. For similar levels of subjective disturbance, the processing delay can be about 4 msec longer in a reverberant acoustic environment than in a near anechoic room."
Tolerable Hearing-Aid Delays: III .Effects on Speech Production and Perception of Across-Frequency Variation in Delay Ear & Hearing	April 2003	Stone & Moore	5 male; 5 female; hearing impaired	Subjects fitted bilaterally with fully-occluding 3 channel aids operating linearly. Tested for ability to discriminate consonants in VCV nonsense syllables in a background of noise at S/N of approximately 0 dB (varied with subject). Delay of 2.5 - 26.5 ms below 1.4 kHz and constant 2.5 ms above 2.2. kHz. CONCLUSION: "Across-frequency delays of 15 msec or more had a significant deleterious effect on the ability to identify VCV nonsense syllables, although the effects were relatively small; the percent correct decreased from 72.6 to 68.1 as the delay increased from 0 to 24 msec." Subjects rated disturbance of own voice and rate of speech production was measured. CONCLUSIONS: "subjective ratings of the disturbance indicated that delays of 9 msec or more had a significant deleterious effect...There was no significant effect of across-frequency delay on speech production rates, for across-frequency delays up to 24 msec."
Tolerable Hearing-Aid Delays: IV. Effects on Subjective Disturbance During Speech Production by Hearing-Impaired Subjects Ear & Hearing	April 2005	Stone & Moore	12 male; 13 female; hearing impaired	Subjects fitted bilaterally with fully-occluding fast-acting 4 channel WDRC processors. Rated disturbance of own voice and rate of speech production was measured. Minimum available delay of 15 ms at all frequencies. CONCLUSIONS: The delay that is likely to be acceptable is around 23 ms for very mild losses, about 15 ms for losses around 35 dB and about 32 ms for losses around 55 dB. There was no effect on speech production rates. There appears to be acclimatization to the effects of the delay.

Sound quality comparisons of advanced hearing aids Hearing Journal	April 2003	Dillon, Keidser, O'Brien, Silberstein	10 normal; 10 hearing impaired	Subjects listened to male, female, male in noise, piano music, own voice and quiet through 5 commercial digital aids in a paired comparison procedure. Hearing aid outputs in 2cc coupler were equalized and presented binaurally through two ER3A insert phones via vented earmolds. Processing delay varied from 1.2 to 10 ms across aids. CONCLUSIONS: "A statistical analysis of the subjective preference scores revealed no overall significant differences among the devices." For impaired listeners, there was no significant correlation between preference and processing delay.
Detection thresholds for frequency-dependent group delay: Implications for digital hearing-aid design IHCON	2004?	Arehart & Kates	10 normal 11 SN loss	Delays varied between 2 and 25 ms below 1KHz. Dropped to about 1/3 by 2 kHz. Listened monaurally through headphones to clicks, vowels & sentence. AB comparison for JND. Large variability in detectable delay among listeners. Thresholds vary across stimuli and differ significantly between most conditions. Lowest for clicks, intermediate for sentences, greatest for steady state vowels. Normal JNDs about 4 - 10 ms. Hearing impaired JNDs about 5 - 25 ms
Localization and speech identification ability of hearing-impaired listeners using phase-preserving amplification Intl. Journal of Audiology	V41-4, Apr 2002	Drennan, Gatehouse, Howell, VanTassell, Lund	7 hearing impaired	"both (*phase-preserving and non-phase-preserving*) processing algorithms reduced the listener's ability to localize but, as the listeners acclimatized to the hearing aids, their ability to localize with the aids approached their ability to localize without the aids". "There were no significant differences observed in the subjective judgments of speech hearing and spatial abilities".
Testing Digital and Analog Hearing Instruments: Processing Time Delays and Phase Measurements Hearing Review	Oct. 2001	Frye	NONE	Speculates that "echo effects may be found" with digital hearing aids and, since "echoes in a room adversely affect intelligibility…the same can be said of artificial echoes generated by delay in a hearing instrument." Speculates that "a digital processing delay of more than a millisecond may be important in a case such as this." Speculates that "delay and phase problems could be part of the "invisible" differences between patient satisfaction and rejection of amplification" but offers no evidence.
Clinical Significance of Digital Delay AAA presentation. Philadelphia	Apr. 2002	Schweitzer	NONE	Speculates that processing delay could cause problems in vented fittings for sloping losses, unilateral losses, drummers, conductive/mixed loss cases and cases where perception of frequency-modulated speech components is important. Reports case where a digital aid with 10 - 12 ms delay in poorer ear made listening from aided side more difficult than no aid. Reports case where drummer preferred an aid with 1 - 2 ms delay over one with 10 ms delay. "Not sure" if delay was a factor in either case.
Processing Delay in Digital Aids: Perception and Measurement AAA presentation. Salt Lake City	Apr. 2004	Henrickson	NONE	Reports delays for analog aids of 0.3 - 0.7 ms. Reports delays for digital aids from 1 - 11 ms. Notes variation between manufacturers and between models within manufacturer. Notes that delay did not vary with gain settings and changed by as much as 0.1 to 0.2 ms from one program to another. Speculates that asymmetric delays or phase between ears may cause clinical problems but offers no evidence.

Localization, hearing impairment, and hearing aids Hearing Journal	June 2002	Flamme	NONE	"Regarding localization, the primary problem I can see with long delay times is destructive interference between the acoustic signal that passes by the hearing aid and the amplified sound. For some amounts of delay, the interference could move into frequency regions where the audibility of localization cues is reduced. A second concern is that delay time might not be bilaterally matched, either because of a unilateral fitting or because of mismatched delays for bilateral hearing aid users. However, if the mismatch in delay times does not change often, people adapt to new interaural time difference cues over a period of hours or days."
Challenges and Recent Developments in Hearing Aids: Part I Trends in Amplification	V8-3, 2004	Chung	NONE	"In clinical practice, clinicians need to test the processing delay of digital hearing aids and choose hearing aids with a balance between the signal processing complexity and the amount of processing delay". It is possible that the long processing delay of some commercial hearing aids with a high number of frequency channels can be rated as objectionable to some hearing aid users…
Principles of Digital Dynamic-Range Compression Trends in Amplification	V9-2, 2005	Kates	NONE	"even before the delay in the digital processing is considered, the other components of the hearing aid (microphone, receiver, A/D, D/A) and the acoustic interactions will contribute from 2 to almost 5 ms group delay. Any manufacturer who only quotes the digital processing delay is misrepresenting the actual delay of the product. " response peaks in an analog hearing aid will be associated with large amounts of group delay because of the steep slopes of the response on either side of the peak." "a low-pass or high-pass filter with a steep slope will have a greater group delay, especially in the region surrounding the cutoff frequency, than a filter having a shallow slope."