Literature Overview
- Digital Hearing Aids and Group Delay -

HADF, June 2017, P. Derleth
‘Delay in HI’ and the perceptual effects became a topic with the widespread market introduction of digital hearing aids in the 90’s

Digital HI typically have delay’s between 2-10ms (in special operation modes up to 13ms, e.g. exchange of audio-signals between L&R device)

Analog HI had typically around ~1ms of delay which did not trigger investigations about potentially negative perceptual effects

Research on DAF (delayed auditory feedback) in the 50’s focused on delay effects (30-300ms) on speech production

Research on the effects of delay between Audio and Visual information in the 80’s found negative effects in the delay range 40-160ms
Literature


- Continuous but sparse scientific publication activities…
Audio Processing Delay (measured in s) in a HI-System

- **Phase Delay:**
  for sinusoidal signals: phase delay $\sim$ phase change / frequency

- **Group/Envelope/Wave-packet Delay:**
  for signals consisting of multiple sinusoidal components:
  a) phase delay is identical for all components
     $\Rightarrow$ envelope preserved (shifted in time), i.e. ‘linear-phase-system’
     typical for ‘block-processing, i.e. FFT based HI’

  b) phase delay is frequency dependent
     $\Rightarrow$ envelope distortion
     typical for ‘sample-processing, i.e. TD based HI, filter-bank’
Delay in HI – Envelope Figures

\[ \Delta t \sim \Delta \theta / f \]

\[ \text{env. distort.} \sim d\theta / df \]
Delay in HI - System View

Mech. -> Elec. Micophone 0.1ms

TD Processing 1-2ms

Elec. -> Mech Receiver 0.2ms

Mech. -> Elec. Micophone 0.1ms

A -> D Conversion 0.25ms

FFT Processing 5-7ms

D -> A Conversion 0.25ms

TD Processing 2-5ms

Elec. -> Mech Receiver 0.2ms
Delay in HI - System View Binaural Audio

Mech. -> Elec. Micophone 0.1ms

A -> D Conversion 0.25ms

wait for contralateral Signal ~5ms

FFT Processing 5-7ms

TD Processing 2-5ms

D -> A Conversion 0.25ms

Elec. -> Mech Receiver 0.2ms
Delay in HI – Multi Audio Path

External sound sources:
- direct air acoustic path
- delayed (HI processed) acoustic path

Own voice:
- bone acoustic path
- direct air acoustic path
- delayed (HI processed) acoustic path

Relative delay and perceptual relevant contribution of each path?

Agnew & Thornton 2000
Strength of comb-filter effect determined by:
- delay (ripple density ~ 1 / Δt)
- ratio of direct and delayed signal (0dB: max. ripple depth, -inf. .. +6dB)
Delay in HI – Comb-Filter

**Figure 1.** Comb filter effect measured on HATS. The instruments were set at 10 dB flat insertion gain (occluded) and the fitting to the ear canal was an open dome. The effect of increasing delay on the total output can be seen from the top and down.

**Bramslove (2010) direct and delayed path, comb-filter effect for external source**
The comb-filter-effect is determined by:
- IG range (-25..+25dB) and variablity (linear gain vs. WDRC)
- Ripple density (i.e. delay) and frequency region of the ripples

The perceptual relevant comb-filter-effect is in addition determined by
- AC&BC part of the hearing loss (i.e. audibility of the comb-filter)
- Residual frequency resolution (comb-filter resolved/unresolved)

For openly fitted HI with delay in the range 5-10ms and IG in the range of 0-20dB => frequency region ~800-2000Hz
Delay in HI – Own Voice

For own voice signals:
- additional bone conduction path with approx. -0.7ms delay and frequency and time dependent (jaw position) contribution to comb-filter

- It is to be expected that acclimatization-effects come into play for altered own voice signals
Delay in HI – Perceptual Effects of Delay

Best perceivable in no/low reverberation conditions by NH listeners
1-15ms : coloration of sound (hollow sound)
>20ms : echo-like perception

Most sensitive signal is own voice and wide-band noise-like signals

Less perceivable in reverberant conditions
and with increasing hearing loss
Subjective acceptance, 7-point scale

20 NH with 4 simulated HL & appropriate HI signal-processing (4 channel WDRC)

Occluded fitting
External sound (voice) 65dB
Delay: 6, 13, 20, 30, 40 ms, constant across frequency
IG 0-27dB
Lab experiment

=> for the lower delays all subjective ratings <3 i.e. ‘just acceptable’
Agnew & Thornton – 2000

- No delay / delay direct comparison (2 values, noticeable and tolerable)
- Occluded fitting + slit vent
- Own voice
- Flat IG, but unknown/individually selected value
- 18NH ‘expert listeners’
- Constant delay across frequency was investigated
- Lab experiment

- => detectable delay 3-5ms
- => acceptable delay below 10ms
Subjective rating, word production rates, speech level, f0 and f0 variation
- 32 SH (various losses)
- Occluded fitting
- IG ~0dB
- Linear processing & 3 channel WDRC
- Own voice
- Dry and live acoustics
- Delay: 7, 18, 30, 43ms constant across frequency
- Lab experiment

=> delay’s lower than 20-30ms seem acceptable
Delay only <2k (see figure) untypical for ‘open’ fitting as of today
- 800-2000Hz transition region for delay
- 10 SH (moderate loss),
- IG according NAL, i.e. 10-20dB effective IG range 800-5800Hz
- Subjective rating, VCV identification speech production

=> delay variation across 0.8-2kHz of 9-15ms led to poor speech identification and subjective disturbance
10NH & 10SH
- Non-occluding
- IG 10dB constant & flat (audibility was given for all signals and losses)
- direct sound <800Hz, delay: 2, 4, 10 ms, 800Hz – ~7kHz
- Own voice, external speech and music
- Lab experiment

=> delays up to 10ms acceptable for NH and SH
=> shorter delays are preferable (at least for NH)
Subjective rating (7-point scale) & speech production rates
4 channel WDRC
Delay 13, 21, 30, 40 ms, constant across frequency
25 SH with different losses
IG determined by CAMEQ => -2 .. 20 dB (loss dependent)
RT60 50ms
Occluded fitting
Lab experiment

=> ‘just acceptable’ ratings (3 and better) for the shorter delays
- Subjective disturbance scale 1-7
- NH (Simulated SH)
- External source
- ‘open’ fitting
- Linear gain
- Delay constant across frequency (2, 4, 7, 12ms)
- IG constant

=> the combination of IG and delay influences disturbance level
- Delay constant across frequency (2, 4, 7, 12ms)
- IG ~0dB in the transition region around 1k or 2k and constant well above transition region

=> the variation of IG and delay influences disturbance level
Subjevtive preference in A/B comparison of sound quality
18NH & 18SH (mild losses)
Open fitting (& delayed path high-pass filtered 500, 1k, 2.2kHz)
External sounds (speech, music, natural noise-like sounds) and own voice
IG 0dB..15dB
Delay: 2, 5, 10ms

=> delays of up to 10ms acceptable for SH listeners with mild loss
=> increasing high-pass filtering of delayed sound prefered for NH
Figure 8. Main effect of delay for NH listeners (grey) and HI listeners (dotted). Geometric means are shown with associated 95% confidence intervals. There are no significant effects of delay.

Figure 9. Main effect of high-pass cutoff for NH listeners (grey) and HI listeners (dotted). Geometric means are shown with associated 95% confidence intervals. Note different y-axis for ‘waves’.
Only a few studies used openly fitted devices with direct sound dominating in the low frequency region.

The range of delays tested for the openly fitted conditions is small.

The variation of IG (WDRC) was not directly monitored, i.e. the amount/variation of comb-filter is not known in detail.

Some experiments were done with simulated SH, i.e. really a good representation of a hearing impairment?

All lab experiments, i.e. no field trial with the chance for acclimatization.

=> the only long-term filed trial we do is the products in the market…