Audibility of linear distortion in loudspeakers

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Outline

- Introduction: what can we hear and what should we measure?
- Audibility of resonances in loudspeakers
- Audibility of phase mismatch

Introduction

- Floyd Toole: “Frequency response is the single most important aspect of the performance of any audio device.”
- In the case of loudspeakers, *what* frequency response?
  - On-axis, off-axis, both?
  - Magnitude only, or does phase matter?
- What are the measurements that are the most useful to predict what we can hear?

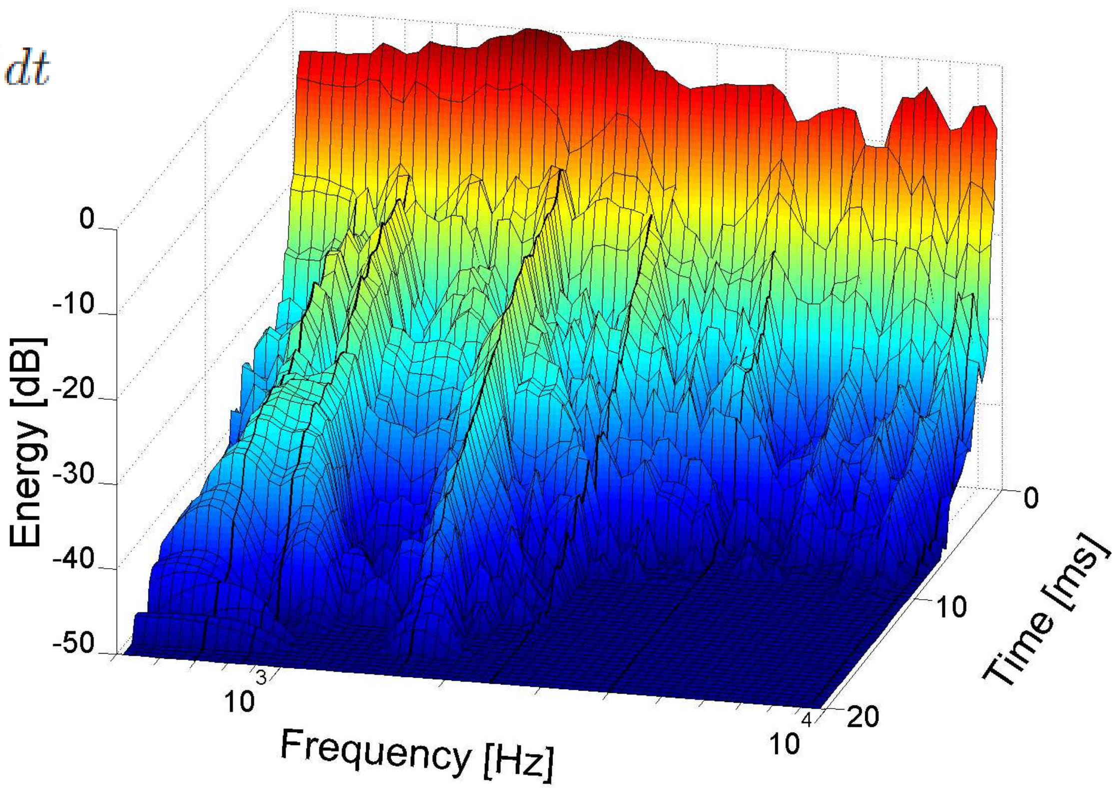
Introduction (cont'd)

- Factors affecting loudspeaker response
  - Transducer bandwidth
  - Diffraction
  - Directivity pattern
  - Cross-over
  - Resonances
  - Non-linear distortion

Time/frequency analysis

- Cumulative spectral decay (CSD)

$$CSD(\tau, f) = \int_{\tau}^{\infty} h(t) e^{-j2\pi f t} dt$$

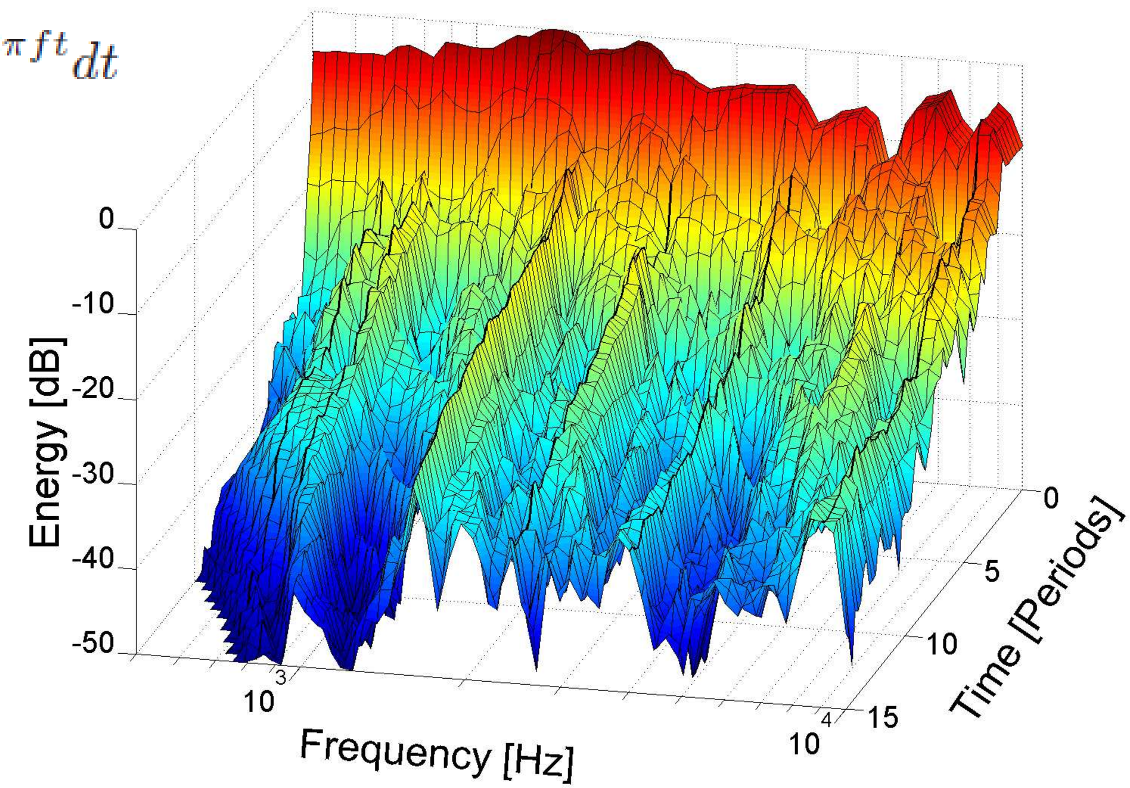


Dyreby & Choisel, 2007

Time/frequency analysis

- Period-based cumulative spectral decay (PCDS)

$$PCSD(p,f) = \int_{\frac{p}{f}}^{\infty} h(t)e^{-j2\pi ft}dt$$



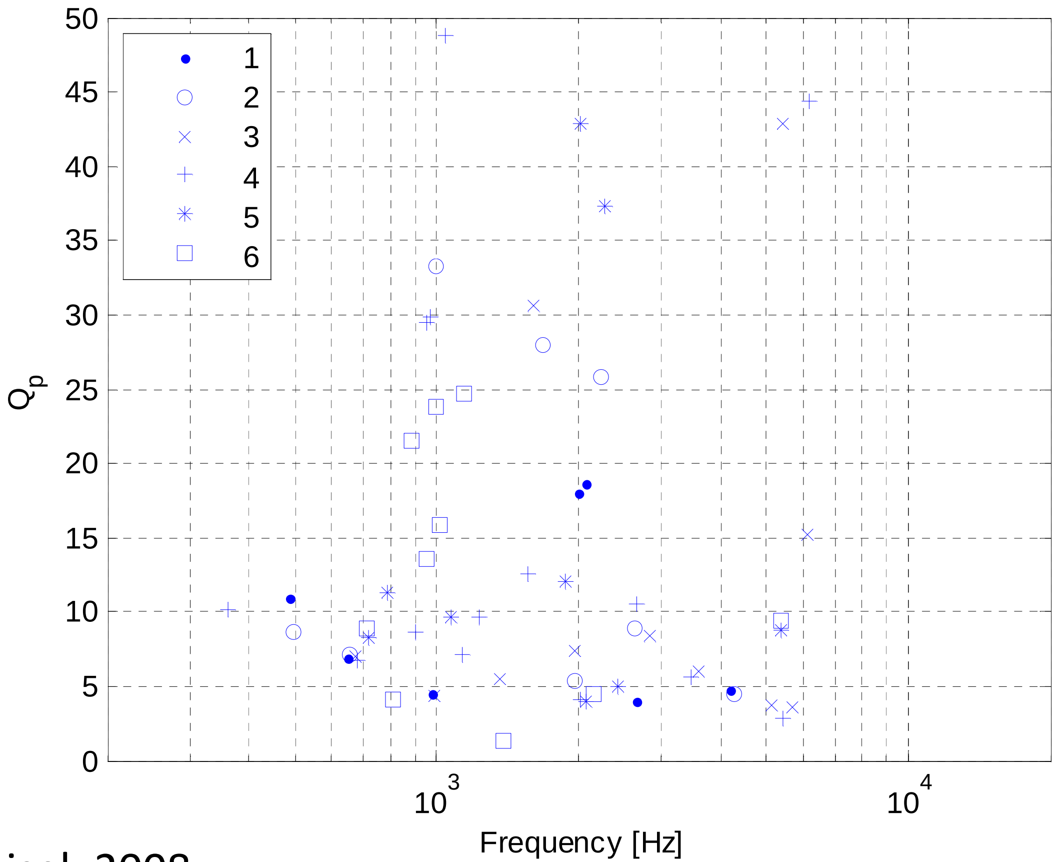
Dyreby & Choisel, 2007

Audibility of resonances

- Summary of literature
  - Peaks more audible than dips
  - High Q factor less audible than low Q
  - High-frequency resonances less audible than low-frequency ones
  - Stimulus type
  - Test environment

Listening test

- Selection of “typical” resonances



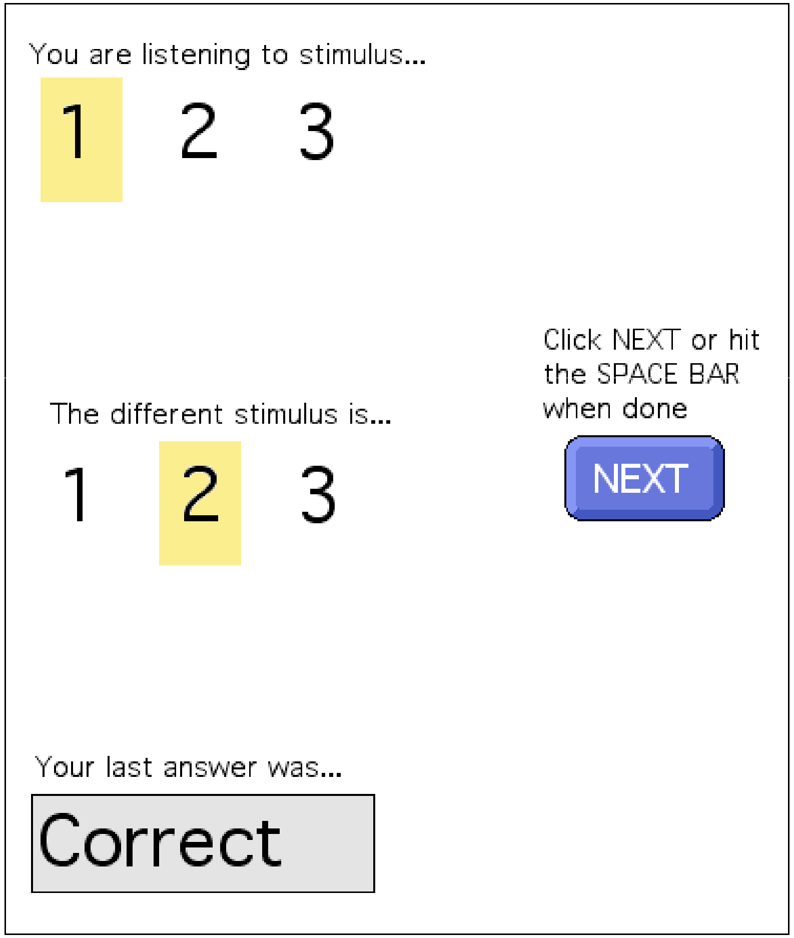
Uprichard & Choisel, 2008

Listening test – factors

- Resonances
  - Low freq. (700-1000 Hz)
  - High freq. (6-8 kHz)
  - Low Q (8)
  - High Q (30)
- Programme material: pop/classical
- 3 actoustic environments
  - Headphones
  - Listening room
  - Car
- 12 subjects

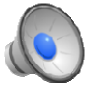
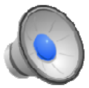
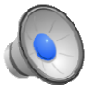
Uprichard & Choisel, 2008

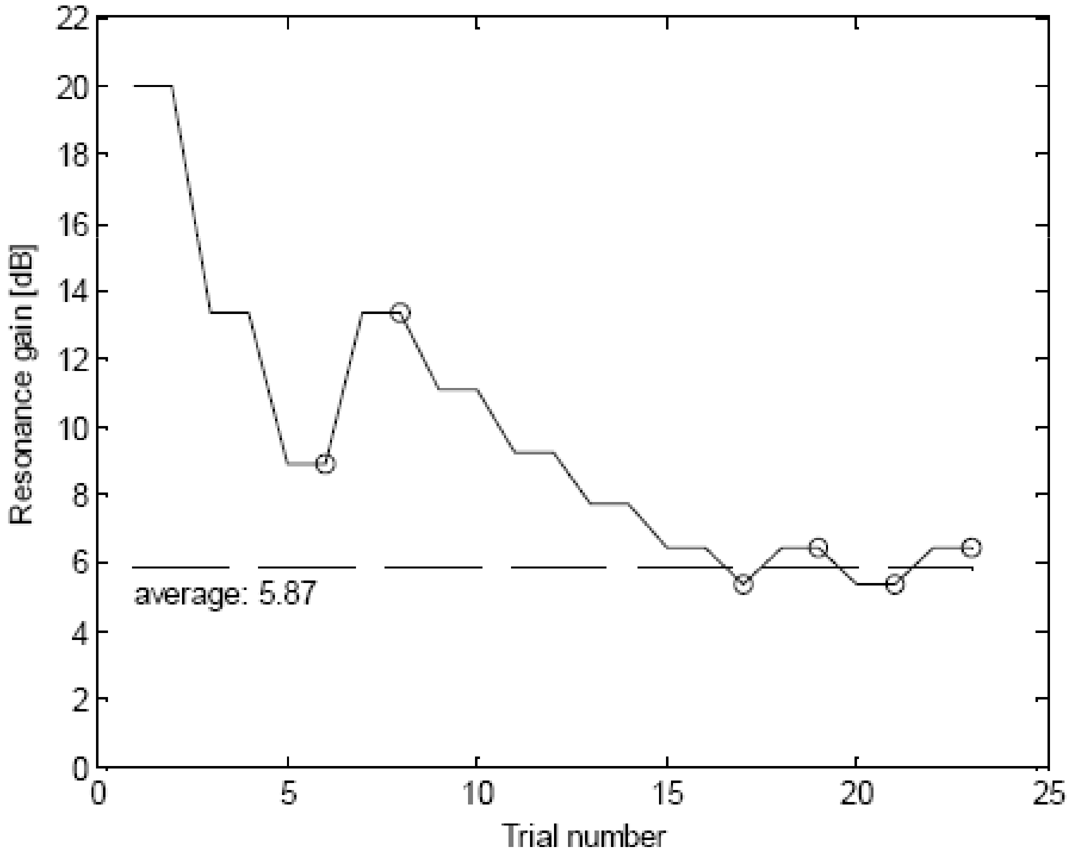
Listening test – GUI



Listening test – procedure

- 3-alternative forced choice

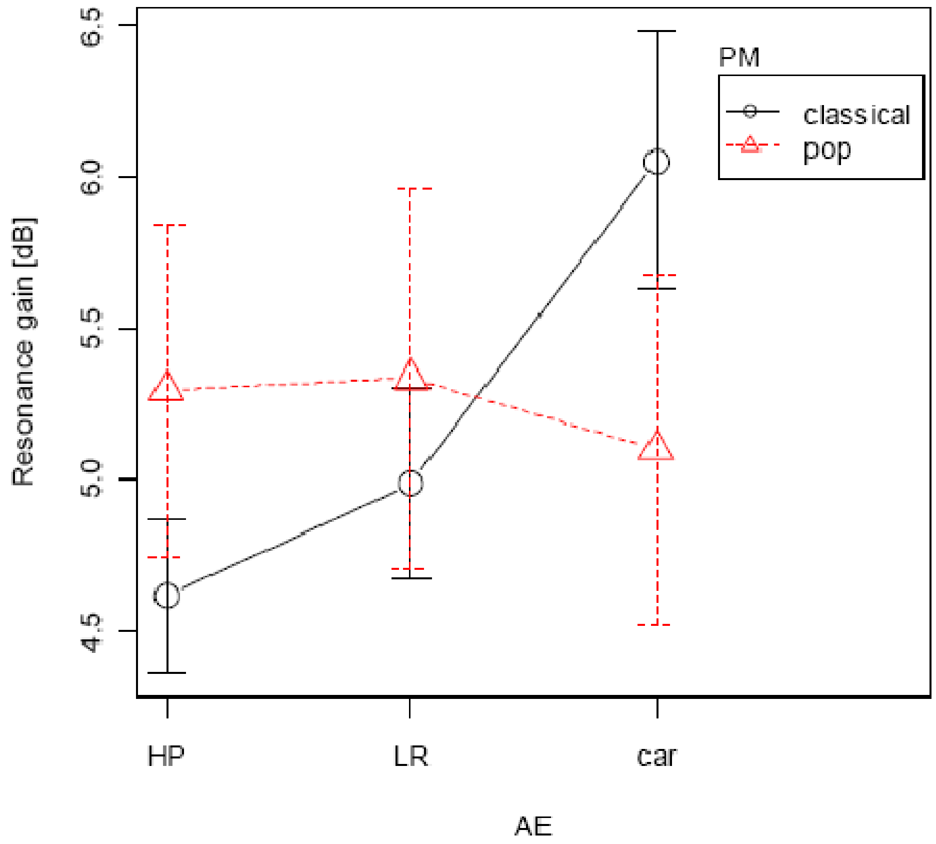






Uprichard & Choisel, 2008

Listening test – results

- Resonances are more audible at a lower Q
- Frequency has a small effect
- Acoustic Environment has a significant effect for Classical music



Uprichard & Choisel, 2008

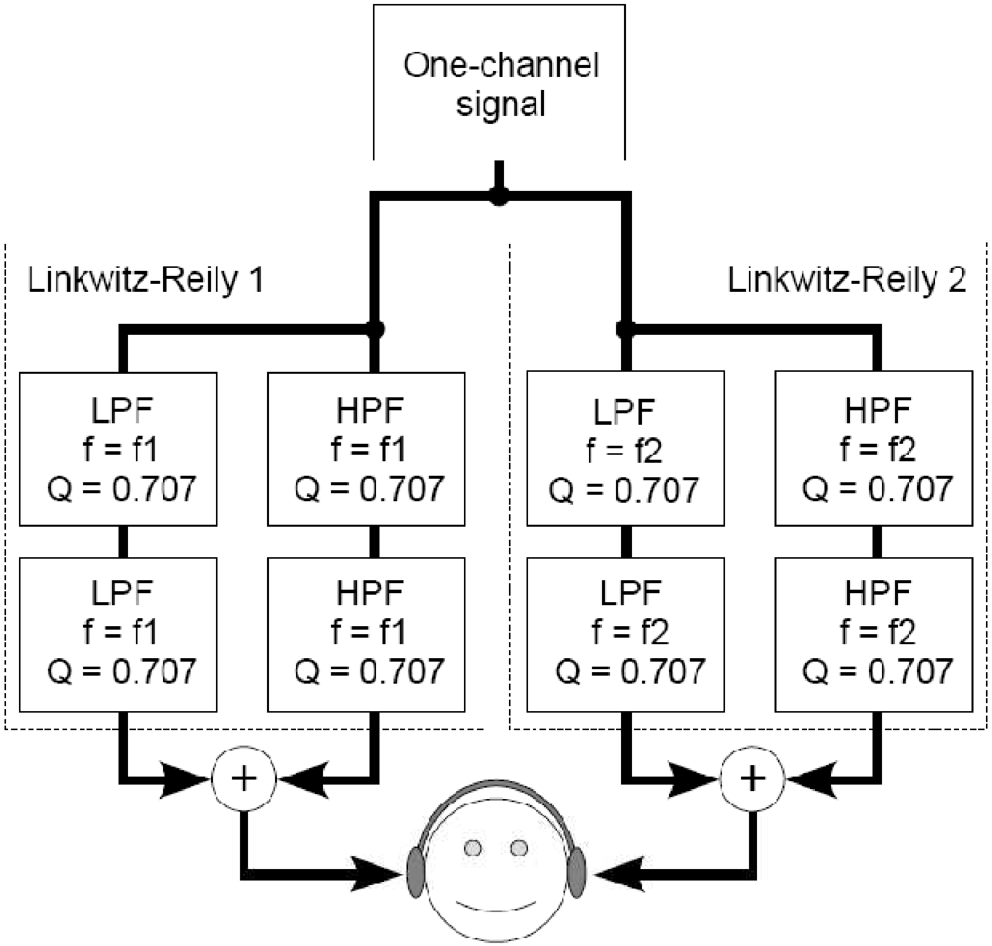
Audibility of phase distortion

- Ohm (1843): The relative phase of the harmonic components has no audible effect.
- Hartmann: In general the relative phase between two signal components should be irrelevant if the two components are separated by more than a critical bandwidth.
- Blauert and Laws (1978): Group delay thresholds between 1 and 3.2 ms.
- Lipshitz et al. (1982): Even quite small midrange phase nonlinearities can be audible on suitably chosen signals.

Audibility of phase distortion

- Toole: within very generous tolerances, humans are insensitive to phase shifts. Under carefully contrived circumstances, special signals auditioned in anechoic conditions, or through headphones, people have heard slight differences. […] When auditioned in real rooms, these differences disappear.
- Summary
  - Absolute phase distortion difficult to hear in realistic conditions
  - BUT relative phase distortion (between channels) may be more audible!

Phase mismatch



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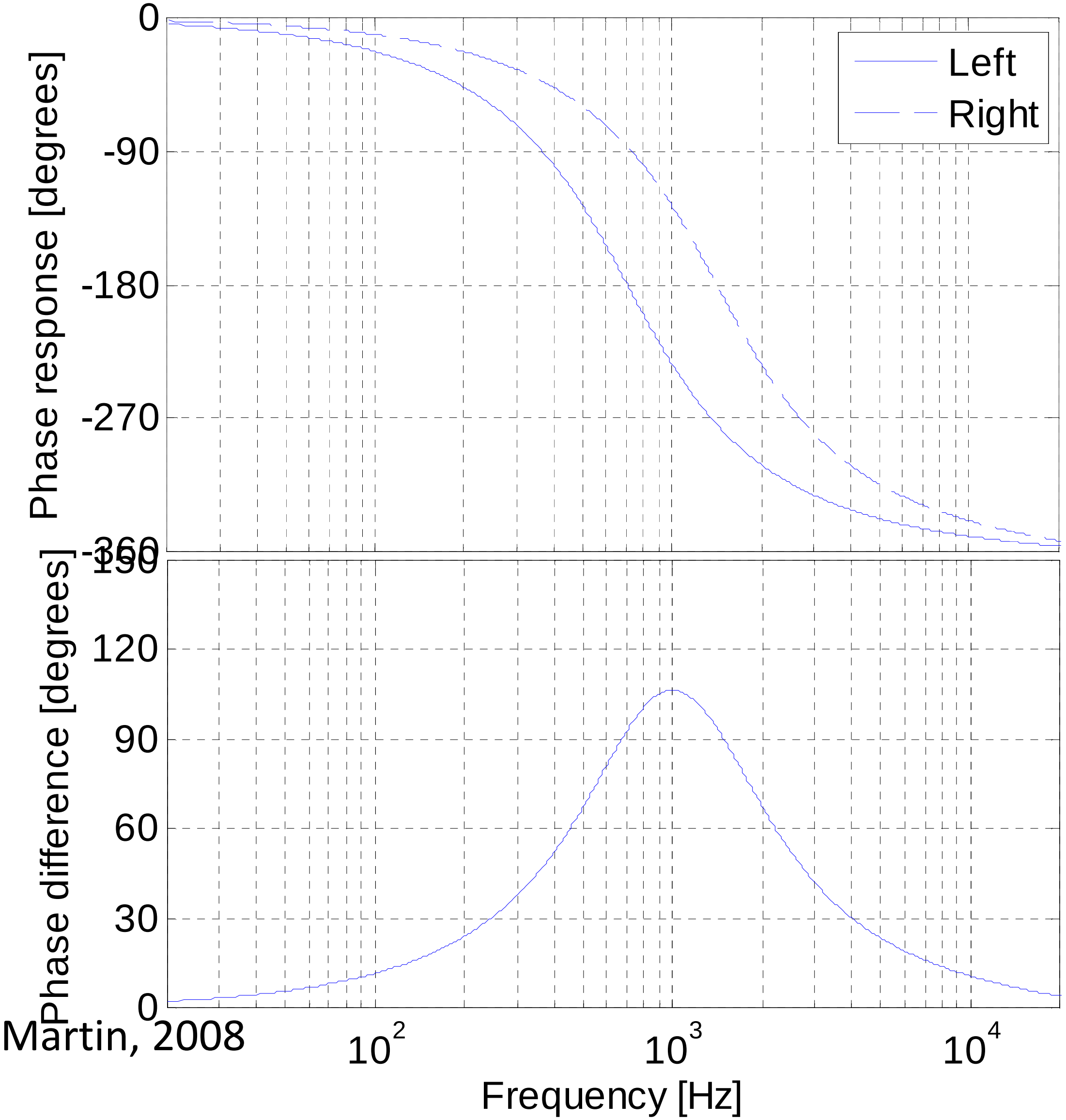
Phase mismatch



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Listening test

- 8 subjects
- Procedure: 3-AFC
- Broad-band pink noise, or
- Octave-band filtered pink noise (3rd order)
  - 8 bands centred at 63, 125 … 8000 Hz
  - Same centre frequency as phase mismatch
- 2 playback conditions:
  - Headphones
  - Loudspeakers

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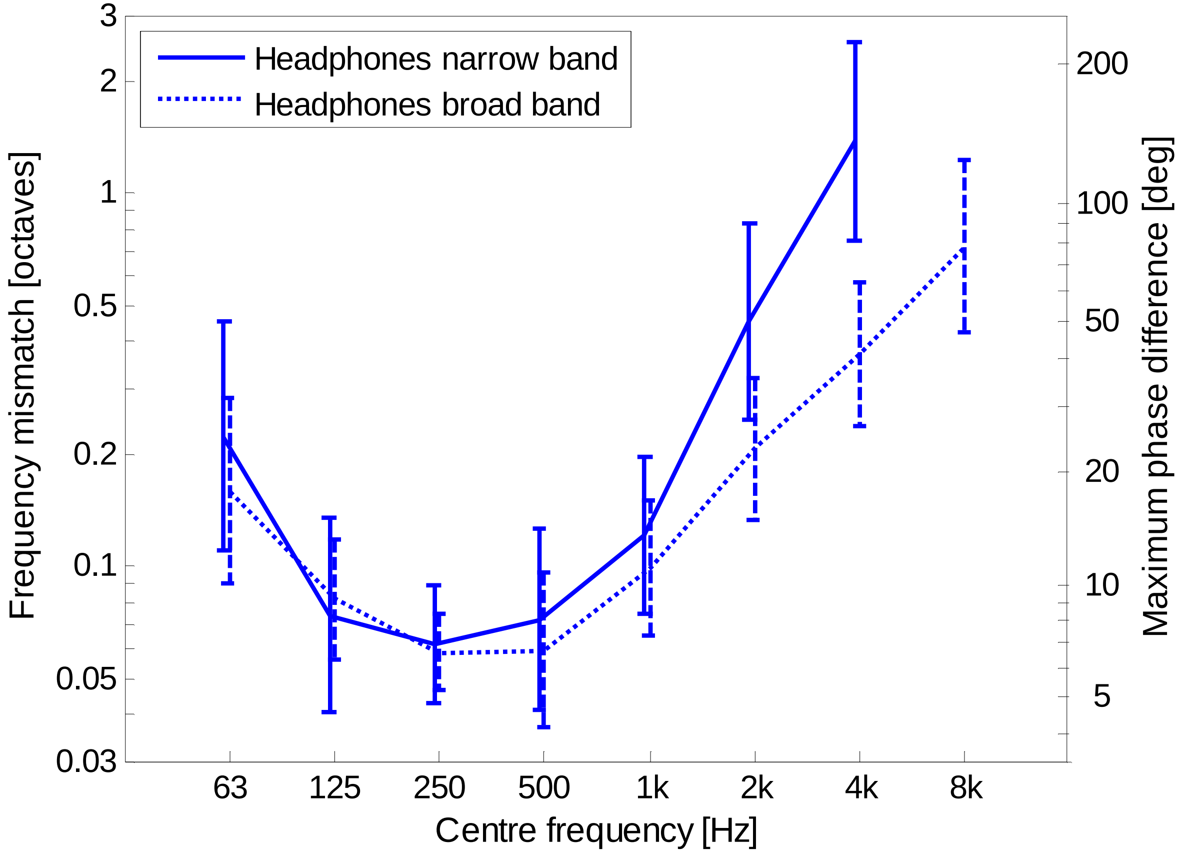
Part 2 – Results

- Narrow-band vs. broadband



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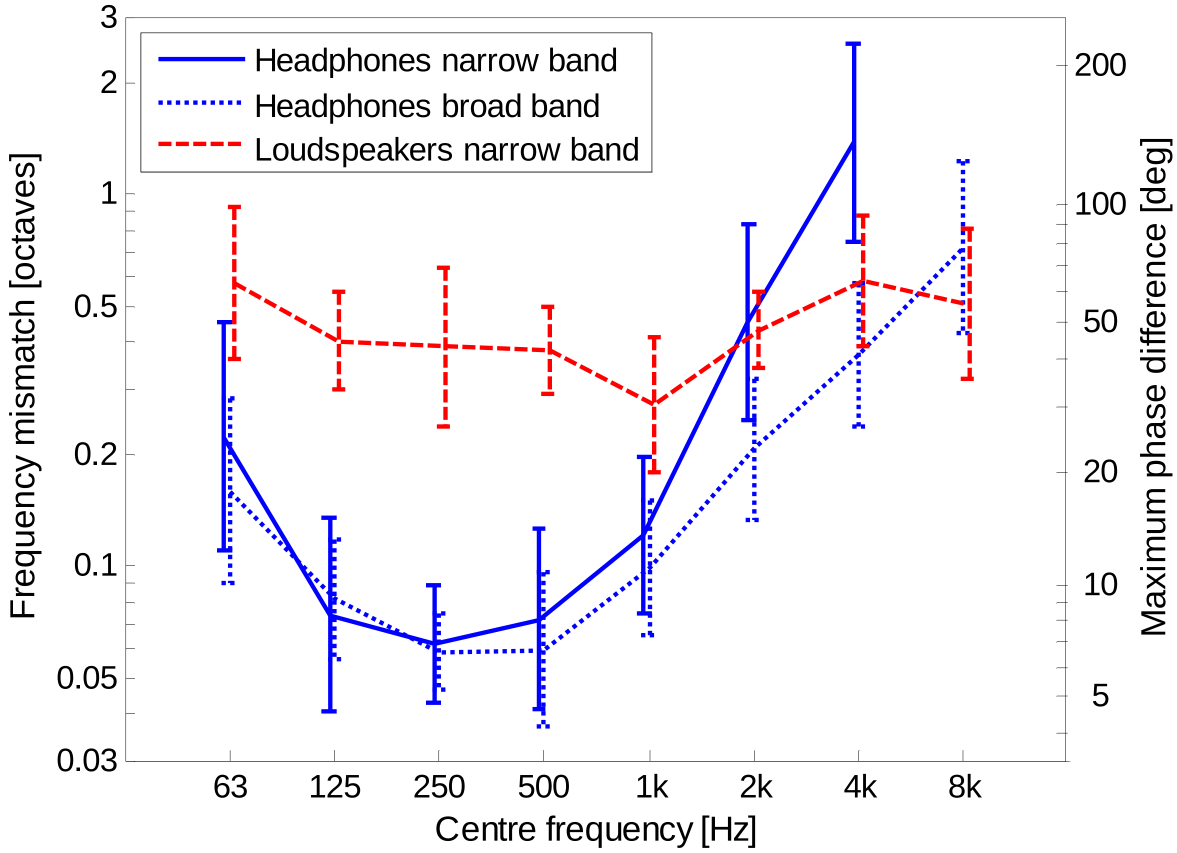
Part 2 – Results

- Narrow-band vs. broadband



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Discussion

- Narrow-band vs. broad-band
  - Higher thresholds for narrow-band noise at high freq. → cues at lower frequencies were used in Part 1
  - Comparable thresholds at low frequencies → refutes the hypothesis of informational masking
  - Decrease in sensitivity might be level-dependent
- Loudspeakers vs. headphones
  - At low frequencies, higher thresholds for loudspeakers → spatial cues, lessened by cross-talk and room
  - At high frequencies, higher thresholds for headphones → interaural (spatial) cues cannot be used, timbral cues used

Implications

- Very low phase mismatch (7 deg) can be heard in headphones, this has implications on
  - Transducer matching
  - Headphone equalisation
- In loudspeakers placed in a listening room, the thresholds are much higher (50 deg. on average)
  - But very large differences between subjects – training increases sensitivity

Questions?