NTNU

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# Processing of low frequencies and infrasound: perceptual consequences

NTAF– Etterutdanningskurs 2024

Carlos Jurado 15/11/2024

# Outline

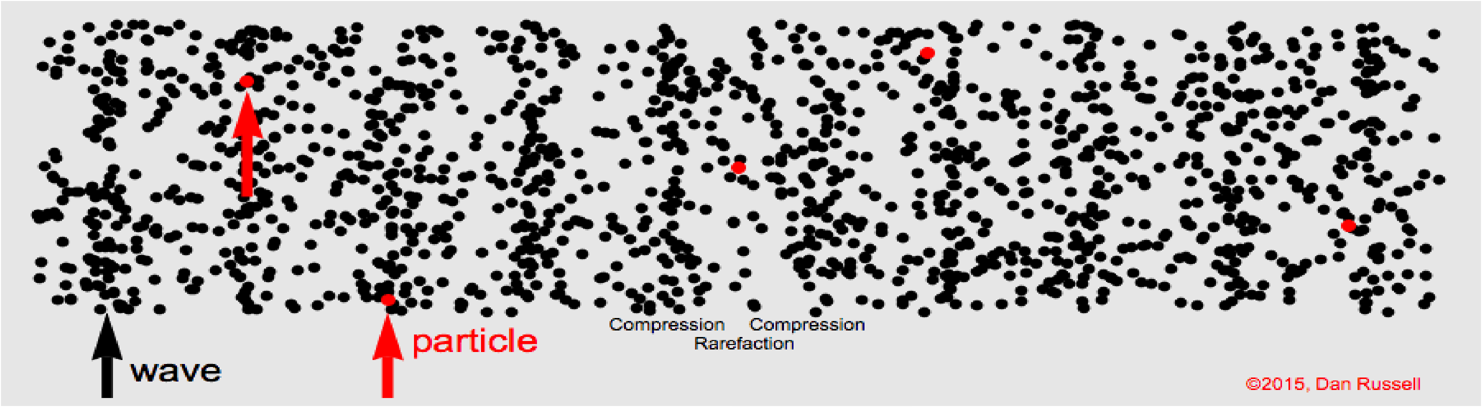
- **Low-frequencies and infrasound: introduction**
- **Background**
- Environmental low-frequency noise
- Hearing at low and infrasonic frequencies
- Generating ISLF sounds

Focused experiments

- **Low-frequency and infrasound hearing**
- Factors that affect ISLF hearing
- **Basilar membrane (BM) displacement and the IHC response shape LF-sensitivity (> 16 Hz)**
- **Infrasound sensitivity is only shaped by BM displacement (< 16 Hz)**
- **OHC generated cochlear potentials may be behind infrasound sensation**
- **OHC generated cochlear potentials may explain basal spread of infrasound suppression**
- **Extended spread of infrasound excitation can also explain acute loudness recruitment in this range**
- **Summary: DPOAE and infrasound suppression experiments reveal a new perceptual mechanism**
- **What about vestibular responses to infrasound and low frequencies?**

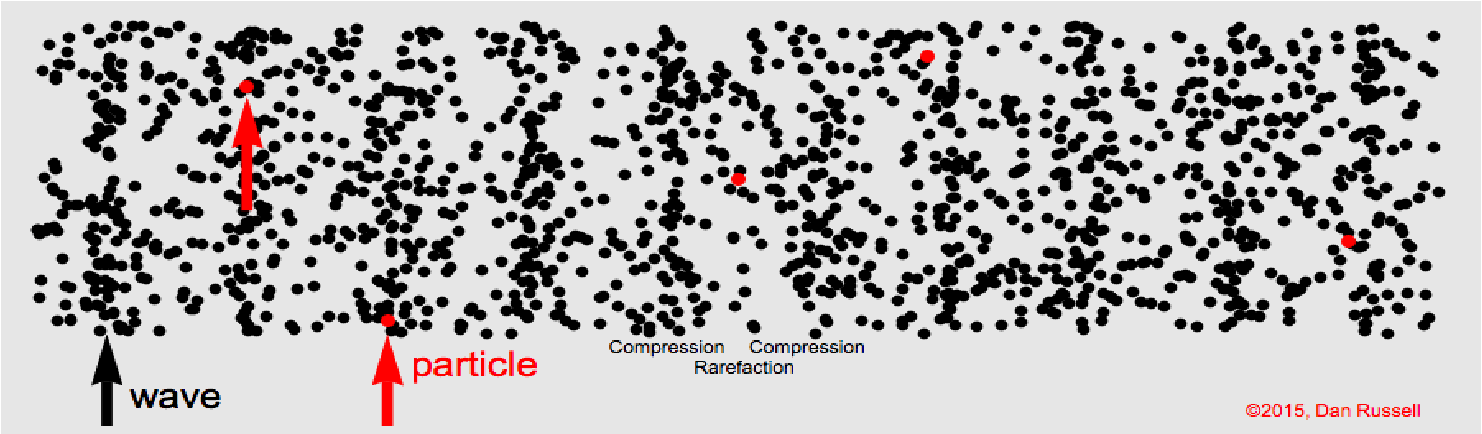
# Low-frequencies and infrasound: introduction

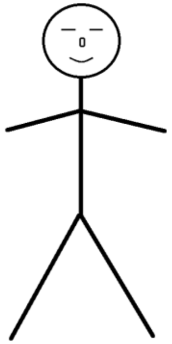
- Higher-frequency sound (e.g. most speech components)




https://www.acs.psu.edu/drussell

- Infrasound ($f$ < 20 Hz) and low-frequency sound (20 ≤ $f$ < 200 Hz) (ISLF; e.g. wind turbines)



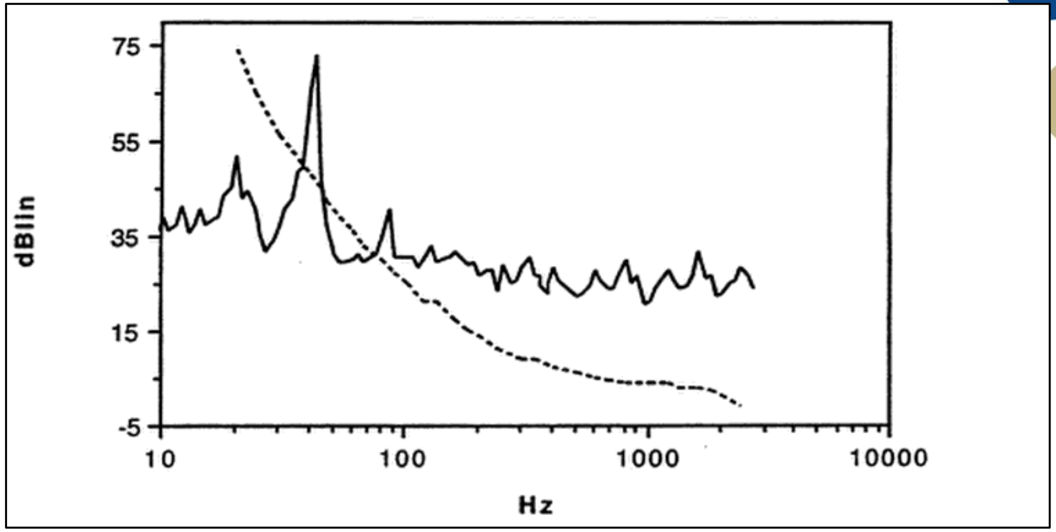



$c = \lambda f$

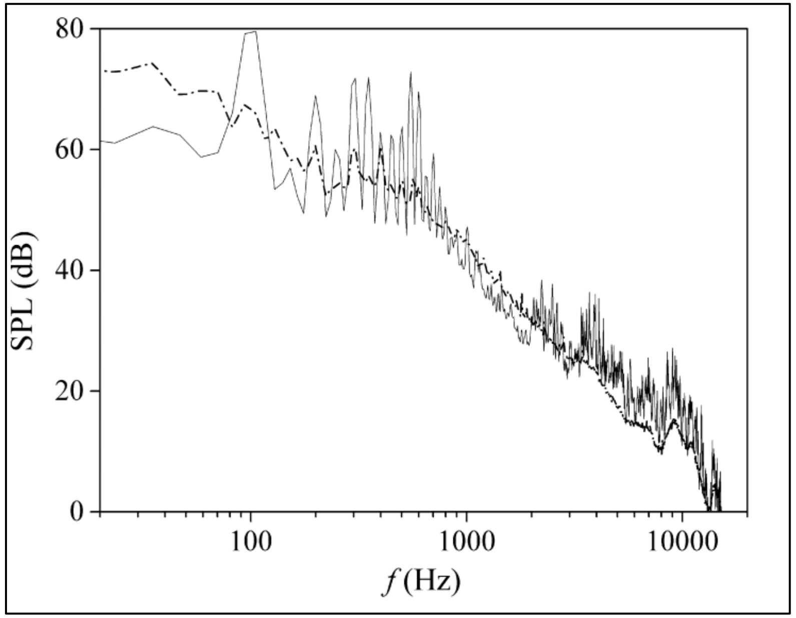
**ISLFs have a large wavelength** and are thus difficult to attenuate and can travel long distances. Further, at sufficient levels for audibility, they can easily produce annoyance

# Background: Environmental low-frequency noise

- Environmental sounds often contain significant energy in the low-frequency range ($f$ < 200 Hz). Effects of infrasound and low-frequency (ISLF) noise are of particular concern (Berglund et al, 1996; Leventhall, 2004; 2009)
- Sources of ISLF-noise, such as transformers, aircraft, and wind turbines are ever more common in industrialized societies
- ISLFs are difficult to attenuate by walls and passive structures
- Can travel long distances as are much less attenuated by the atmosphere than higher frequencies
- ISLF sound can rattle structures
- Can mask higher frequencies easily
- Once audible, ISLFs can easily produce sleep disturbance, annoyance, and also absolute threshold shifts for HFs
- Negative impact on the quality of life (Andersson and Lindvall, 1996; Leventhall, 2004; 2009; Drexl et al, 2014)
- Marked individual differences in perception. Mechanisms involved are of critical interest



Example ventilation noise spectrum (Andersson and Lindvall, 1996)



Example transformer noise spectrum (—220 kV, -500 kV; Di et al, 2015)

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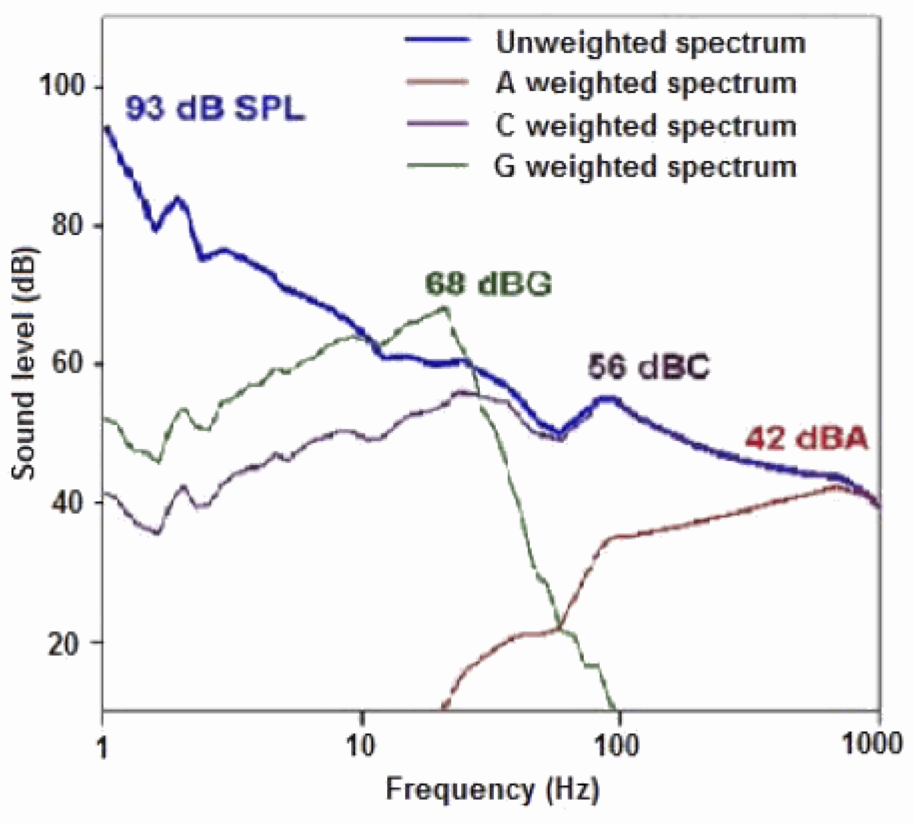



Wind turbine spectrum
with four different weightings

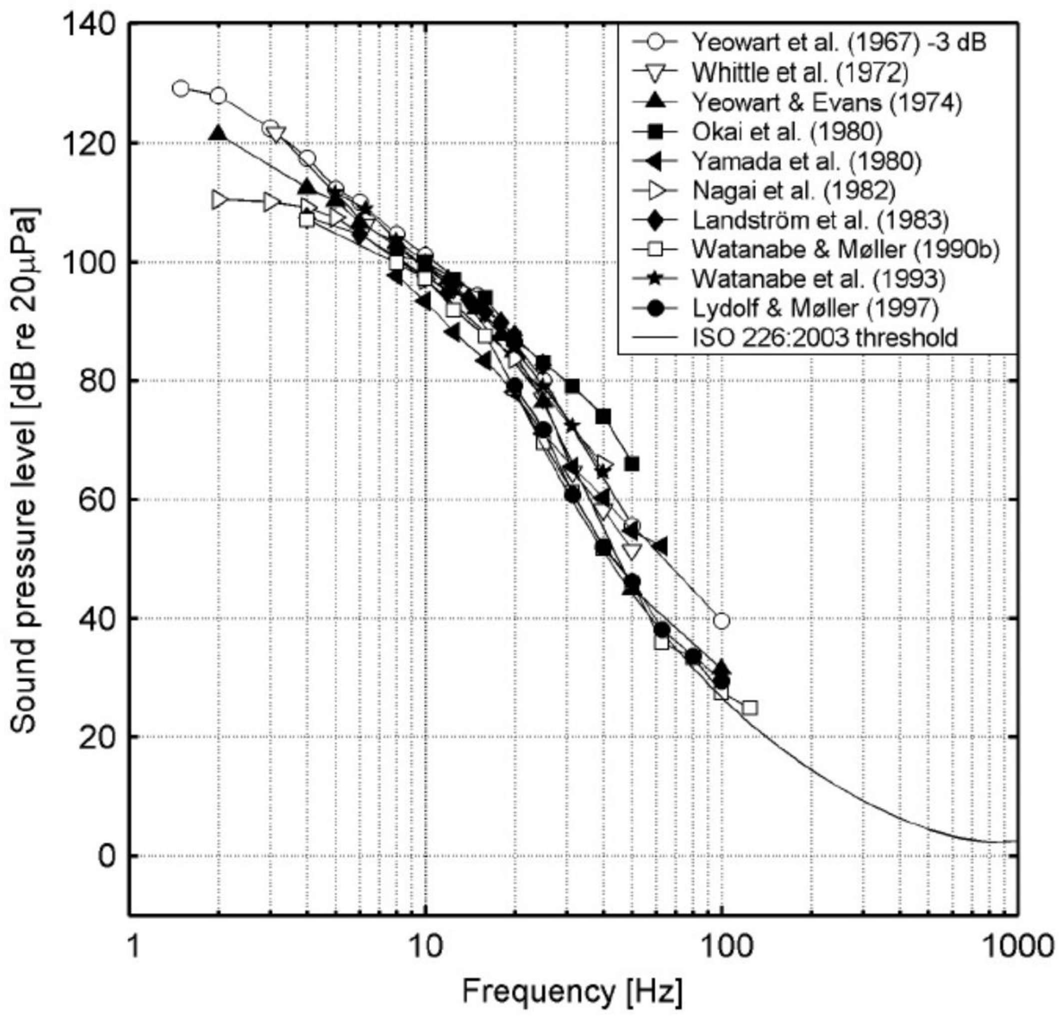
https://www.wind-watch.org/documents/low-frequency-noise-a-biophysical-phenomenon/

# Background: Environmental low-frequency noise

- Topic has gained general interest seemingly also in Audiology
- E.g.: Last World Congress of Audiology (https://wca2024paris.com/) had its own (crowded) session dedicated to ISLF hearing
- What remains a challenge for clinical settings is the difficulty in generating ISLF sounds at the high sound-pressure levels (SPL) required and with low distortions
- The advent of wind turbines, a positive green energy generation alternative, has called for assessment of their environmental impact. Governments around the world often run/fund their own assessments
- Increased media recognition of ISLF noise, due to intriguing phenomenon of widespread complaints called “the Hum” (MacPherson, 2024).

# Background: Hearing at low and infrasonic frequencies

- At sufficient levels, we do hear very low-frequency sounds (e.g. down to a couple of Hz)
- We perceive these sounds with our ears before they are sensed as body vibrations (i.e. the ear remains being the most sensitive organ to sound)
- Loudness and annoyance grow fast with increasing sound pressure, especially below 20 Hz
- Sound below 20 Hz (*infrasound*) looses its tonality / pitch sensation
- Sound below ~12 Hz is heard as segmented / discontinuous (pressure cycles can be distinguished)




Møller and Pedersen (2004). Noise and Health 6(23):p 37-57

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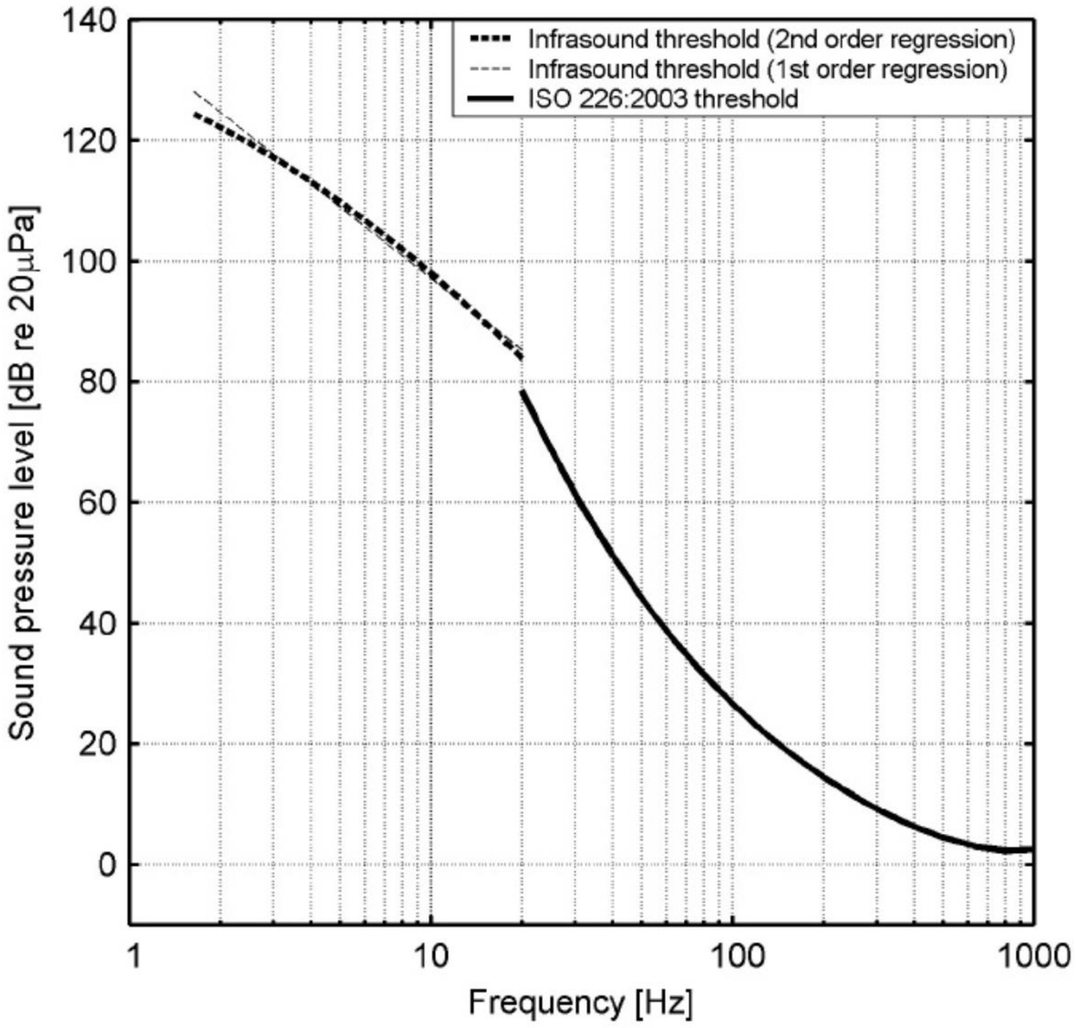


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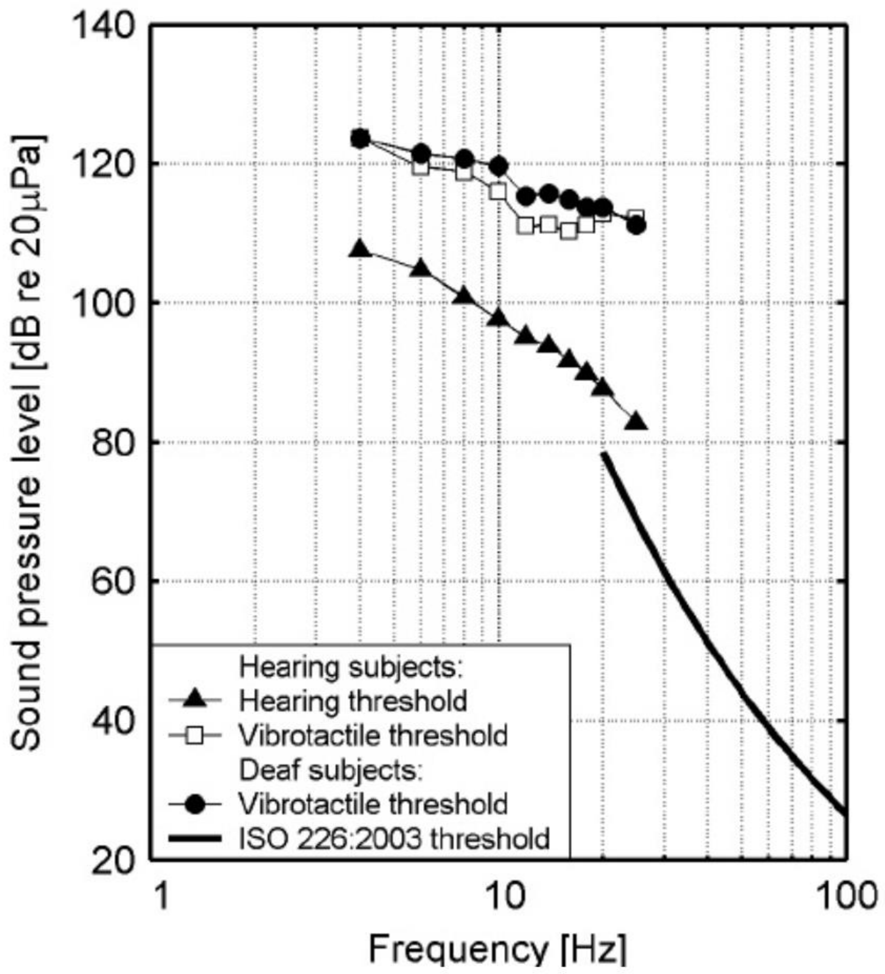


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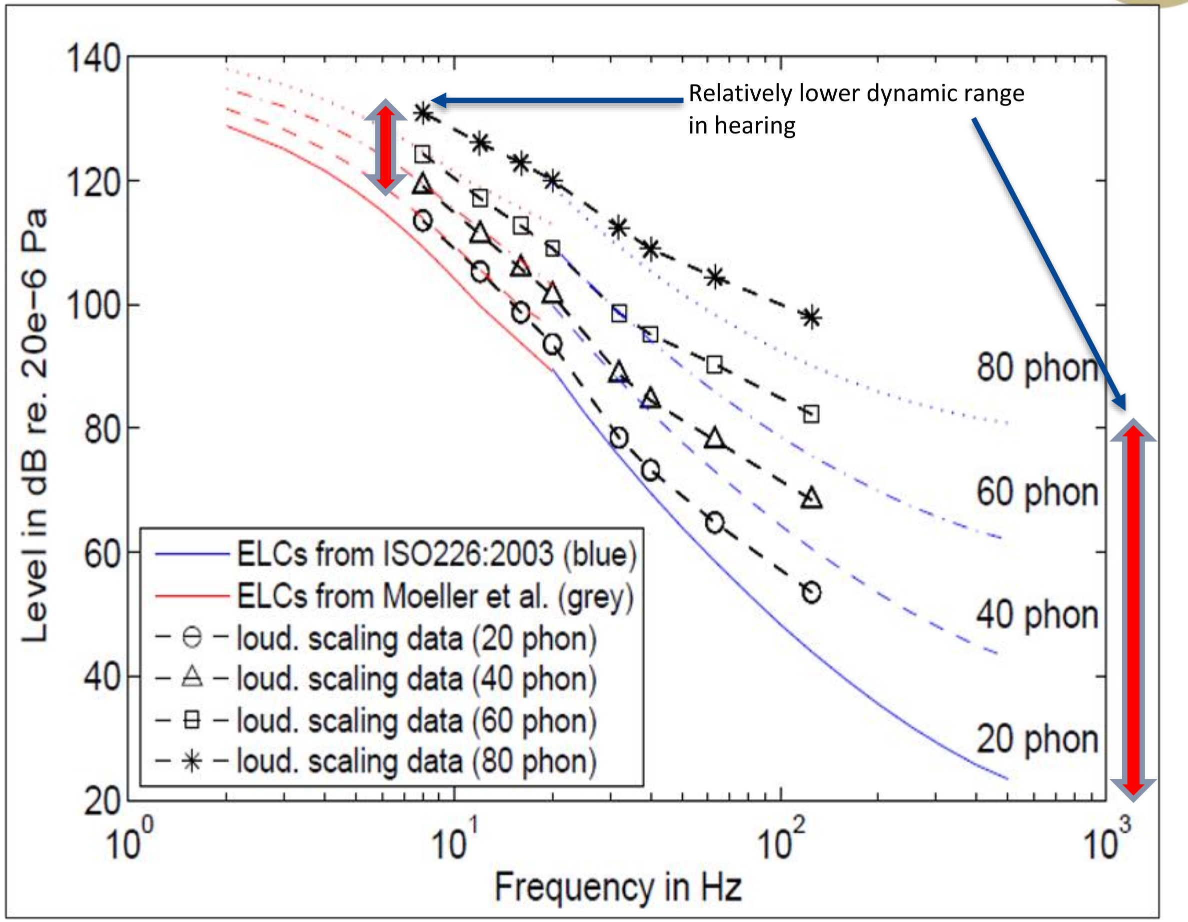


EARS project. https://www.euramet.org/research-innovation/search-research_projects/details/?tx_eurametctcp_project[project]=1127

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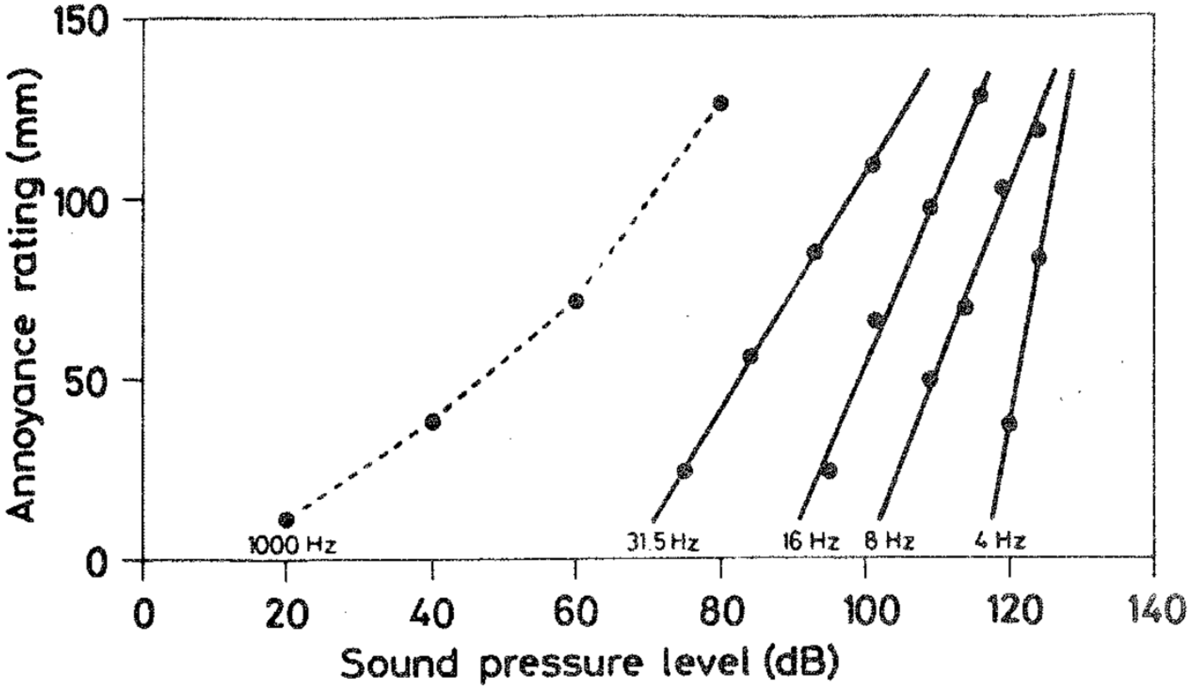


Andresen and Møller (1984). Journal of Low Frequency Noise, Vibration and Active Control, 3(3), 1-8

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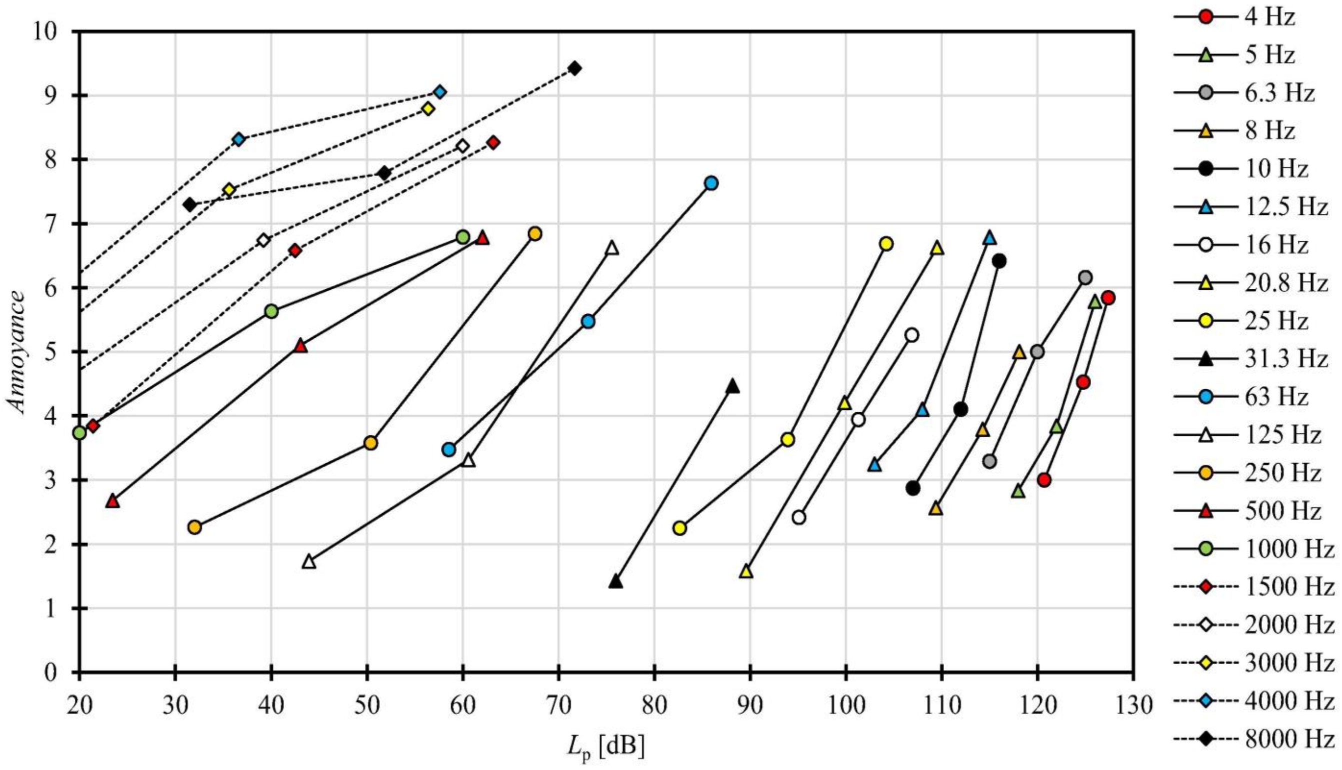
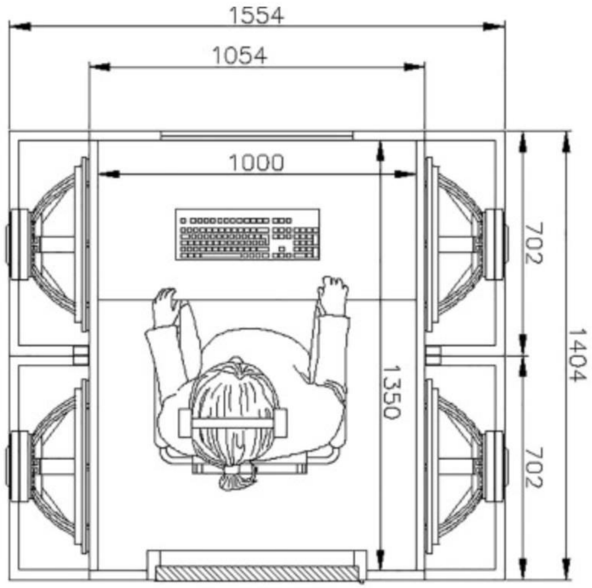



Rajala et al. (2022). Applied Acoustics, 198. https://doi.org/10.1016/j.apacoust.2022.108981

# Background: Generating ISLF sounds

**Whole body**

**Low-frequency cabin (Aalborg)**

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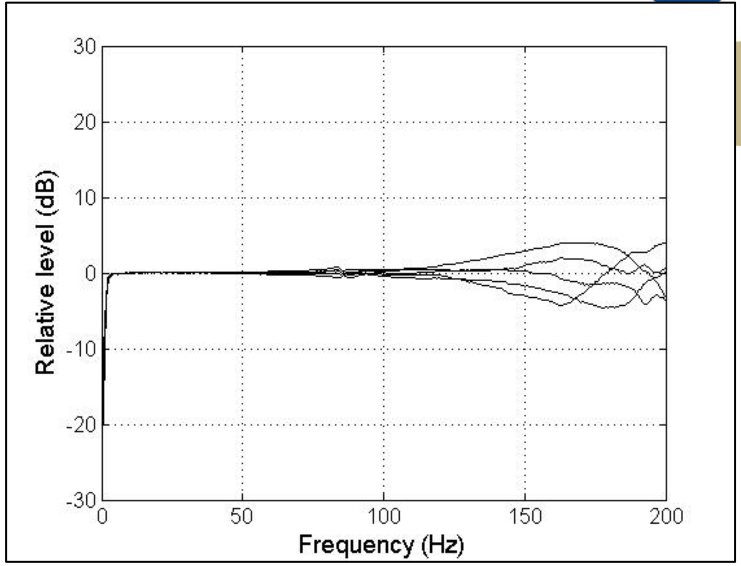
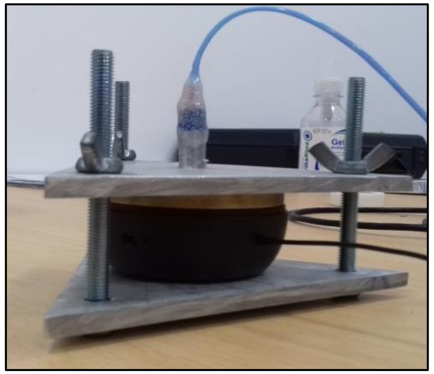


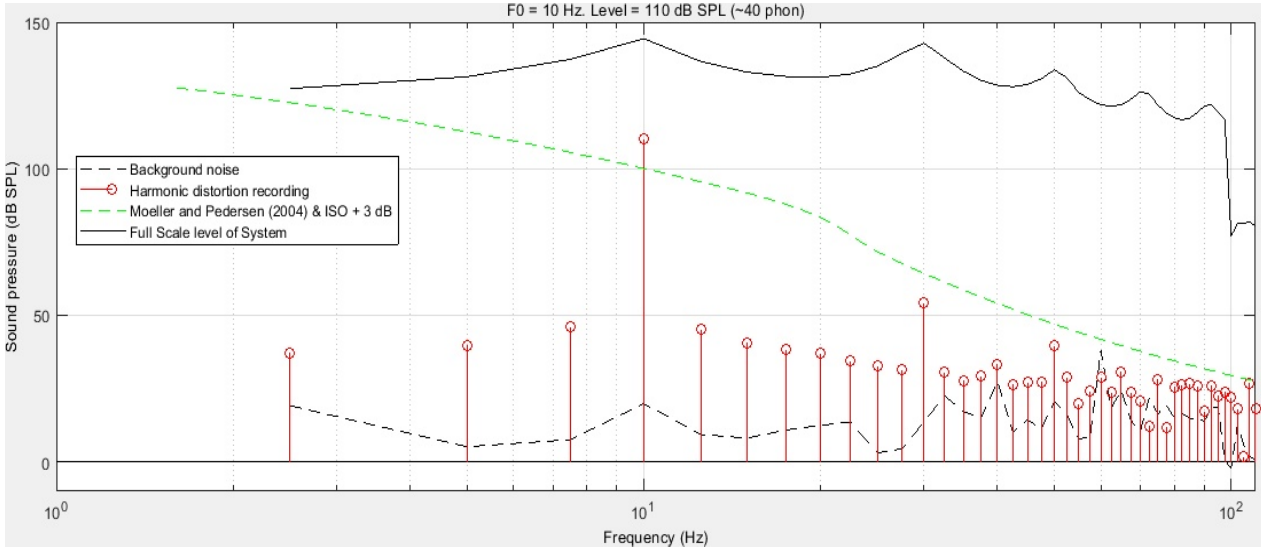

**Spatial variation in SPL (LF-cabin, Aalborg)**

$\Delta p \propto \Delta V / V$

→ High SPLs – low harmonics

**In-ear**





# Low-frequency and infrasound hearing

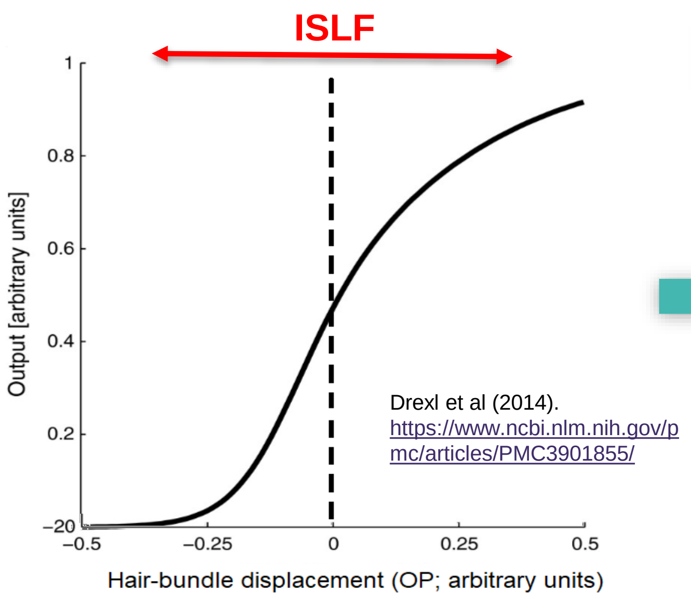
→ Physiological factors behind ISLF hearing will be described next

→ Then new experimental data will be shown where these factors are evaluated

→ A new state-of-the art interpretation for infrasound hearing will be introduced. This involves an alternative mechanism of cochlear sound transduction

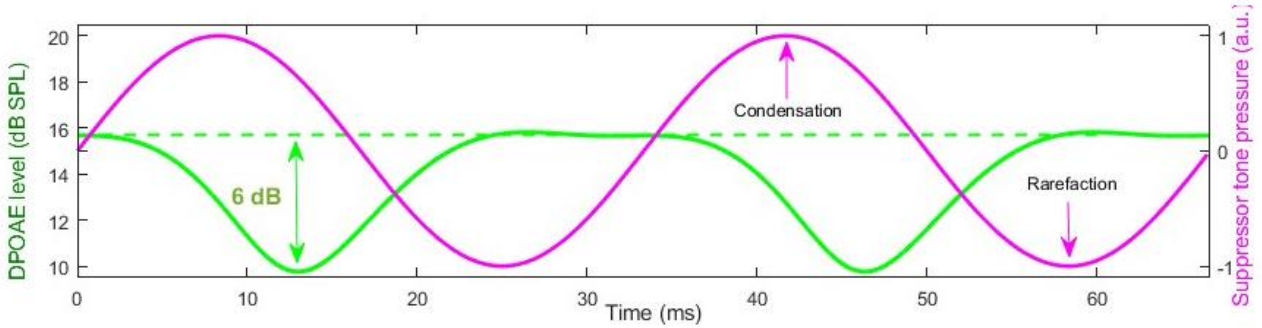
# BM displacement and the IHC response shape LF-sensitivity (> 16 Hz)

- Suppression of OHC-generated distortion-product otoacoustic emissions (DPOAE) has been used to study the BM displacement produced by ISLF tones
- It is assumed that a fixed suppression corresponds to a fixed BM displacement (e.g. **Bian *et al.*, 2002**)
- An iso-displacement curve(*f*) can be obtained by varying the suppressor frequency and keeping a constant (e.g. 6 dB) suppression of DPOAE. This has been called distortion-product isomodulation curve (DPIMC; also can be assumed to be proportional to the inverse of the middle-ear transfer function; METF; $\frac{(p_{sv}-p_{st})}{p_T}$)
- This was compared with the ELC of individual subjects (Jurado and Marquardt, 2016)




Drexl et al (2014). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3901855/

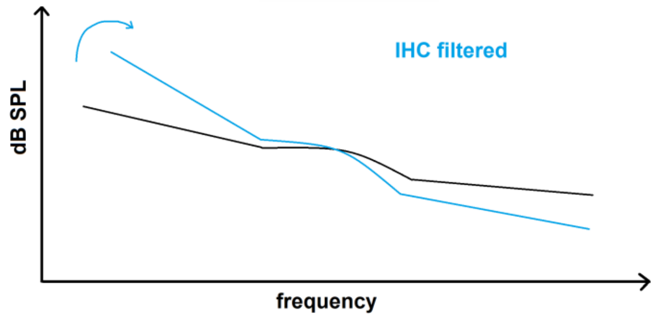
DPOAE suppression experimets

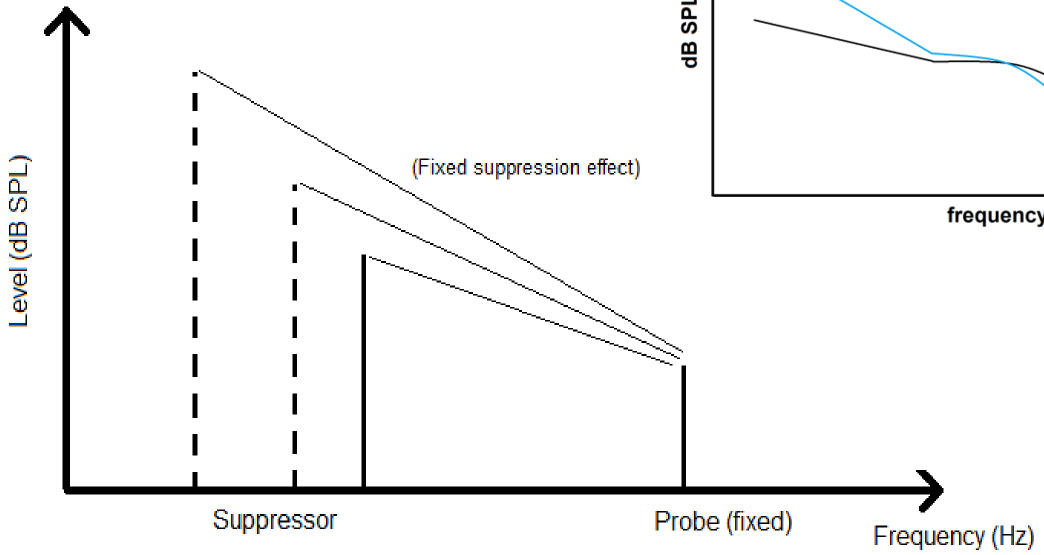



Marquardt et al (2007). https://pubmed.ncbi.nlm.nih.gov/17552714/

# BM displacement and the IHC response shape LF-sensitivity (> 16 Hz)

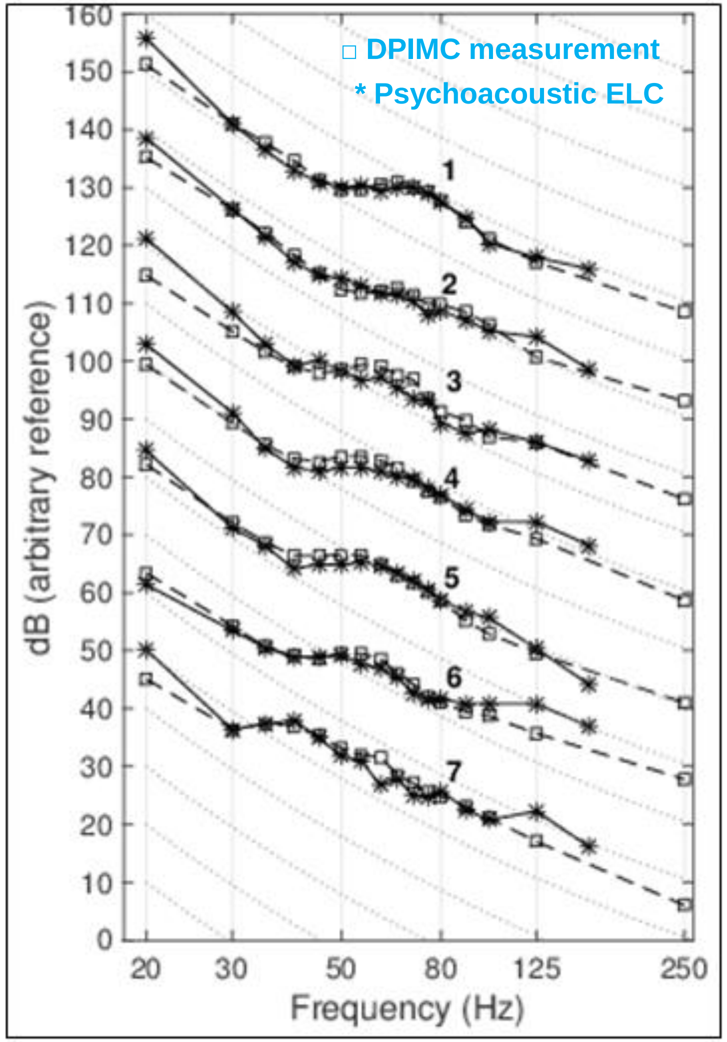
- On average and often in individual curves, the iso-displacement DPIMCs matched well the ELC shape
- The ELCs were steeper than the DPIMCs, suggesting the additional IHC response filter (6 dB/octave). This additional filter also explains the general threshold steepness below 40 Hz (at least 18 dB/octave)




The suppressor frequency was varied and a constant suppression of DPOAE was found for fixed primary frequencies [DPIMC($f_{BT}$)]

DPIMC($f_{BT}$) and ELC

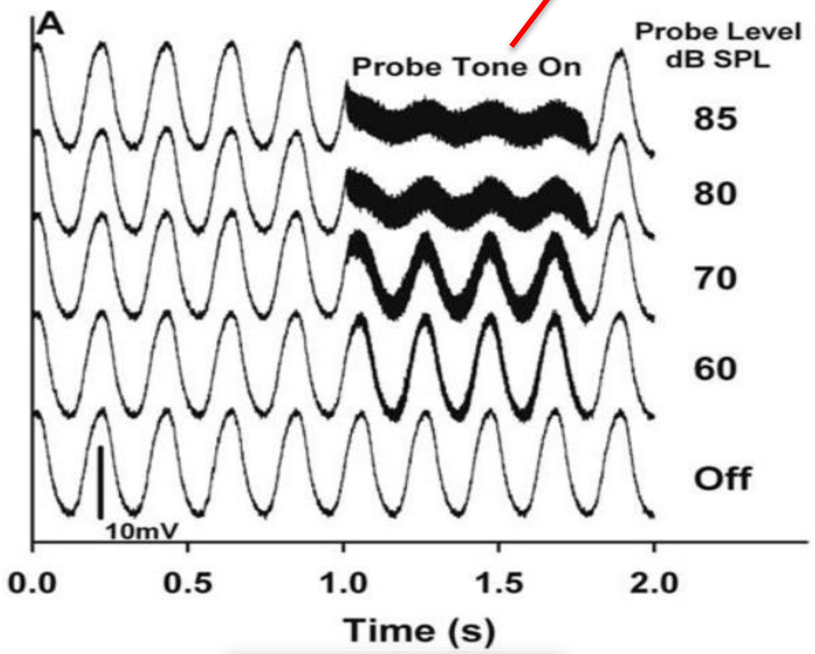



Jurado and Marquardt (2016). https://doi.org/10.1121/1.4967295

# Infrasound sensitivity is only shaped by BM displacement (< 16 Hz) (IHC filter "bypassed")

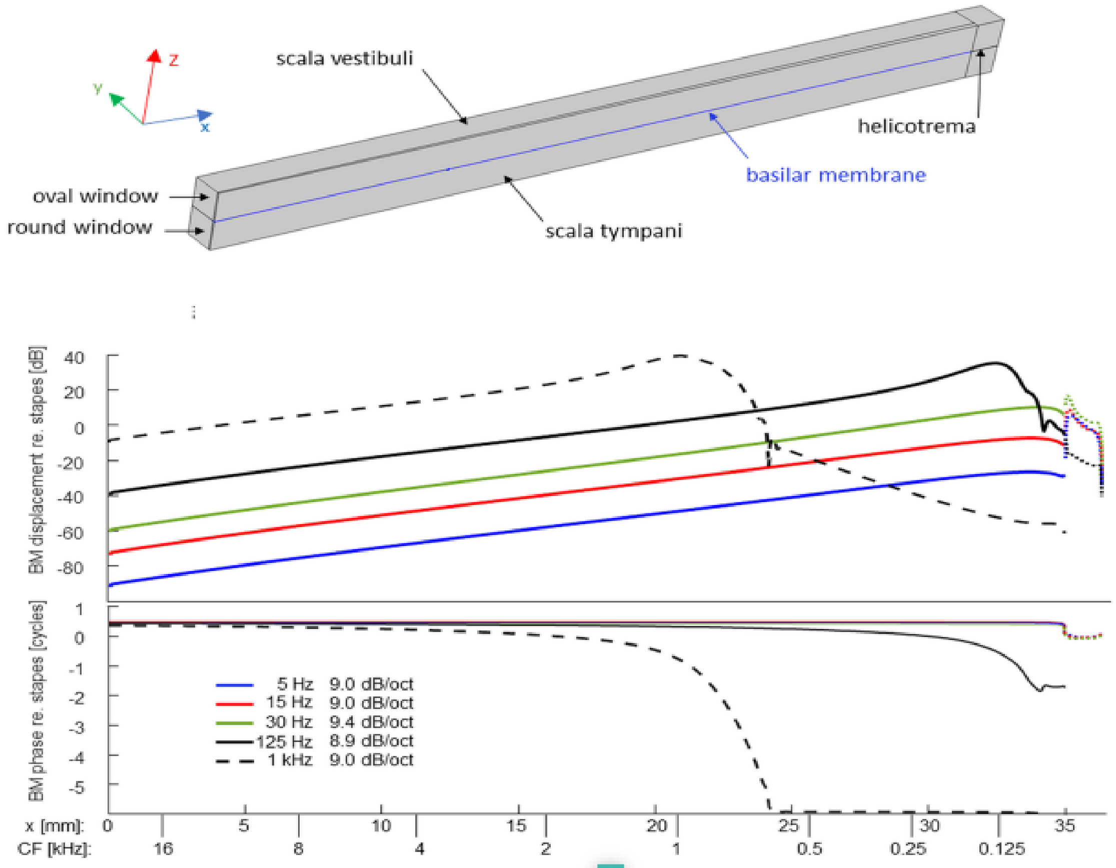
Large cochlear endolymphatic potentials (Salt et al. 2013) in response to infrasound

suppressed by a HF tone (500 Hz)




Evidence in humans?

In a couple of experiments, we tested the hypothesis that infrasound is detected due to these OHC generated potentials (indirectly, non-invasively) .




Cochlear FEM. Dr. Torsten Marquardt (UCL)

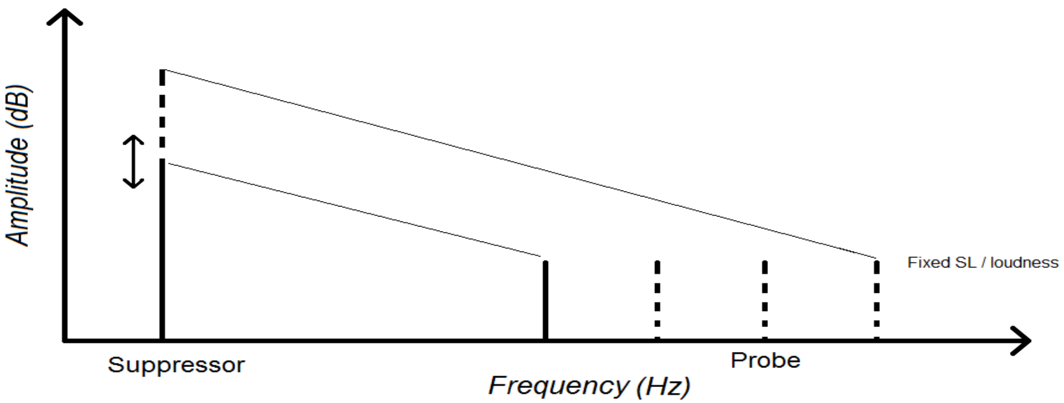
A 500-Hz tone may produce suppression but no classic masking on infrasound. But a lower frequency tone (140 Hz) would produce masking

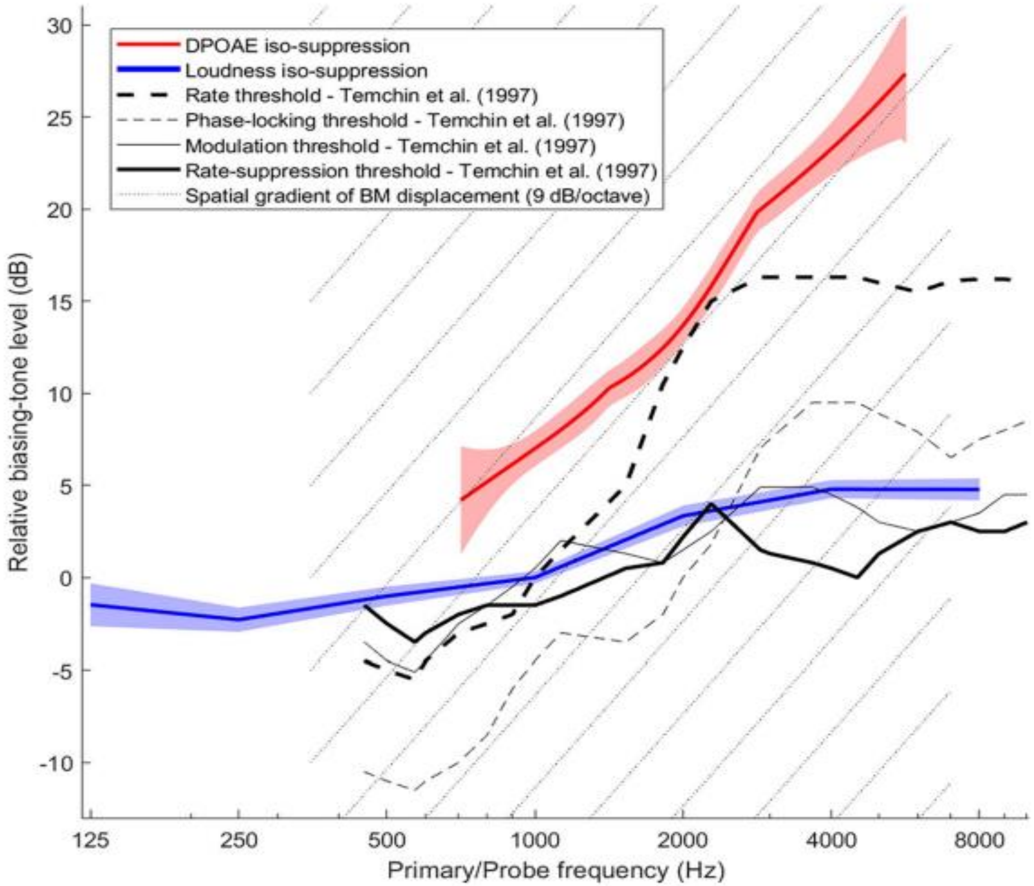
# OHC generated cochlear potentials may explain basal spread of infrasound suppression

- Infrasound can modulate the loudness of higher frequency probes (even up to 8 kHz) at low-sensation levels (not more than 10 dB SL required)

- The dependence on probe frequency has a very shallow slope (2-3 dB/octave). This contrasts the slope expected from BM displacement and observed in DPOAE suppression (~9 dB octave)

- Again, this points to a non-mechanical and likely electrical factor behind infrasound processing. Electrical potentials may easily spread along the cochlear ducts and would explain the shallow slope with frequency/characteristic place






Jurado et al (2022). https://link.springer.com/article/10.1007/s10162-021-00830-2

# Summary: DPOAE and infrasound suppression experiments reveal a new perceptual mechanism

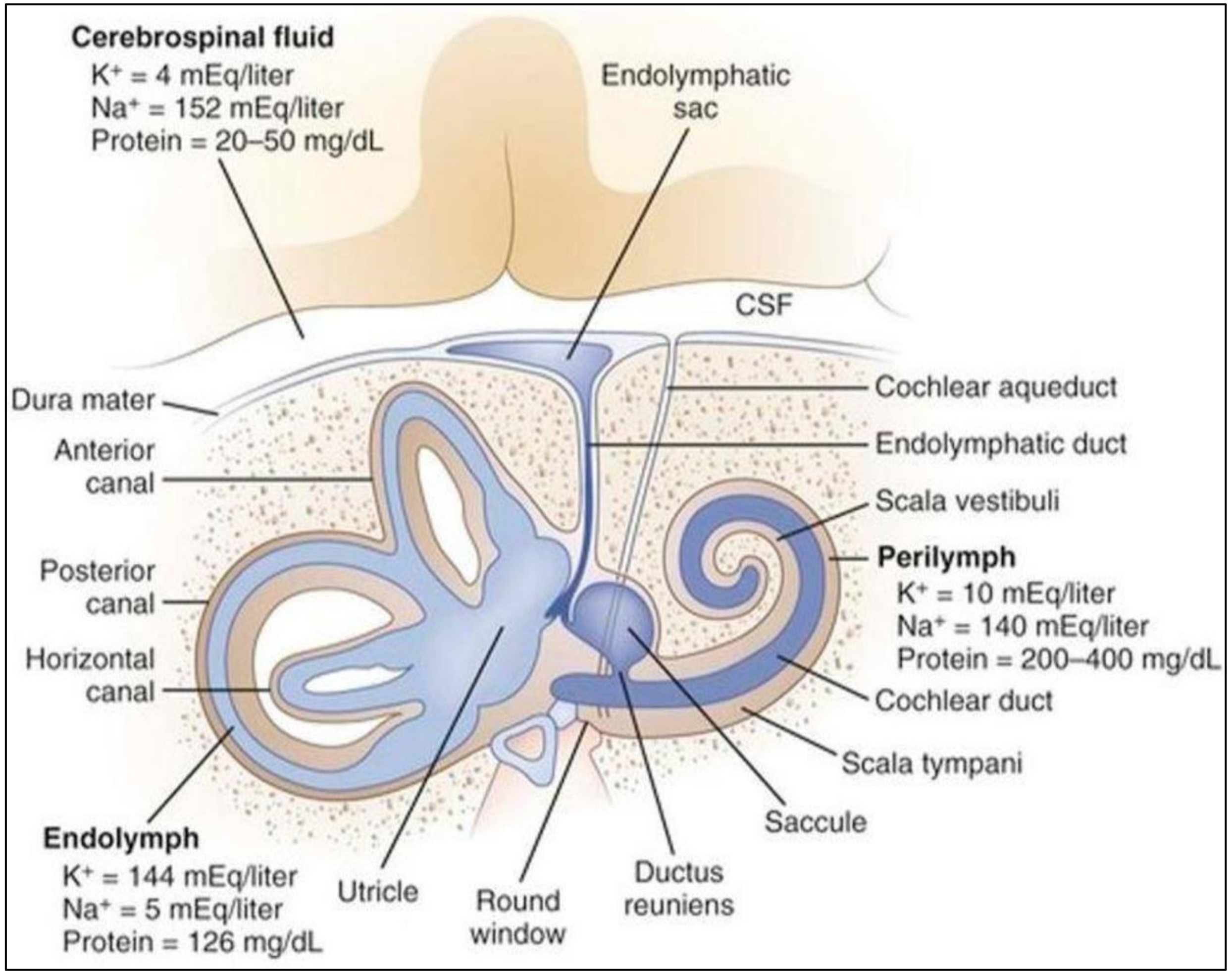
→ New data suggests that several phenomena related to infrasound perception might be explained if **infrasound processing strongly depends on the OHC response.** The IHC response appears to be "bypassed". Some evidence (direct in animals; indirect in humans) suggests OHCs generate strong electrical potentials which may directly trigger auditory nerve responses, bypassing the IHC mechanical filter

# What about vestibular responses to ISLFs?

- Cochlea and vestibule share the same bony structure. VEMPs: Vestibular evoked myogenic potentials. “Sound induced vestibular responses” (clinic)

- As the vestibular system is tuned to very low-frequencies of vibration, it has been claimed that ISLFs can activate it

- Reported motion-sickness symptoms by people living near wind-turbines have further raised this question



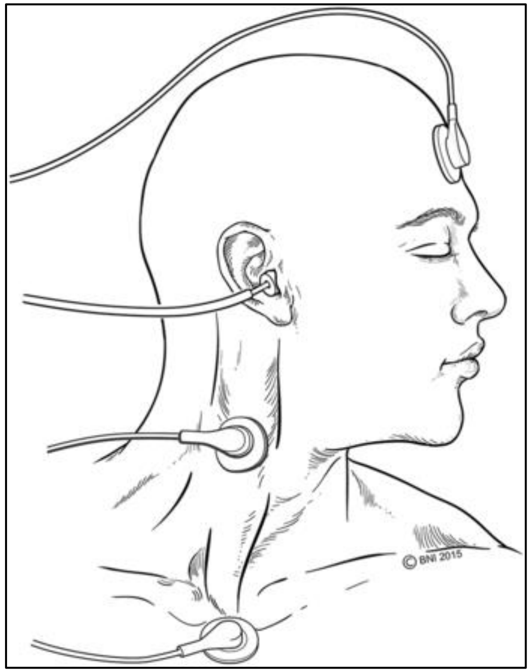

Source: Azad, K. (2018). https://www.semanticscholar.org/paper/Brain-Stethoscope%3A-A-Non-invasive-Method-for-Azad/d9b0939b25fcfd0e23c1ac4a2f0144bdf382a3b9

# What about vestibular responses to ISLFs?

- We put this question to the test, at least for normal-hearing participants (and without known vestibular pathologies)

  → cVEMPs were measured in 30 ears (15 subjects, L & R ears)

  → Electrodes: in SCM muscle, a reference in the sternum and ground in the forehead



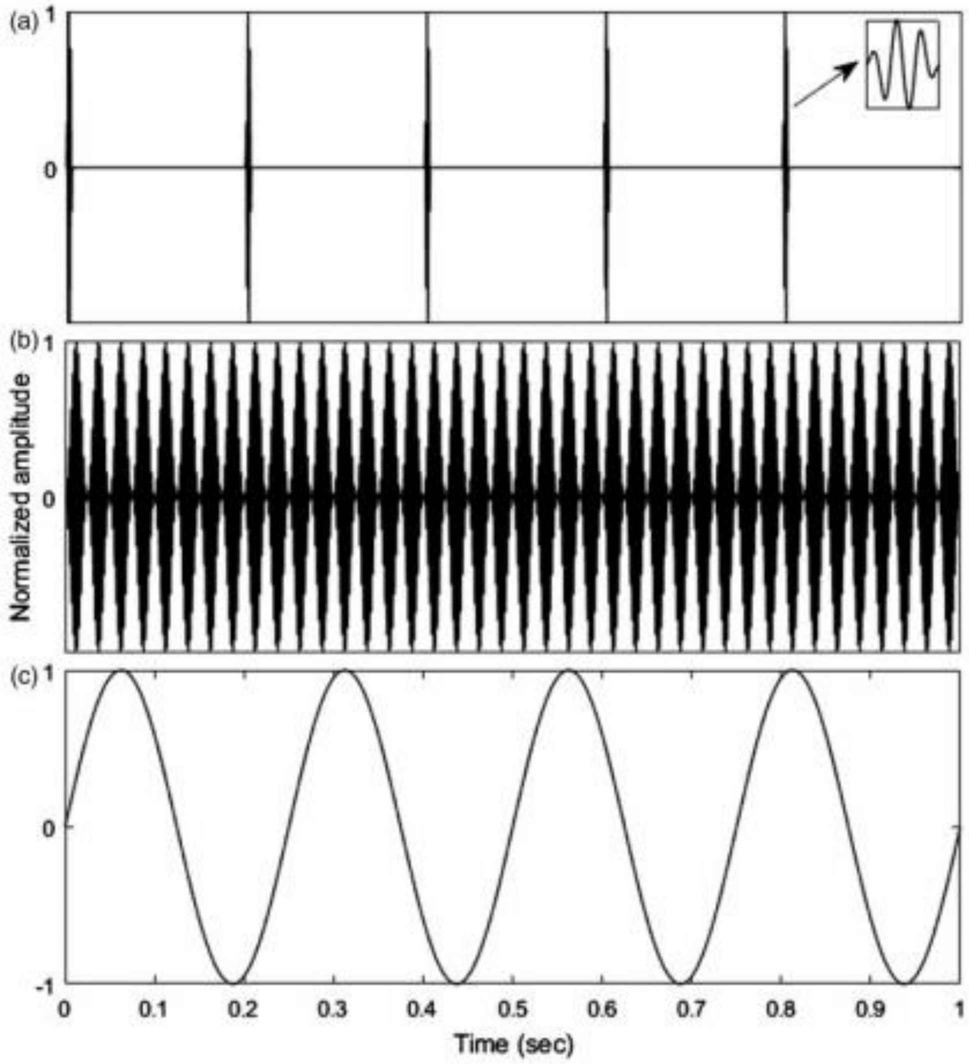

Source: https://n.neurology.org/content/89/22/2288

(a) 500-Hz tone pip stimulus (clinical)

(b) SAM 500-Hz tone (40-Hz modulation)

(c) Pure tones (4, 16 and 40 Hz)

80-90 phon level - higher than levels connected with complaints about ISLFs



# Low-frequency and infrasound hearing

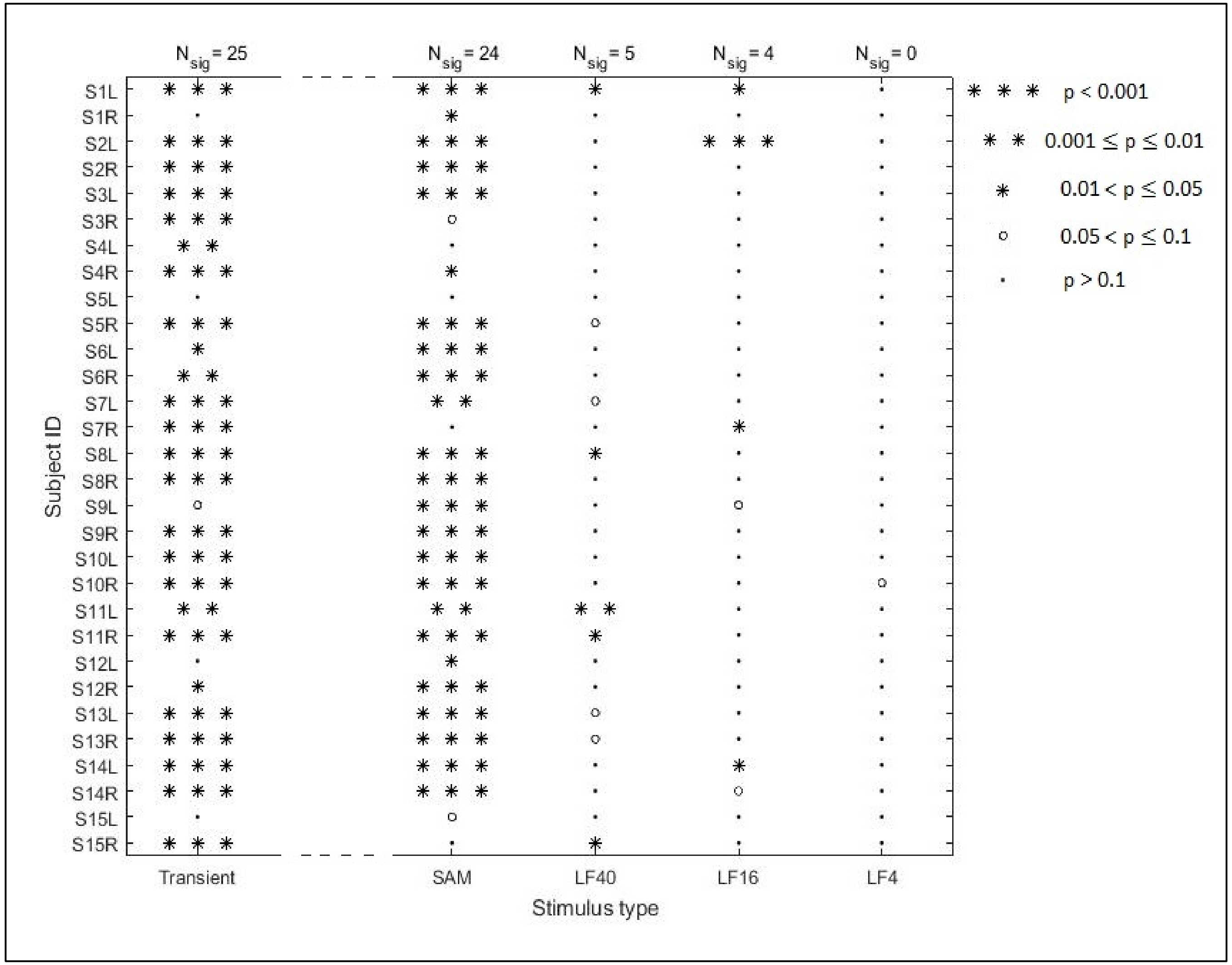
- What about vestibular responses to ISLFs?

**Summary:** Clear overall negative result

**However:**

- S2 presented a **h**ighly significant VEMP in left ear for the 16-Hz IS. This may have occurred if the subject presented SSCD (Raufer et. al, 2018; https://doi.org/10.1121/1.5046523). This syndrome has a prevalence of ~3 % (Masaki, 2011, https://doi.org/10.3109/00016489.2010.526145) and would explain why a small percentage of people present motion-sickness symptoms when exposed to infrasound

- **Pending**:
  - ISLF VEMP thresholds in vestibular pathology (e.g. SSCD)
  - ISLF oVEMPs (utricule sensitivity; cVEMP: saccule)




Source: Jurado and Marquardt (2019). https://doi.org/10.1177/1461348419833868

# Low-frequency and infrasound hearing

- For the hearing impaired? ISLF sensitivity and effects on the perception of higher-frequency sounds/speech?

# THANK YOU!