Towards clinical evaluation of frequency selectivity using stimulus frequency otoacoustic emissions

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Background

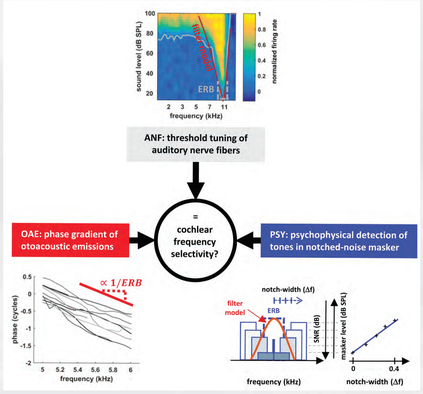
- With regard to tonotopic processing, the ear is both ***sensitive*** (e.g., audiometric thresholds) ***& selective*** (e.g., filter bandwidths)
- Loss of selectivity affects important functional aspects like speech detection in noise (Badri et al. 2011)

Fig. 1 – Sensitivity vs Selectivity



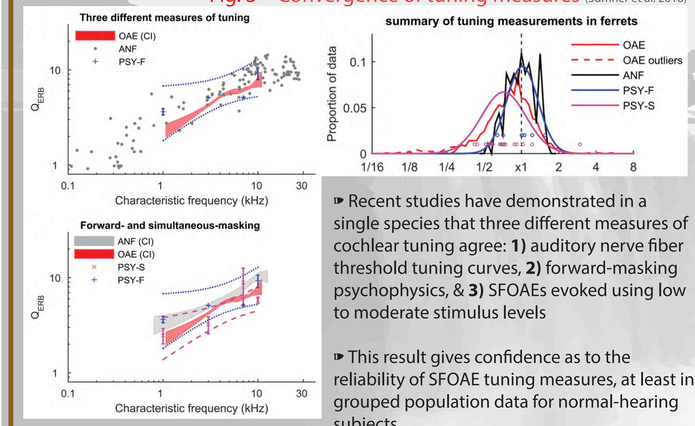
Note
frequency selectivity = sharpness of tuning

Fig. 2 – Different measures of tuning (Sumner et al. 2018)



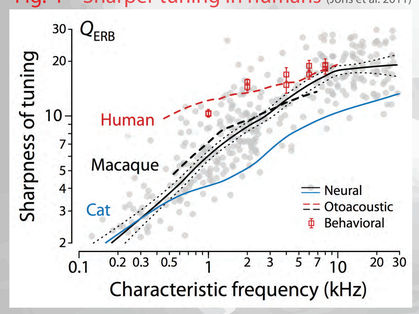
- While different methods exist to quantify sharpness of tuning, their convergence has been controversial (e.g., forward vs. simultaneous masking, iso-level vs. iso-response, etc...)
- One relatively rapid and non-invasive objective measure has been through the use of stimulus frequency otoacoustic emissions (SFOAEs)
- The method entails determining the SFOAE phase-gradient delay: **sharper tuning = longer delay**

Fig. 3 – Convergence of tuning measures (Sumner et al. 2018)



- Recent studies have demonstrated in a single species that three different measures of cochlear tuning agree: **1)** auditory nerve fiber threshold tuning curves, **2)** forward-masking psychophysics, & **3)** SFOAEs evoked using low to moderate stimulus levels
- This result gives confidence as to the reliability of SFOAE tuning measures, at least in grouped population data for normal-hearing subjects

Fig. 4 – Sharper tuning in humans (Joris et al. 2011)



- Revised cochlear tuning estimates for humans indicate selectivity is relatively sharp (e.g., Shera et al. 2002, 2010), potentially an important facet for speech processing
- Selectivity is fundamentally determined at the level of the cochlea and **not** "sharpened" per se as information ascends the central nervous system (e.g., Bitterman et al. 2008)

Study Overview

- Rapid & objective measure of *selectivity* would be of significant clinical value
- SFOAE phase-gradient methods correlate well with auditory nerve and/or psychophysical measures in a wide variety of species (incuding humans). However such has been limited thus far to "population" data pooled across normal-hearing (**NH**) subjects.
- Potential exists to extend SFOAE selectivity measures to hearing-impaired (**HI**) individuals

GOAL: Improve empirical foundations by characterizing for individual NH subjects the stimulus level-dependence & relationship to SOAEs (the most salient evidence of an "active ear")

Methods

- Data were acquired from 33 normal-hearing adult subjects (McKetton et al. 2018)
- SFOAEs were acquired using a swept-tone suppression paradigm (Kalluri & Shera, 2013)
- Stimulus probe levels were presented at 20-50 dB SPL in 10 dB steps. Suppressor level was fixed 15 dB above the probe
- A "peak-picking" algorithm could be employed to extract phase-gradient delays (Shera & Bergevin, 2012)

Fig. 5 – Swept-tone SFOAEs (McKetton et al. 2018)

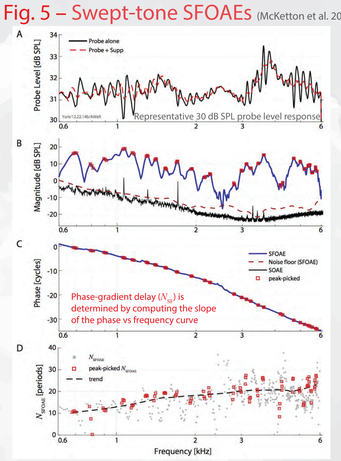
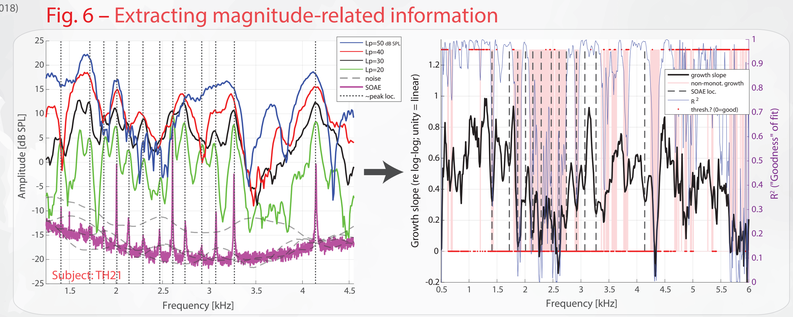
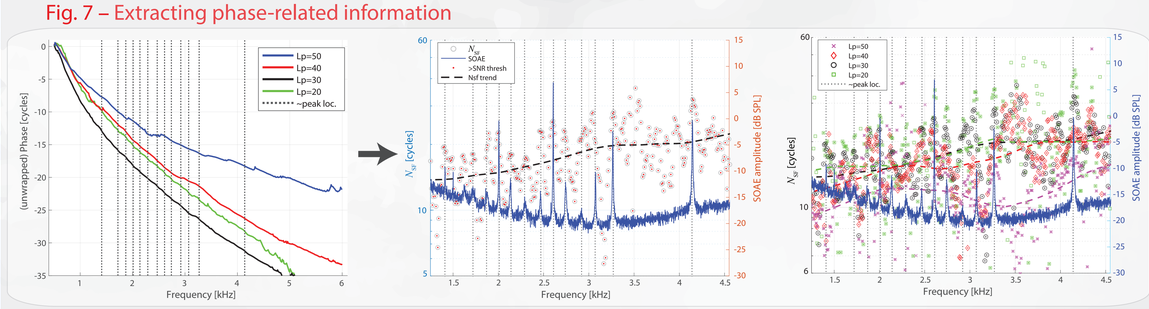


Fig. 6 – Extracting magnitude-related information



- From SFOAE magnitude data for an individual subject (left), quantitative aspects (right) can be computed across frequency in a variety of ways: • rate of growth (black curve; linear growth is at unity and values less than indicate nonlinear compressive growth), • existence of non-monotonic growth (pink areas), • deviations from a linear fit (blue curve), and • effective signal-to-noise strength (red dots)

Fig. 7 – Extracting phase-related information



- From SFOAE phase data for an individual subject (left), the phase-gradient delay (quantified as N_{SF}) and trend can be computed for a given level (middle) and then compared across levels (right)

Results

NOTE: Only a small subset of individual subjects are shown here for clarity. In general, subjects with little or no SOAE activity tended to exhibit relatively smaller SFOAE responses, particularly for stimulus levels of 30 dB SPL and less

Fig. 8 – Subject AM

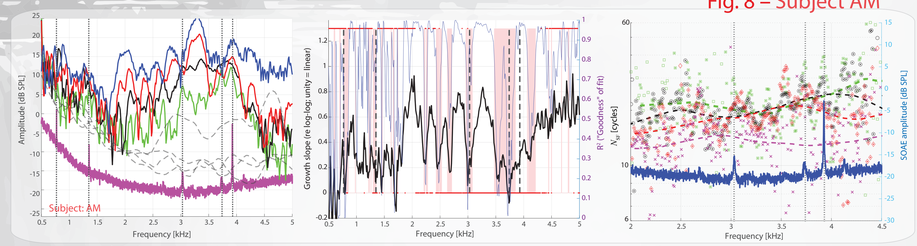


Fig. 9 – Subject TH30

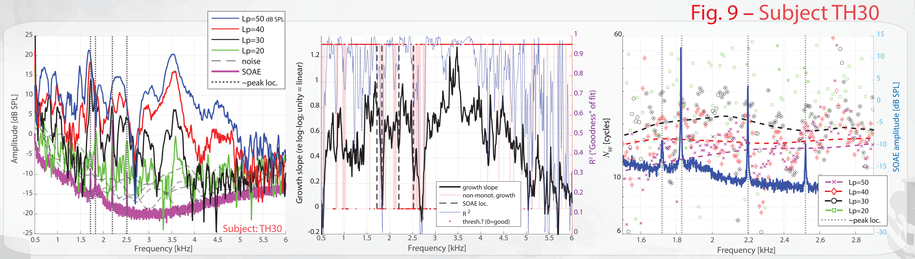


Fig. 10 – Subject JW

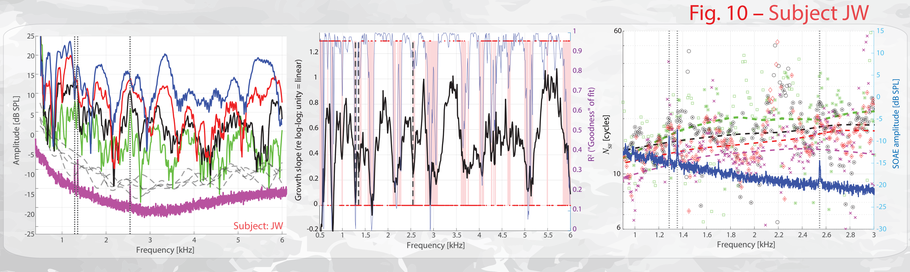


Fig. 11 – Subject TH28

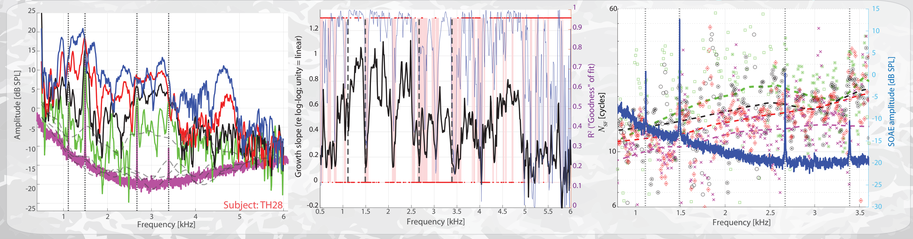


Fig. 12 – Pooled delay level-dependence

- **SFOAE growth is highly nonlinear** - Generally compressive in nature (black curves in middle panels of Figs.8-11 sit well below unity), as output grows as ~0.25-0.75 dB/dB rel. to input. Though growth rate varies in a complex frequency-dependent fashion
- **Non-monotonic growth** (NMG) - Fairly common (pink areas of middle panels in Figs.8-11), especially near SOAEs, if present. These come & go in a frequency-dependent fashion
- N_{SF} **systematically decrease w/ increasing probe level** - Readily apparent in individual N_{SF} trends (right panels of Figs.8-11) and pooled data (Fig.12)
- N_{SF} **trends can reasonably be determined from NH individuals for probe levels of 30-40 dB SPL**
- N_{SF} **trends shows localized increases at certain (idiosyncratic) frequencies** - Typically corresponds to SOAE peaks (if present; e.g., middle panel of Fig.7)
- If SOAE peaks were not observed, SFOAE properties show characteristics consistent with their presence (e.g., localized increases in N_{SF})

Discussion

- **How low is *low*?** - Not all NH subjects exhibit robust SFOAEs, though presence of SOAEs typically leads to increased SFOAE activity. Probe level of 30 dB SPL appears a reasonable minimum stimulus level (to obtain a signal above the noise for an average subject).
- ***Another fine mess...*** - Dependence upon stimulus level reveals SFOAEs to be highly nonlinear (e.g., compressive growth, even at low stimulus levels). Ultimately the present data are not consistent with a linear picture of SFOAE generation (e.g., Kalluri & Shera, 2007). Supression methods may also complicate matters...
- **Source-unmixing**: Complexity of SFOAEs likely stems in part from being an amalgamation of energy from distributed sources (e.g., basal vs "near the peak") and disparate mechanisms (e.g., distortion versus reflection). Appropriate theoretical models will be important to further guide signal processing strategies to better parse out tuning-specific information (e.g., Shera & Bergevin, 2012).
- ***Make things simple, but not too simple*** - Coherent reflection model (Zweig & Shera, 1995) widely accepted to describe SFOAEs. However, unclear to what extent a "piecewise-linear frequency-domain model" implementation (Choi et al. 2008) is sufficient. Nonlinear formulations (e.g., Epp et al. 2010; Verhulst et al. 2012) may be required, but also present additional challenges (e.g., Ku et al. 2008).
- **Spontaneous & synchronized emissions** - The presence/absence of SOAEs introduce further complexities. For subjects lacking SOAEs, SFOAE characteristics appear suggestive of synchronized spontaneous emissions (SSOAEs) that readily manifest when a stimulus is present (e.g., Jedrzejczak et al 2008, 2018; Kalluri & Shera, 2007).
- **Looking ahead** (w/ an eye on clinical applications):
  - Compare SFOAE & psychophysical forward-masking tuning measures in *individual* normal-hearing subjects for low to moderate stimulus levels
  - Characterize SFOAEs in HI subjects (e.g., Probst et al. 1987)
  - Compare tuning measures between SFOAE & evoked potential methods (e.g., CAP, ABR) [e.g., Verschooten et al., 2012]
  - Compare level-dependence of SFOAE delays w/ level-dependent changes in tuning as measured with evoked potentials & psychophysical masking

Summary

- SFOAE delays can be used to rapidly and objectively assess frequency selectivity
- Despite highly nonlinear growth, SFOAE delays systematically decrease with stimulus level, qualitatively similar to filter broadening
- Delay trends can be extracted from individuals (at least for normal hearing subjects)

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Biophysics

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