Neural Fluctuation Profiles: Yet Another Model for Pitch

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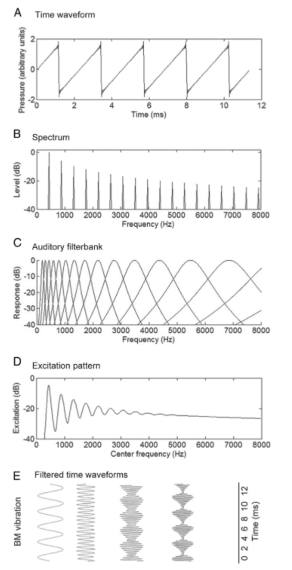
INTRODUCTION

Pitch models often focus on excitation patterns, or on timing cues in the frequency channels tuned to harmonics, and address issues such as resolved or unresolved harmonics, excitation patterns (place), temporal fine-structure and envelope cues. The models are generally based on stimulus properties or on responses of linear filter banks.

Here we focus on modeled **NEURAL** responses to several types of sounds with pitch. Peripheral nonlinearities interact with the structure of periodic signals to create strong cues for pitch in the form of neural fluctuations. Peripheral nonlinearities also create neural fluctuation cues for pitch in response to aperiodic sounds. Fluctuation cues are appropriate for decoding by inferior colliculus (IC) neurons that are sensitive to low-frequency fluctuations.

This poster introduces neural fluctuation cues for pitch and illustrates several examples.



From Oxenham, 2012

Several periodic and aperiodic stimuli associated with pitch percepts are illustrated at the right, along with corresponding model responses. Note the sensitivity of IC model rates to information contained in the temporal response of the AN model. This information is **not** reflected in the AN rate profile or in AN temporal fine structure.

BASICS

- In the healthy ear, AN fibers tuned near a harmonic are "Captured" by the harmonic, and respond almost as if in response to a pure tone (Deng et al., 1987). Capture is due to IHC saturation and is affected by cochlear amplification (Zilany & Bruce, 2007).
- Fibers tuned away from harmonics are not captured. Their PSTHs fluctuate at F0 (middle column).
- The pattern of fluctuation amplitudes across frequency channels provides a strong cue for pitch.
- AN-rate-based excitation patterns are highly level-dependent, but fluctuation cues are robust to SPL.
- Midbrain IC neurons that are excited by fluctuations in their inputs have rate profiles that encode pitch cues.
- Fluctuation cues are attenuated in the ear with SNHL due to reduced "Capture" (right column).

Model with Freq Channels only at Harmonics: AN responses are "tonal" due to capture by each harmonic.

Model with Freq Channels at & between Harmonics: Large cross-channel differences in fluctuation amplitudes. Some channels are captured by harmonics, some are not.

Model with SNHL: reduced capture yields smaller differences in fluctuation amplitude across channels. (SNHL: Cohc = Cihc = 0.3)

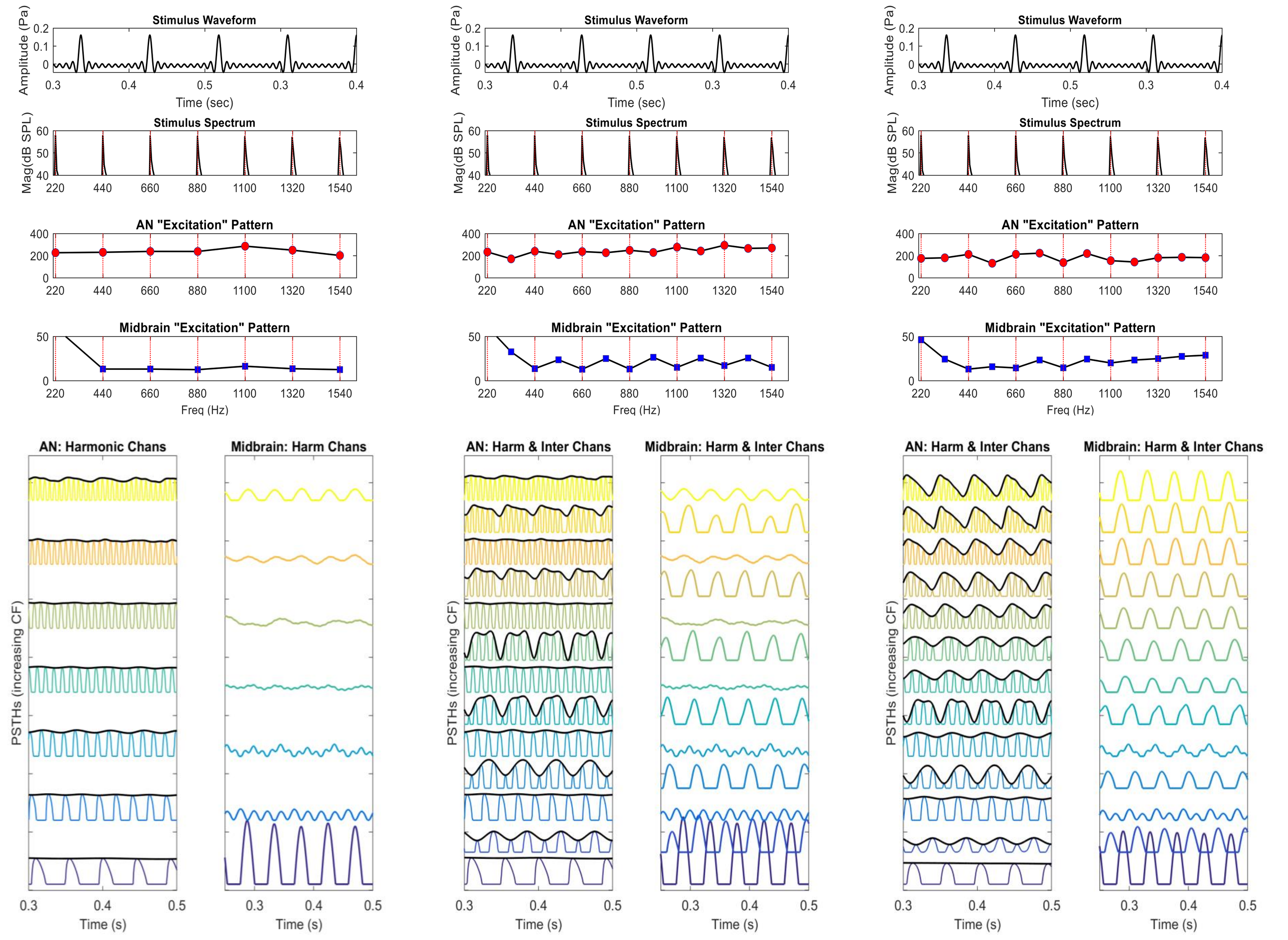
Stimulus: F0=220 Hz, 65 dB SPL Waveform (top) & Spectrum

Average Rates of model AN: Neural "Excitation pattern"

Average Rates of model IC cells

PSTHs of model AN fibers (left) & IC cells (right)

Model IC cells with bandpass modulation tuning shown. These cells (~50% of IC) are driven by low-freq fluctuations.



MODELING METHODS

Auditory-nerve rate functions (Zilany et al., 2014) were inputs to the Same-Frequency Inhibitory-Excitatory (SFIE) model for IC neurons with Bandpass MTFs (Nelson & Carney, 2004).

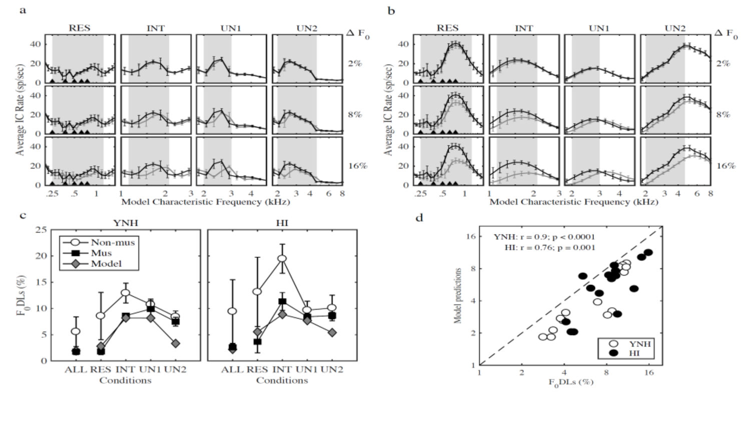
Unless otherwise stated, IC cells had best-modulation-frequencies (BMF) of 100 Hz, a common BMF in the IC.

Sensorineural hearing loss (SNHL) was included in AN model by reducing compression and IHC sensitivity, assuming 2/3 of HL is due to changes in OHC function and 1/3 of HL due to IHCs.

Models available at: https://www.urmc.rochester.edu/labs/carney/publications-code/auditory-models.aspx

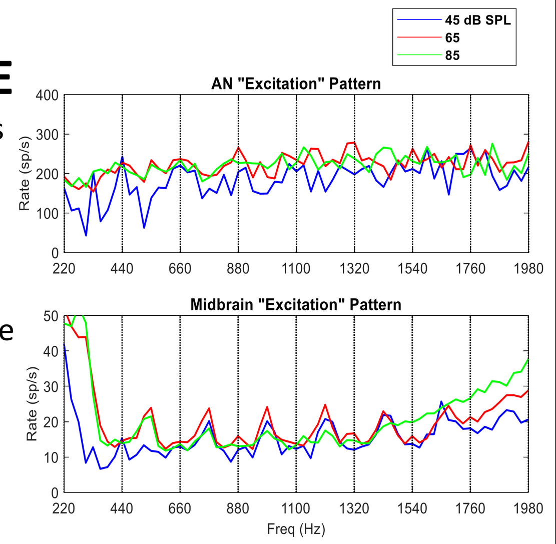
BACKGROUND

From Bianchi et al (JARO, 2019): Neural fluctuation model explains F0 Discrimination for listeners with NH and SNHL. These results suggest that IC sensitivity to fluctuations is adequate to explain F0 DLs.



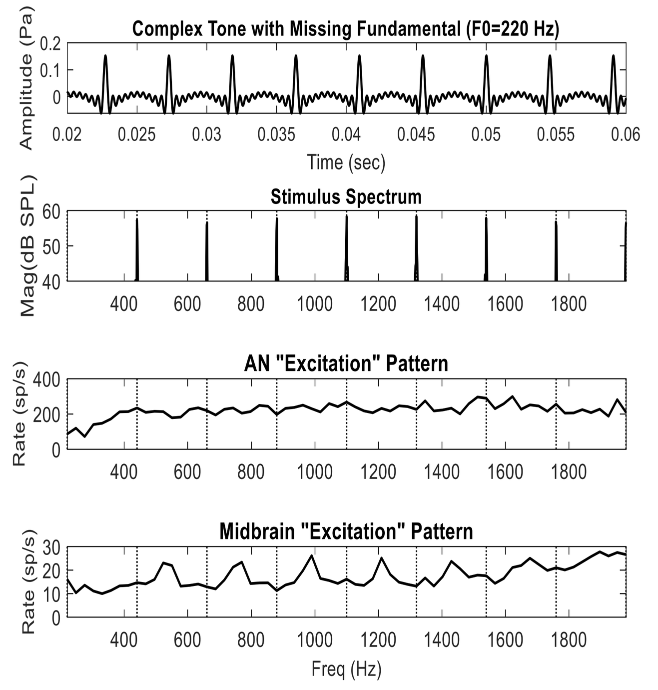
SPL DEPENDENCE

Level dependence is a problem for place-based pitch models. Unlike the AN excitation pattern (top), the IC response profile (bottom) is relatively robust across a wide range of SPLs. Responses here are for a complex tone with F0 = 220 Hz.



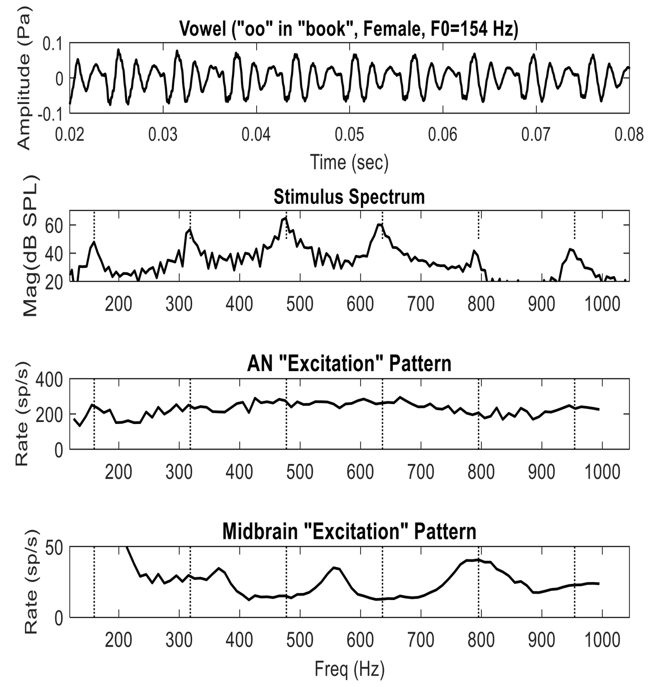
Examples: Periodic Sounds

Missing Fundamental



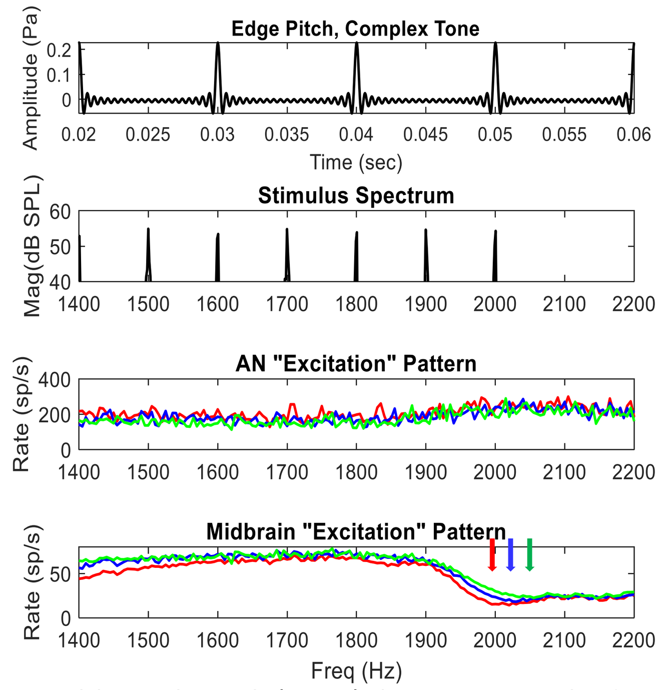
IC Rate profile in response to a harmonic complex with a missing fundamental lacks the peak at F0, as expected, but is otherwise unchanged.

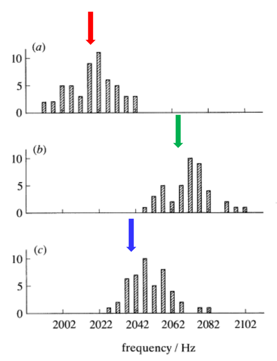
Voice pitch (Vowel)



Voice pitch for vowels affects IC rates for CFs spanning lower harmonics. Further work is required to tease apart interactions between pitch and formant structure; both influence the IC response profile (Carney et al., 2015).

Edge Pitch: Harmonic Complex





From Kohlrausch et al, 1992: Perceived pitch associated with edge of complex tone, with F0=100 Hz and harmonics up to 2000 Hz.

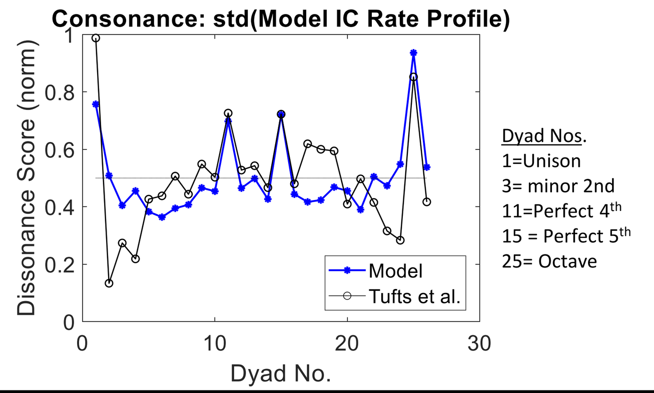
AN Model:
Red: Cohc = Cihc = 1.0
Blue: Cohc = Cihc = 0.7
Green: Cohc = Cihc = 0.6

In Kohlrausch et al. (1992), listeners matched a sine tone to the edge pitch of a complex tone. Mean edge pitch varied across subjects (right). Dips in the IC rate profile occur at perceived pitch frequencies. These dips are due to two-tone suppression in the AN model and vary with the amount of compression, which presumably varies across listeners, even those with normal hearing.

Pitch Salience & Consonance/Dissonance

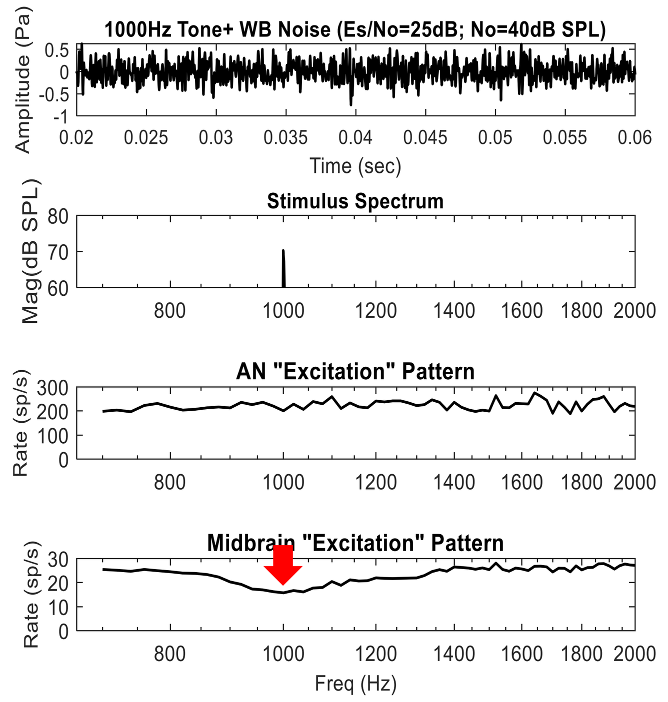
Bidelman and Heinz (2011) proposed a model for Consonance/Dissonance based on pitch salience, derived from a population of AN model fibers, followed by autocorrelations, pooling across fibers, and a pitch-sieve mechanism.

Comparable results were achieved by a population of model AN fibers, each followed by an IC SFIE model. The normalized standard deviation (contrast) of IC rates, for CFs covering low harmonics (430-1600 Hz), is shown below (blue). The mean std was shifted to 0.5, for comparison to dissonance scores from Tufts et al. (2005). For the equal-tempered chromatic intervals, the correlation between IC model contrast and listener scores was r=0.78 (cf. r=0.70 for the AN/pitch-sieve model).



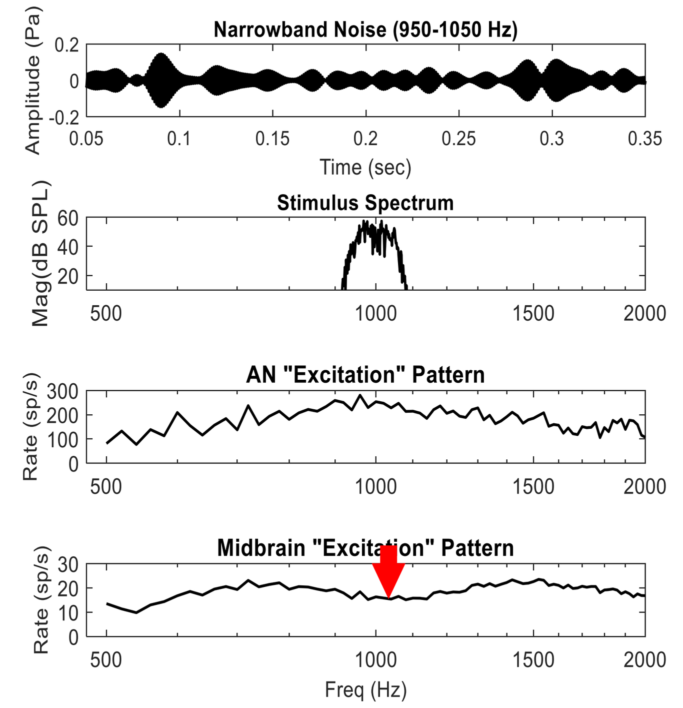
Examples: Aperiodic Sounds

Tone-in-Noise Profile



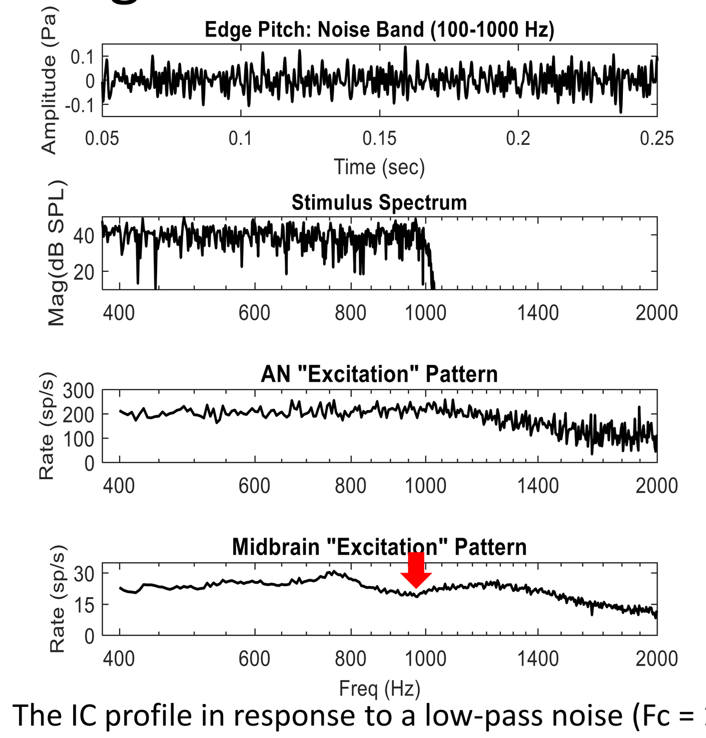
The IC profile in response to a Tone+Noise has a dip at the tone frequency, due to reduced neural fluctuations in this frequency channel. (Mao et al., 2013). This response pattern is observed for other noise stimuli with pitches, even in the absence of an added tone.

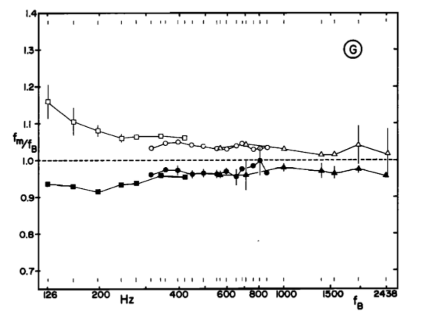
Narrowband Noise "Pitch"



The IC profile in response to a Narrowband Noise (65 dB SPL) is broad, but has a dip at the center frequency at the perceived pitch. This dip is due to two-tone compression, which varies the gain of different frequency channels and thus affects the amplitudes of AN neural fluctuations.

Edge Pitch: Noise





From Klein & Hartmann, 1981
Edge pitches associated with low-pass (filled symbols) and high-pass noise (open symbols).

The IC profile in response to a low-pass noise (Fc = 1 kHz) has a minimum rate at CFs just below Fc, near the perceived pitch reported by Klein & Hartmann (1981). This dip can be attributed to two-tone compression: Noise energy decreases the gain of the cochlear amplifier. The lack of energy above Fc results in an increased cochlear gain for channels tuned below Fc, which increases saturation and reduces the amplitude of neural fluctuations in those channels. In contrast, channels above Fc have effectively narrower band inputs, and thus increased fluctuation amplitudes.

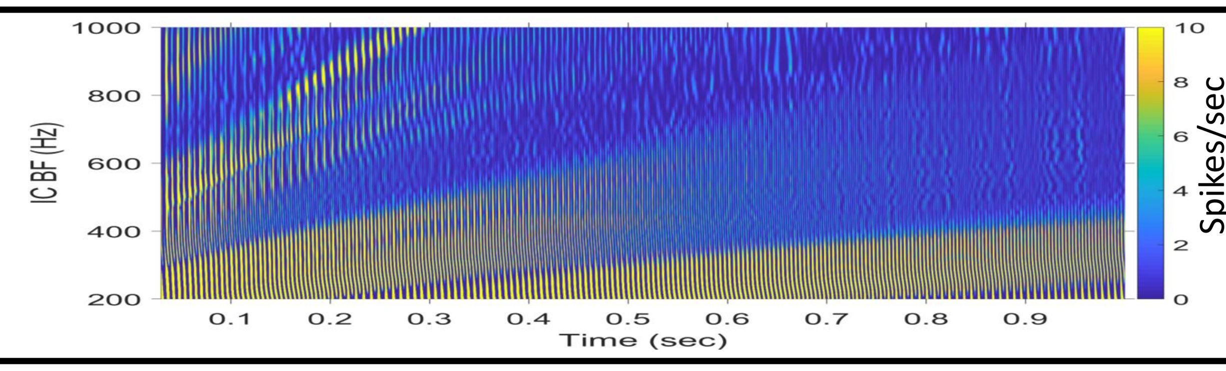
Summary

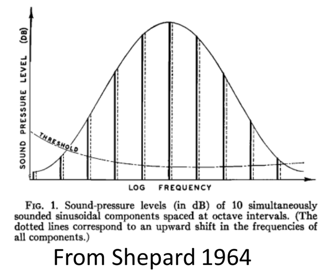
We outline a framework for neural coding of pitch:

- Neural fluctuation amplitudes in AN fiber responses vary across frequency channels, due to capture by harmonics and/or changes in cochlear amplification caused by the stimulus spectrum.
- A simple IC model with bandpass tuning to amplitude modulations converts peripheral neural fluctuations into an IC rate profile.
- Pitch is encoded in patterns across the IC rate profile:
  - For harmonic sounds, the pattern is a series of troughs at harmonic frequencies and peaks in intermediate channels.
  - For aperiodic sounds, the patterns have minima (similar to the troughs in response to harmonic sounds) at frequencies corresponding to perceived pitches.
- In general, single or multiple minima in the IC rate profile encode the pitch of these examples.
- Other IC response types, such as band-reject or low-pass modulation transfer functions, would contribute to richer and more robust response patterns.

SHEPARD TONE

When individual harmonics shift in frequency over time, as in the Shepard-Risset glissando (see Vernooij et al., 2016), the contrast in fluctuations across AN channels and corresponding contrasts in the IC rate profile vary over time. The long-term increase in frequency of dips in the IC rate profile are consistent with the perceived pitch, which continuously increases over time.





From Shepard 1964

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