

WHY DO OCTAVES SOUND THE SAME

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## Octave

Relation between two tones which fundamental frequencies ratio stands on 2:1

Base of the tonal music worldwide

Melodies played in parallel octaves are in unison

## Why octaves sound the same?

Hyphothesis:

Our perceived similarity of octave-related tones derives from other properties of octave interval – namely spectral fusion, sensitivity to interval tuning, and generalization of response to common fundamental – which are qualitatively similar to properties of larger intervals in harmonic series.

There is a mechanism in which neural circuits in the brainstem inferior colliculus detect coincident firing of neurons tuned to harmonics of a fundamental to compute the periodicity pitch; occasional skipped firings lead to excitation of subharmonically tuned neurons, causing a note to sound like its subharmonic octave.

## Consonance

Western tonal music tradition emphasizes a particular set of intervals called consonances, meaning, literally, 'together-sounding.' Not all musical cultures value this same set of intervals, and untrained observers show no evidence for 'natural' categories for musical intervals (Burns 1977). One consonance, however, is absolutely universal across all music cultures. This is the octave.

## Pythagorus

Circa 500 BCE, Pythagorus explained that simple ratios of the lengths of vibrating strings gave consonance.

## Helmholtz

In 1885 von Helmholtz correctly hypothesized that the ear takes a Fourier-like transform of the pressure wave and consonance was actually the minimization of beat patterns risen from tones and their harmonics.

## Lipps

Lipps modified Helmholtz's argument, saying that it applied not to physical vibrations but to mental excitations (1905).

## Comparing the similarity of each harmonic to its fundamental

Kallman (1982) attempted just such a study, and found that similarity decreased monotonically with interval size: octaves were no more similar to the target than any other nearby interval. One of his musical subjects did rate octaves as more similar than neighboring intervals, but this is uninterpretable: for this subject, do octaves sound the same because musical training taught they did, or was there a genuine perceptual similarity?

Allen (1967) found precisely the same dichotomy between musically trained and untrained subjects.

To investigate the octave, one must use measures of similarity that do not rely on subjective judgments.

## Perceptual similarity between two octave-related tones

Bachem (1954) realized that people with absolute pitch sometimes place notes in the wrong octave with the right note name.

Plomp (1973) found that pure-tone pairs are sometimes confused with their inversions, counterparts in which one note is transposed in the direction of the other by an octave.

Shepard (1964) demonstrated that a harmonic complex containing all frequencies standing in a ratio of  $2^n$  to a given reference frequency — all octaves of a given pitch — fuse into a single organ-like pitch with ambiguous tone height; and that pairs of these tones are perceived non-transitively.

Demany (1984) presented evidence that 3-month-old infants are less surprised by tonal sequences in which one note is replaced by its octave than those in which that note is replaced by a seventh or a ninth.

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## Perceptual similarity between two octave-related tones

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Blackwell and Schlosberg (1943) showed that rats trained to respond to one frequency have stronger generalization to an octave subharmonic than to other lower inharmonic frequencies.

Humphreys (1939) based on skin galvanometry measurements revealed that after mild shock conditioning against one frequency humans have subconscious generalization to octaves.

## Octave equivalence

All-octave equivalence is the perception that all octave-related notes, e.g. double-octaves, triple-octaves, sound the same.

Nearest-octave equivalence is the perception that single octaves sound more similar than multiple-octaves do, and that non-octave harmonics sound more similar than even slightly higher octave harmonics.

## Hypothesis

only nearest-octave equivalence is present in the musically untrained; training or musical exposure creates all-octave equivalence by transitively associating octaves.

## Pitch Perception

Our brains are capable of recreating a missing fundamental which we perceive as a pitch when we artificially stimulate with a few upper harmonics of some base frequency, or mask the fundamental with noise (Licklider 1954).

Experiments:

Schouten (1962) : a complete harmonic complex without the fundamental;

de Boer (1976) : a set of five;

Ritsma (1962) : three;

Houtsma (1971) : two harmonics;

Houtgast (1976): a single harmonic \*

(\* ) only if noise were present and if attention were directed to the expected pitch region

## Pitch Perception and Auditory Nerve firing

Auditory nerve fibers are known to phase-lock with acoustic waveforms, firing stochastically at peaks of vibration.

Cariani and Delgutte (1996) demonstrated that the perceived pitch for both resolved and unresolved harmonic stimuli was predicted by pooling the temporal information of all auditory nerve firings and identifying the most common interspike interval one could predict.

## Time dependence of pitch identification

According to Steinschneider (1998), stimuli with resolved and unresolved harmonics seem to be perceived by different mechanisms.

White and Plack (1998) showed that the dependence of pitch identification on stimulus duration was different for these two categories of tones: pitch determination from unresolved harmonics improved with continuous stimulus duration up to 80 ms, whereas that from resolved harmonics was established within about 20 ms.

One implication is that resolved harmonics generate useful information in spatially separated neural channels, whereas unresolved harmonics yield information only through temporal structure of pooled responses which must be interpreted for a longer time.

## A possible neural mechanism of pitch perception

Recent psychophysical, encephalographic data, brainstem single-unit recordings, and anatomical evidence suggests a specific neural circuit in the inferior colliculus may generate the missing fundamental (Braun 1999).

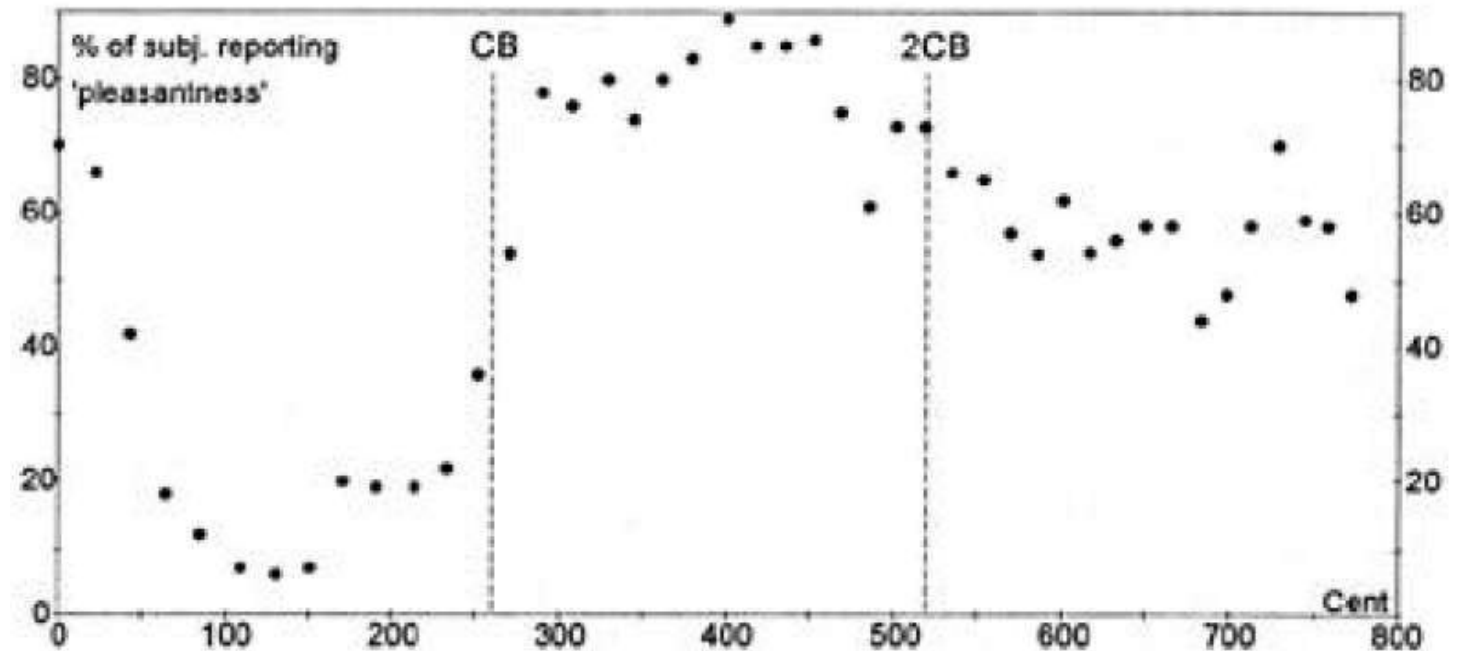
Frequencies within the critical band, typically one quarter-octave in width, fuse into a single percept, while frequencies separated by more than one critical band are resolved (Rasch 1982).

This poorly resolved frequency response is not present in cochlear vibrations or in auditory nerve responses (Pickles 1979), but is found in noise-masking curves of single-neuron recordings from the inferior colliculus (Ehret 1985). Neurons in the inferior colliculus are excited maximally by a particular frequency (Schreiner 1997).

## A possible neural mechanism of pitch perception

Critical bands are hypothesized to arise from this structural arrangement (Schreiner 1997); anatomical evidence supports this notion. Inhibitory effects of stimuli within a critical bandwidth were found to exist at a cellular level and were localized to individual lamina, measured by activity-induced labeling of tissue in the inferior colliculus (Webster 1985).

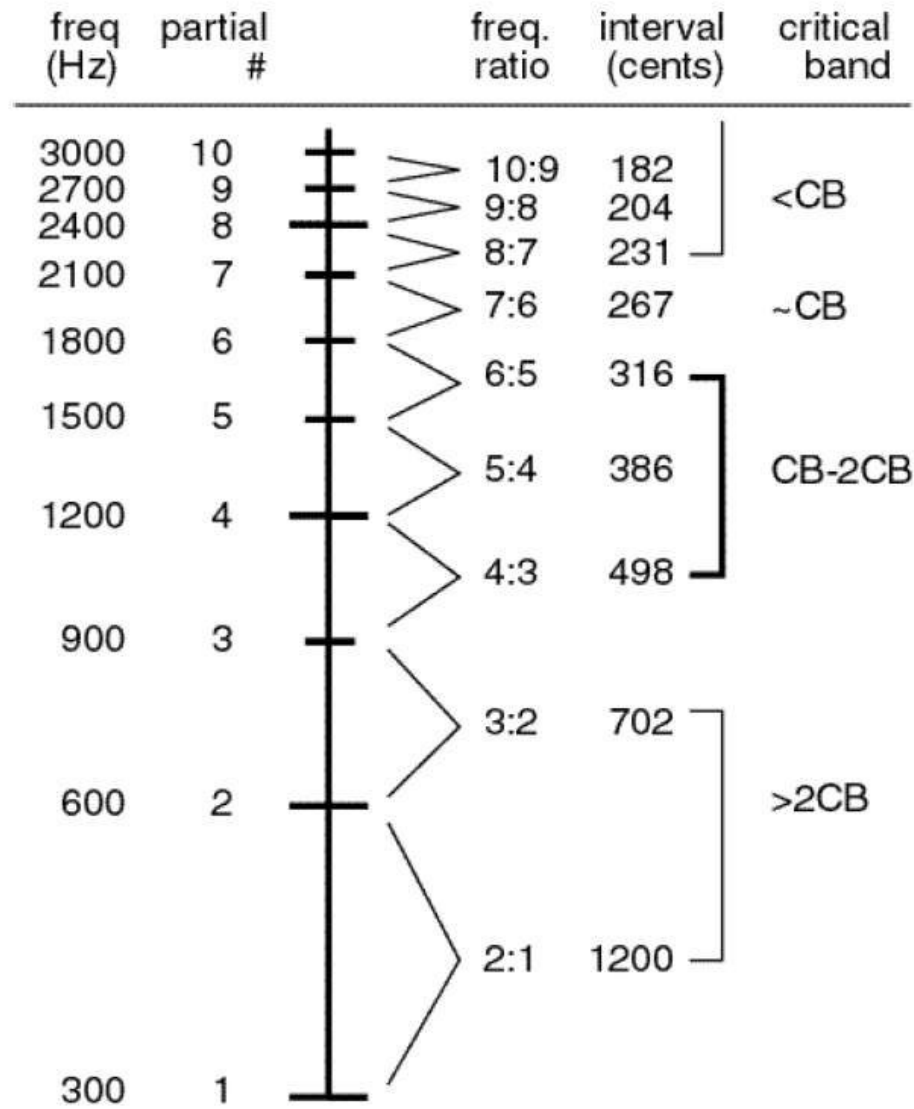
Braun (1999) emphasizes the finding of some specific next-neighbor axonal connections in Malmierca (1995), and claims this as a possible anatomical substrate of a previously unnoticed double-critical bandwidth (2CB) which he observes in pooled psychophysical data.



Compiled data of psychophysical percepts as a function of interval size (in cents, which is a logarithmic measure of frequency ratio  $r$ : cents =  $1200 \log_2 r$ ). Note here the vertical lines demarcating pitches' trends toward unpleasant for intervals less than one critical band (CB = 260 cents), neutral for those larger than two critical bands (2CB), and pleasant for those between one and two critical bands (from Braun 1999).

# Introduction

Why do octaves sound the same?

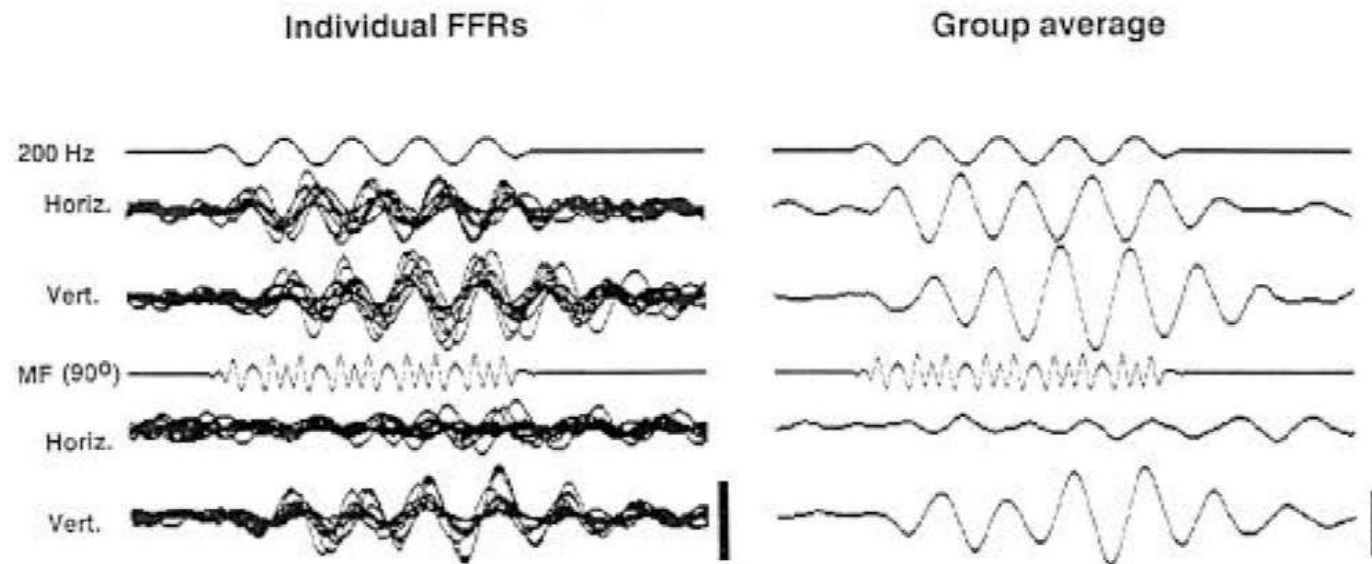


Harmonics 3-5 fall between one and two critical bands (from Braun 1999).

## Phaselocked Neurons

A coincidence detector may have already been found in the whole-cell patch-clamp recordings of Covey et al. (1996).

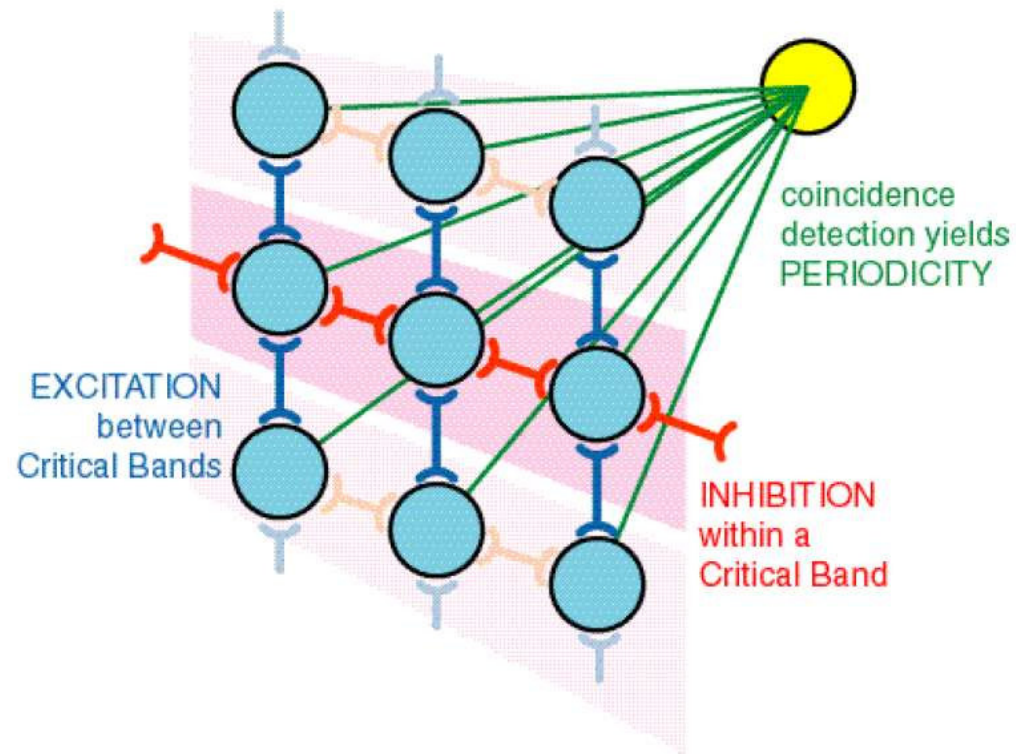
Schwarz et al. (1993) also found oscillating cells in the rostromedial area of the inferior colliculus, which had preferred frequencies that varied from cell to cell to cover four octaves despite the lack of any phaselocked input due to a surgical removal of the entire inner ear.



Electroencephalogram (EEG) of Frequency Following Response (FFR) to pure tone and missing fundamental stimuli. From top to bottom, traces are: pure-tone stimulus waveform, horizontal and vertical current dipole responses, a missing fundamental (MF) stimulus of three harmonics with one component 90° out of phase with the others (for minimum amplitude modulation), and horizontal and vertical current dipole responses. EEGs from horizontal current dipole correspond to auditory nerve fibers; those from vertical dipoles correspond to brainstem activity. Vertical bars represent 0.5  $\mu\text{V}$  for individual and 0.25  $\mu\text{V}$  for group FFRs; horizontal dimension shows 50 msec of time. Note that the vertical current dipole response to the missing fundamental is larger than the horizontal response (from Galbraith 1994).

## Hypothesis

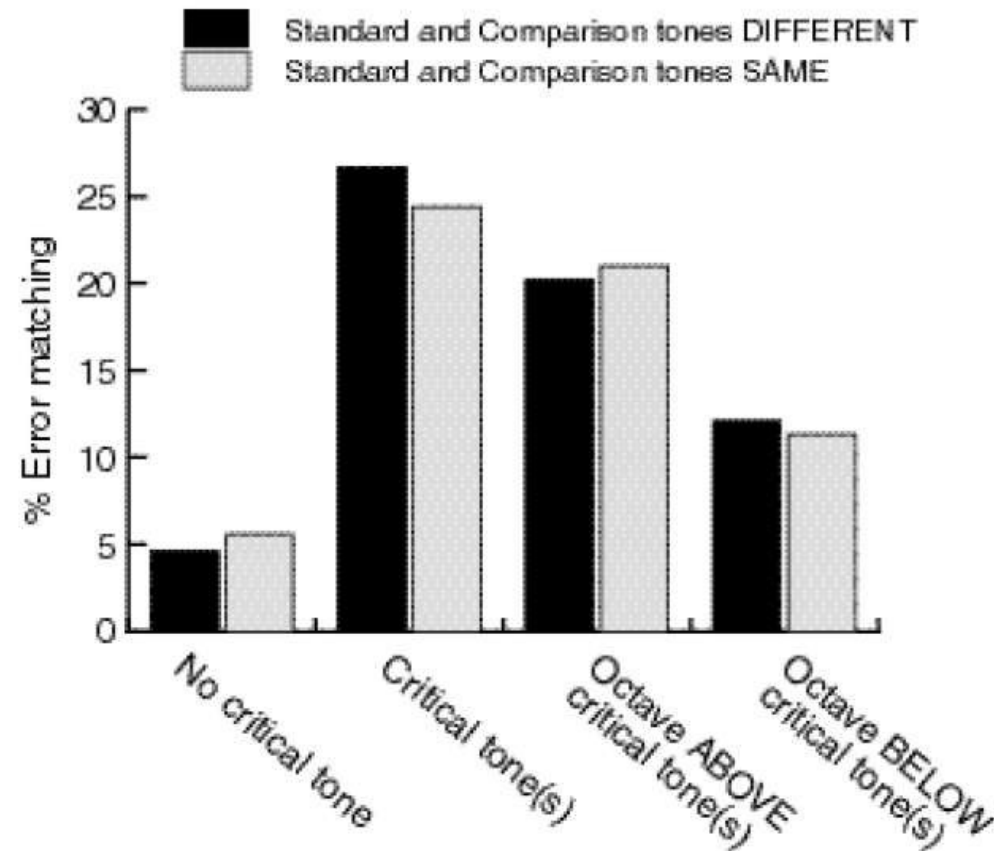
Why do octaves sound the same?



Neural networks for calculating the missing fundamental or periodicity of a stimulus. Frequency-tuned neurons (cyan circles) in the inferior colliculus are arranged in bands of similar tunings (light magenta). Connections are inhibitory (red) within a layer, and excitatory (blue) between neighboring layers. A coincidence detector (yellow) receives input (green) from nearby neurons and then fires with periodicity of the stimulus waveform.

## Hypothesis

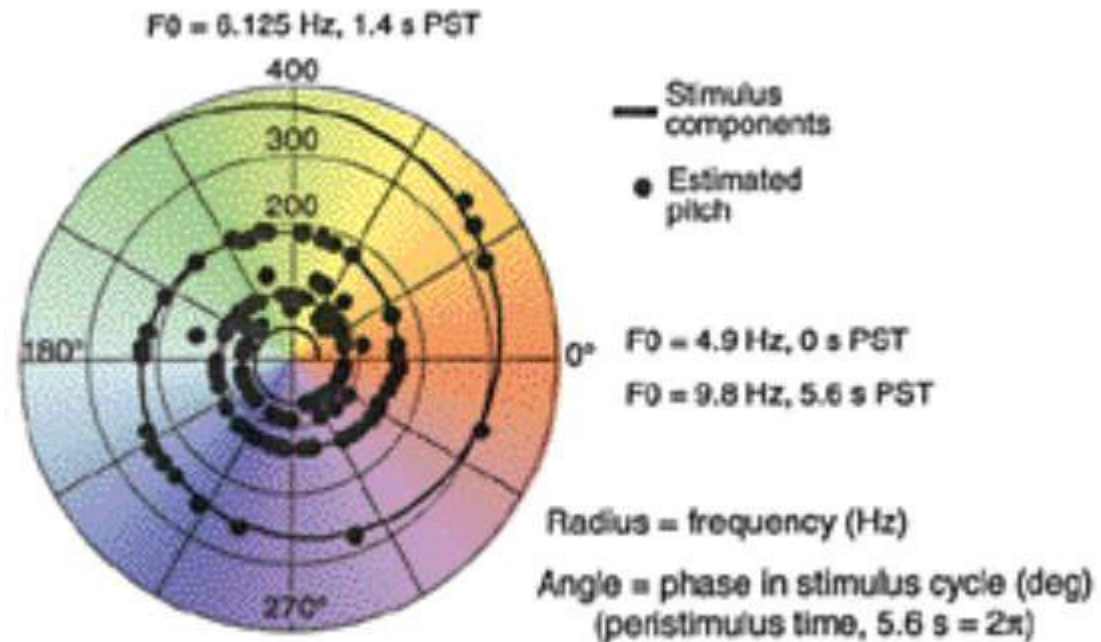
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Octave generalization demonstrated by interference with pitch memory. Two tones are presented, subjects are asked whether they are the same or different, and the fraction of errors is recorded. Other 'interfering' tones are presented between the standard (target) and comparison tones, lowering the fraction of correct responses. When an interfering tone matches the target tone, subjects make more mistakes in pitch memory; the same holds for the octaves of the target tone, but more so for an octave above than for an octave below (from Deutsch 1973).

## Hypothesis

Why do octaves sound the same?



Cariani and Delgutte's algorithm (1996) predicts subharmonic pitch mistakes. Dots represent pitches estimated as the most common interspike interval in pooled recordings from cat auditory nerve fibers, when stimulated by Shepard tone complexes composed of all octaves of a given pitch. The color represents the pitch chroma on which the tone is based. The black spiral line represents frequency components physically present in the stimulus. Most estimated pitches lie on this line. Those that do not lie instead on another spiral (not drawn) which corresponds to the second subharmonic of one of the frequency components, which is not present in the stimulus.

## Hypothesis

octave similarity arises because periodicity detection in the inferior colliculus can mistakenly excite subharmonic responses, and that the octave, while naturally the most similar interval amongst harmonics, gives rise to alloctave equivalence only as a result of learning.

## Consequences

all comparisons between a fundamental and its harmonics or subharmonics would exhibit anomalous psychophysical effects (in tuning sensitivity, pitch fusion, generalization) that differ from comparisons between inharmonically related frequencies;

certain effects would be stronger for harmonics than for subharmonics;

effect strength would decrease with harmonic number;

all-octave generalization would be stronger in trained musicians than in untrained.