AUDL 4007
Auditory Perception

Week 6

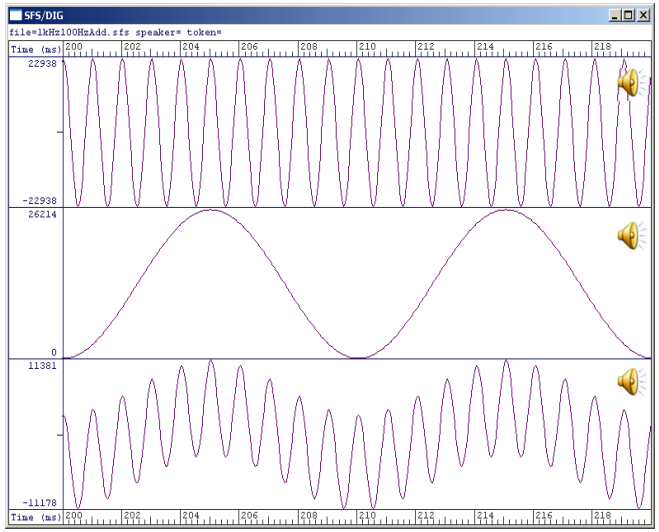
Envelope and temporal fine structure (TFS)

- Envelope and TFS arise from a method of decomposing waveforms

The 'classic' decomposition of waveforms

- Spectral analysis ...
  - Decomposes a complex wave into a sum of sinusoids to give a *spectrum*

Adding waves



1 kHz sinusoid

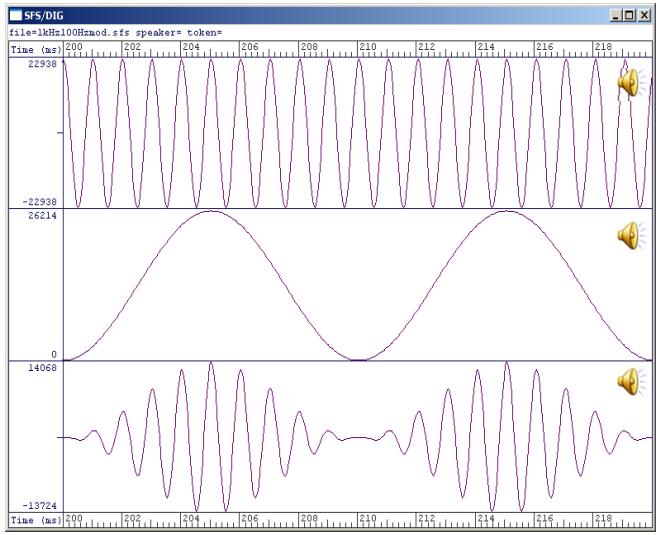
+

100 Hz sinusoid

=

a complex wave (with two spectral components)

Multiplying (*modulating*) waves



carrier at 1 kHz (fine structure)

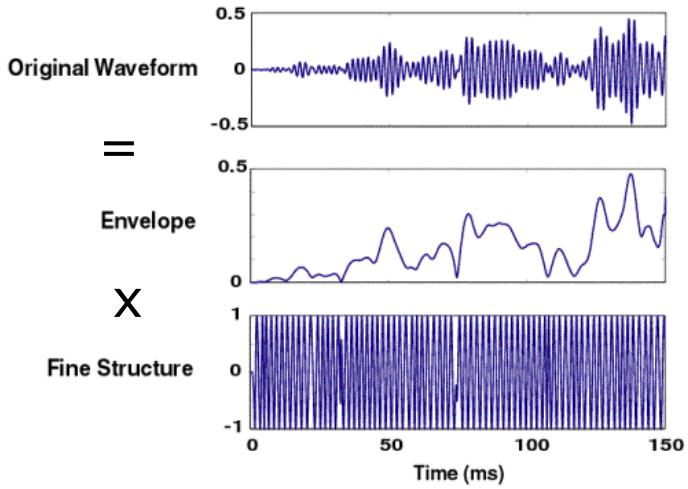
x

modulator at 100 Hz (envelope)

=

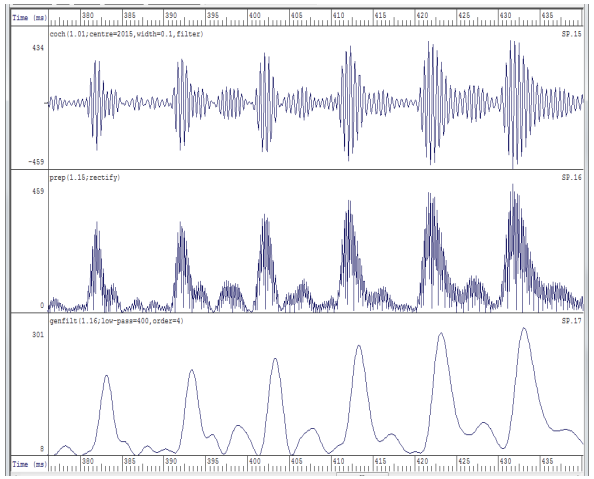
amplitude-modulated wave

Can work this backwards too



http://research.meei.harvard.edu/Chimera/motivation.html 24 JAN 2010

Extracting envelopes



original wave

full-wave rectification

smoothing at 400 Hz (low-pass filtering)

A Hilbert transform

- can uniquely decompose a wave into the *product* of two waves
  - *envelope*
  - *temporal fine structure* (TFS)
- Unlike spectral analysis, the constituent waves are usually complicated
- A warning!

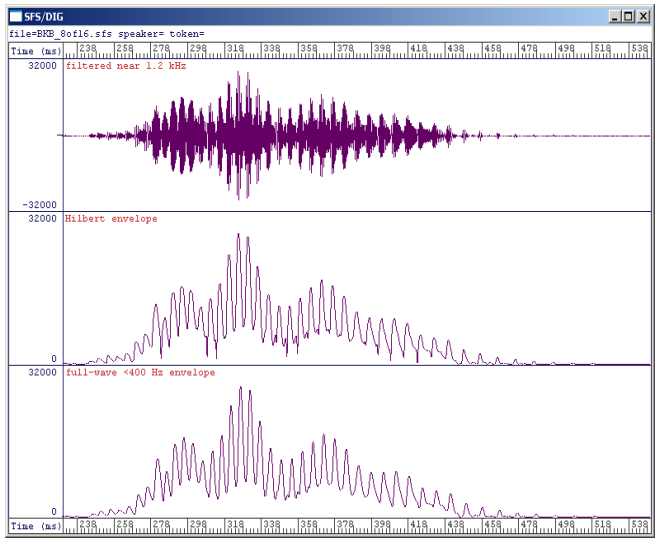
The outcome of a Hilbert decomposition

a time-varying envelope

a constant amplitude sinusoid varying in frequency/phase

think of all waves as being made by multiplying one wave (the *envelope*) against another (the *temporal fine structure*)

There's more than one way to extract an envelope

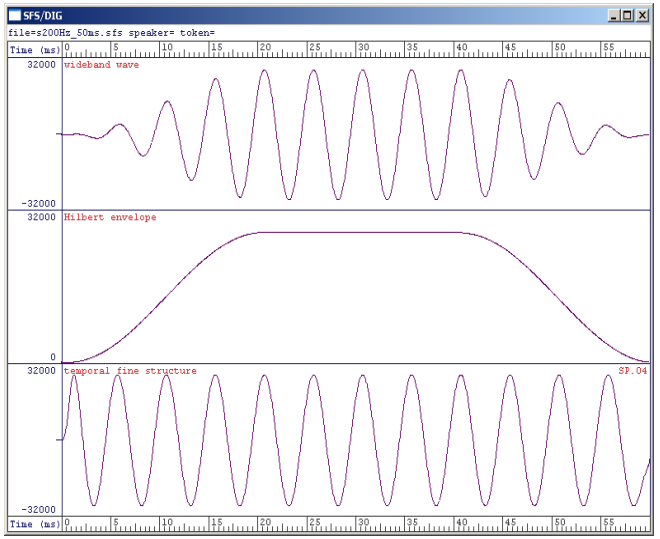


original wave

Hilbert envelope

envelope from full-wave rectification and smoothing at 400 Hz

A simple example: a tone pulse



original wave

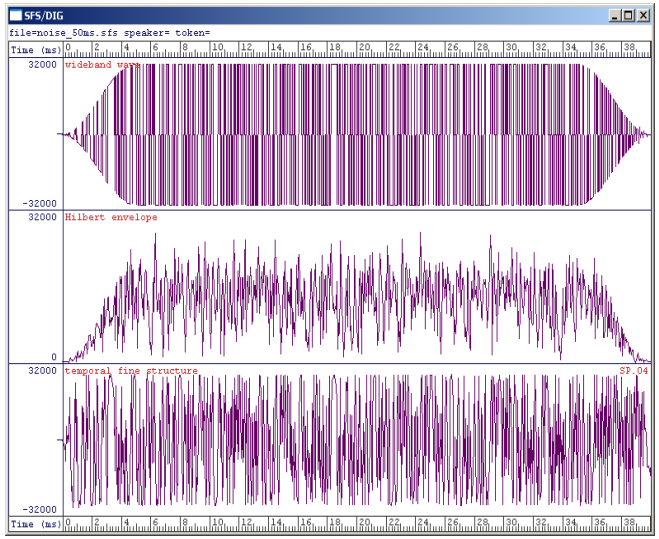
=

envelope

x

TFS

A simple example: a noise pulse



original wave

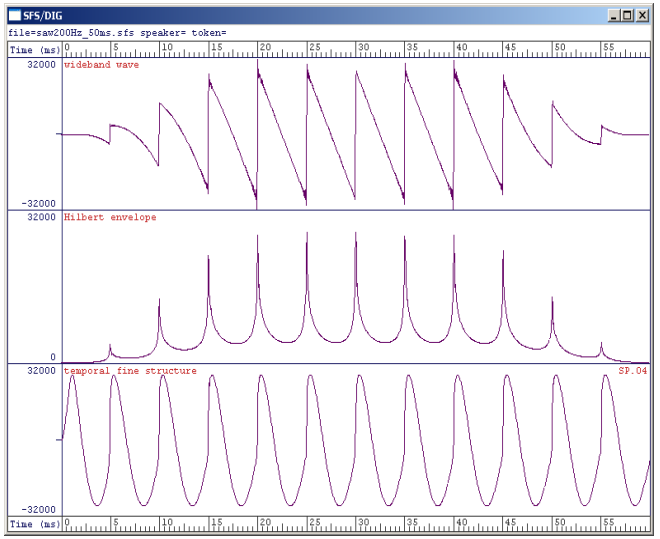
=

envelope

x

TFS

A simple example: a sawtooth



original wave

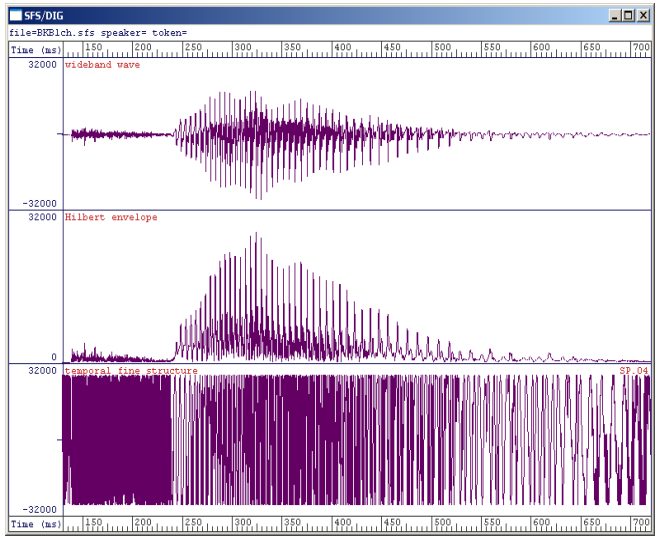
=

envelope

x

TFS

Decomposing a ‘clown’



original wave

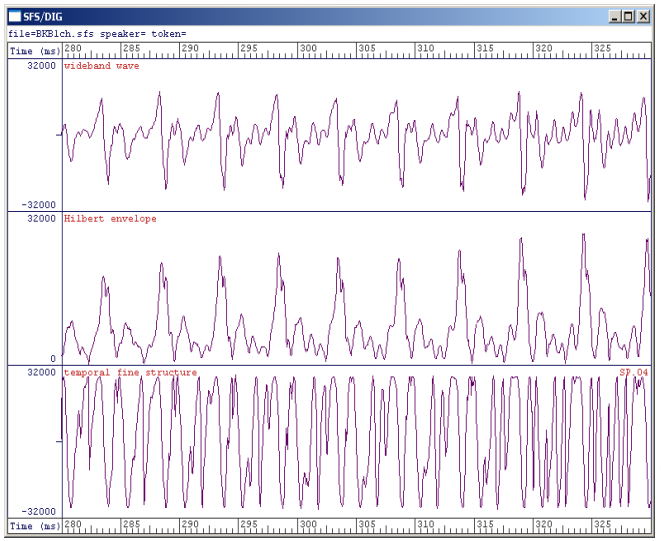
=

envelope

x

TFS

Look up close



original wave

=

envelope

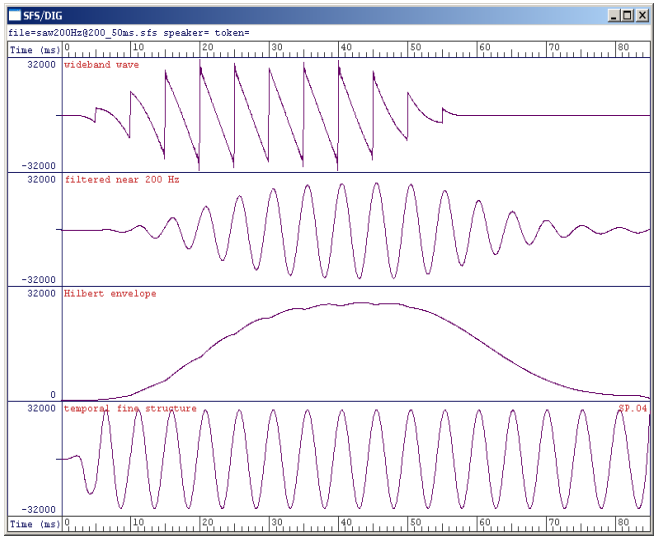
x

TFS
(hardly a ‘sinusoid’!)

A complication

- The auditory periphery acts as a kind of a filter bank
- So auditory nerve fibres transmit information about a bandpass filtered version of the original wide-band wave
- It only makes sense to apply the decomposition to a bandpass filtered version of the original wave
- Filter bandwidth will depend on
  - whether a listener is hearing-impaired
  - frequency in normal and hearing-impaired listeners
  - whether a listener is using a cochlear implant

Sawtooth: auditory filtering @ 200 Hz



original wave

filtered wave

=

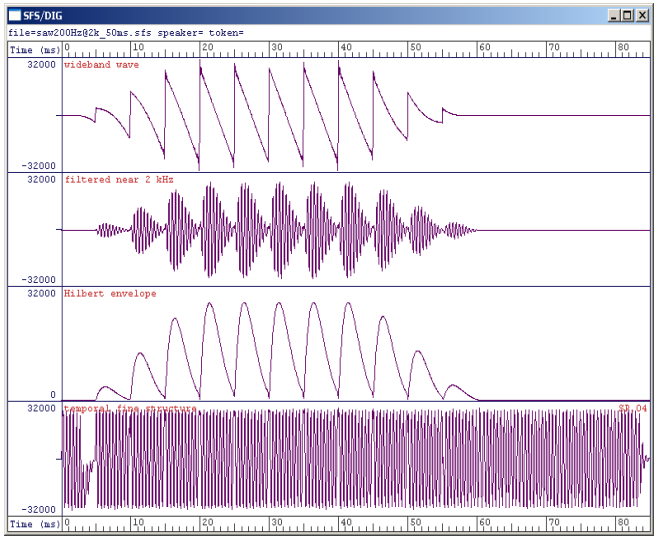
envelope

x

TFS

resolved harmonics — no evidence of periodicity in envelope; strong in TFS

Sawtooth: auditory filtering @ 2 kHz



original wave

filtered wave

=

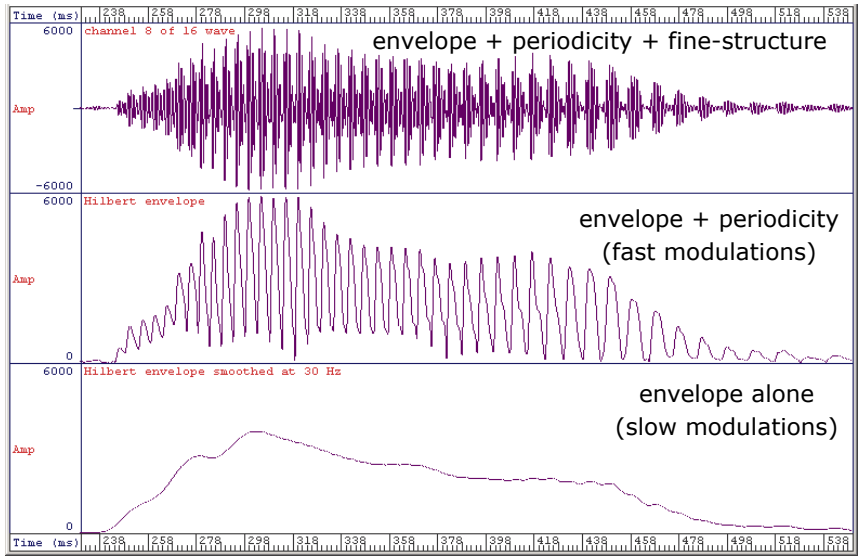
envelope

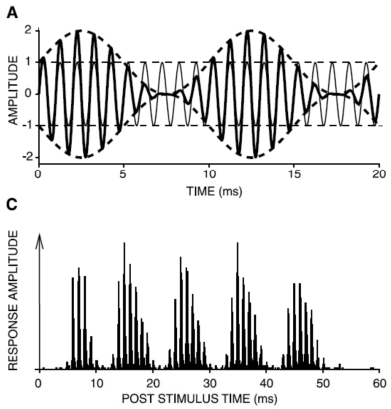
x

TFS

unresolved harmonics — periodicity evident in envelope; weak in TFS

A 3-way partition of temporal information





All 3 temporal features preserved in the auditory nerve

(slower modulations not shown)

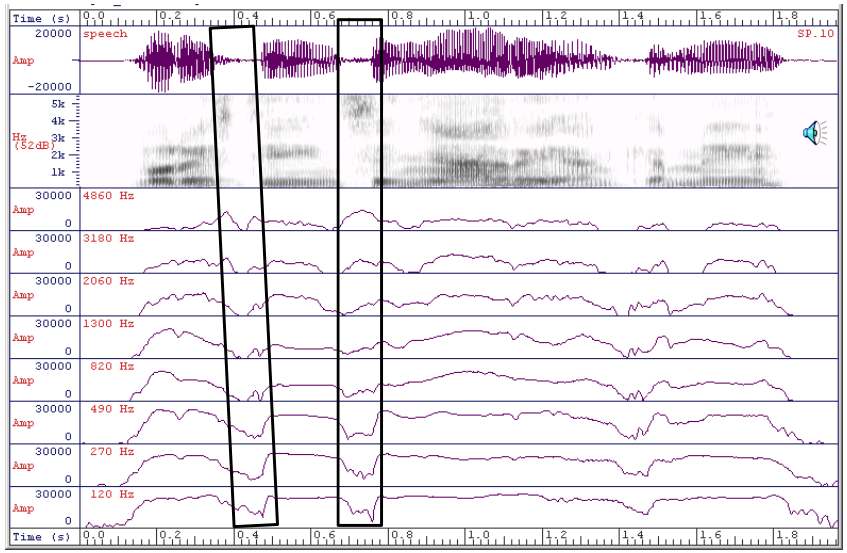
FIG. 1. *A*: superimposed waveforms of an unmodulated 1,000-Hz tone (thin line) and the same tone sinusoidally amplitude modulated (AM) (thick line) at 100% with a modulation frequency of 100 Hz, according to *Equation 1*. Dashed lines indicate the envelope. The amplitude is referenced to the peak amplitude of the unmodulated tone. *B*: idealized spectrum of the AM tone in *A*. At 100% modulation, the amplitude of the sidebands is half that of the carrier, i.e., a difference of 6 dB. *C*: average response in the form of a poststimulus time (PST) histogram of a nerve fiber to the signal shown in *A* (stimulus duration, 50 ms). *D*: spectrum of the PST histogram in *C*. The components at carrier frequency (f_c) and $f_c \pm$ modulation frequency (f_m) indicate that there is phase-locking to the fine-structure of the stimulus waveform. The component at f_m is prominently present in the response but is absent in the stimulus (*B*). The small circle on the ordinate indicates the average firing rate.

Joris *et al.* 2004

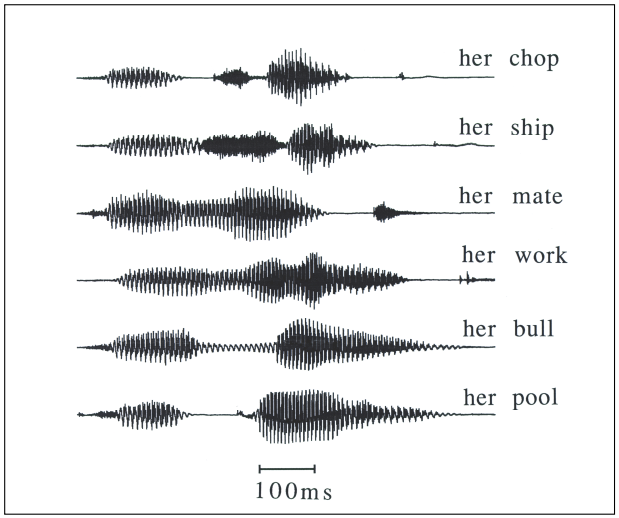
Everyone agrees that …

- 'Slowish' envelopes (<30 Hz or so) are really important for speech perception
- Distinguish two features
  - Envelope variations that are highly correlated across frequency
  - And those that are not.

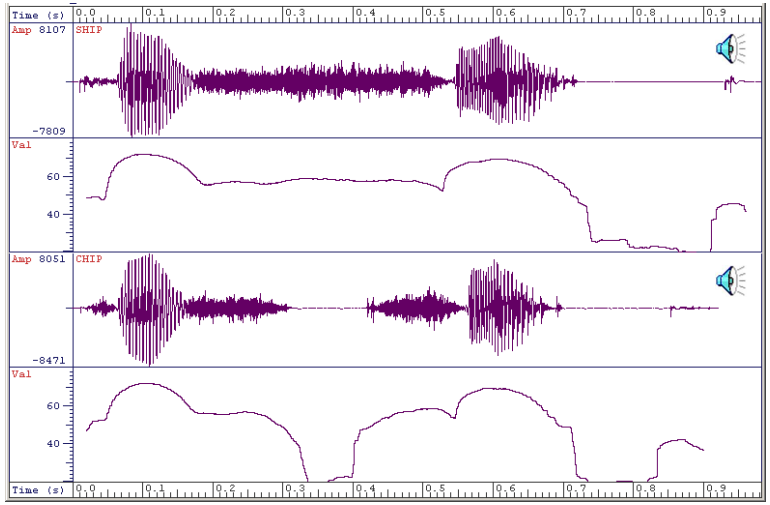
Correlated and uncorrelated (across frequency) envelope modulations



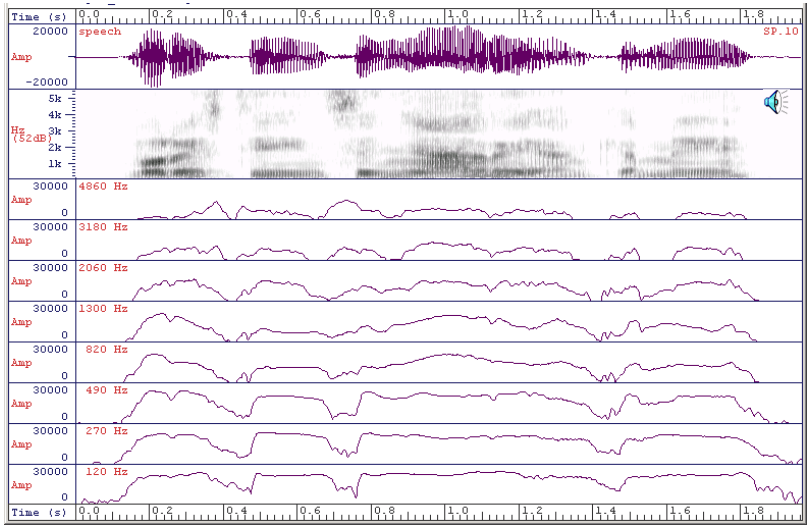
Correlated envelopes in speech – one source of cues to consonants



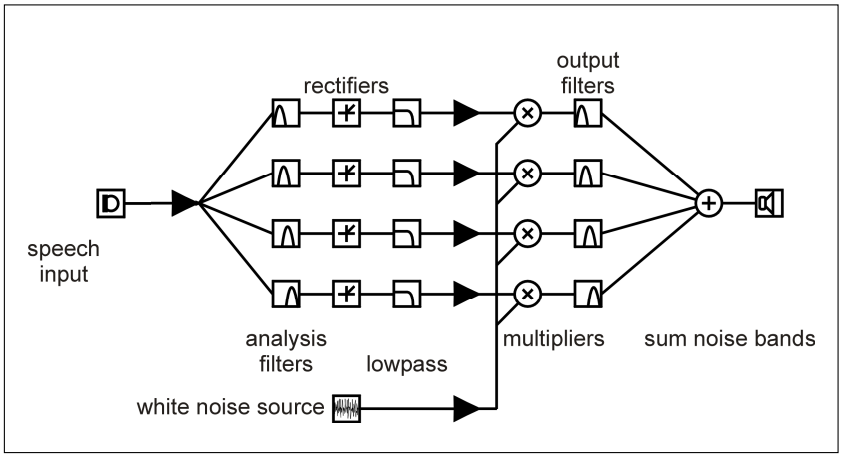
Changing manner of articulation *push ship* vs. *push chip*



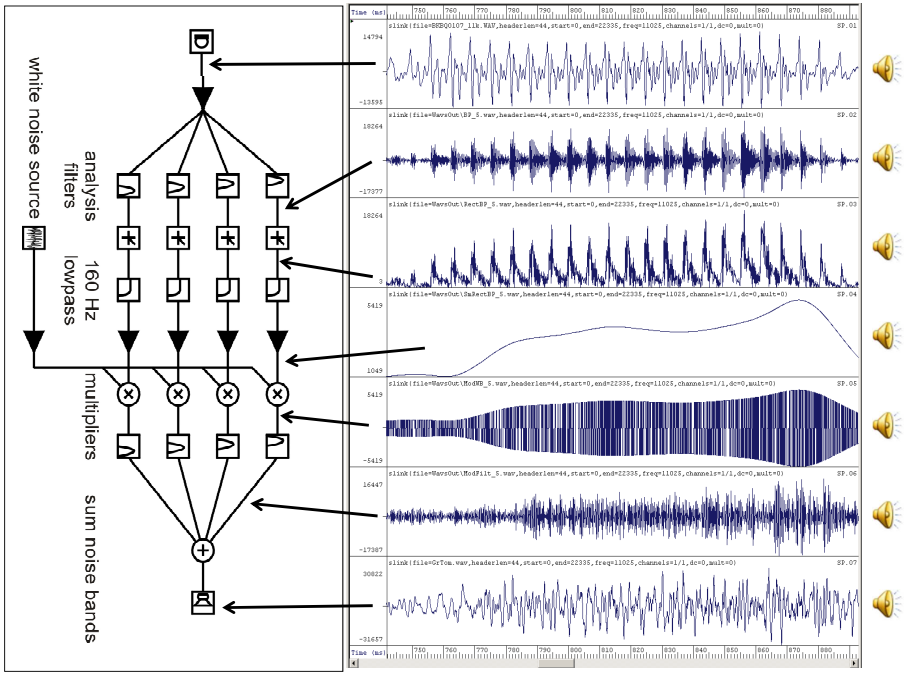
Spectral dynamics are encoded in uncorrelated across-channel envelope modulations

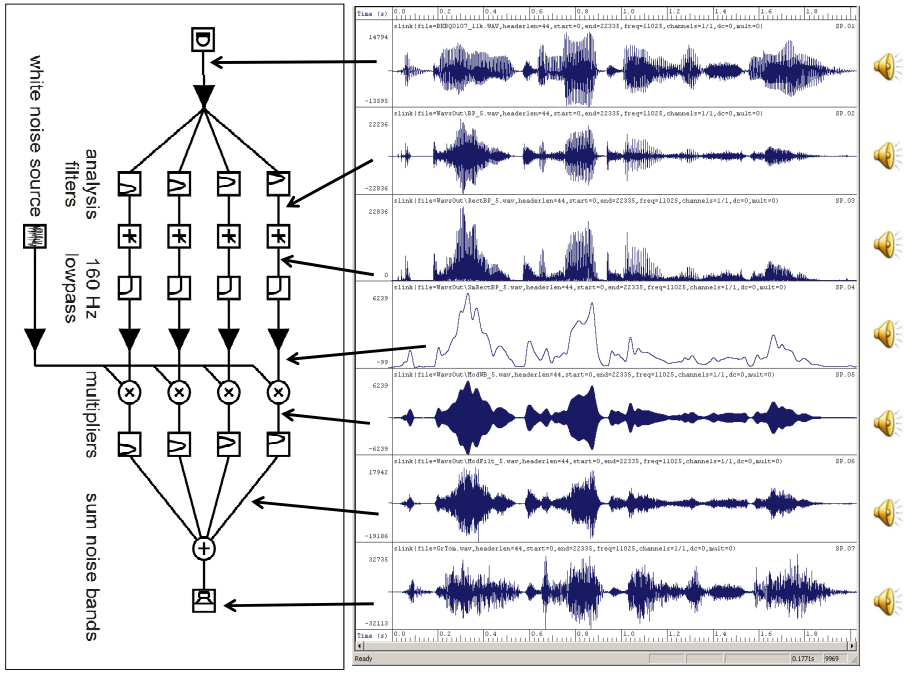


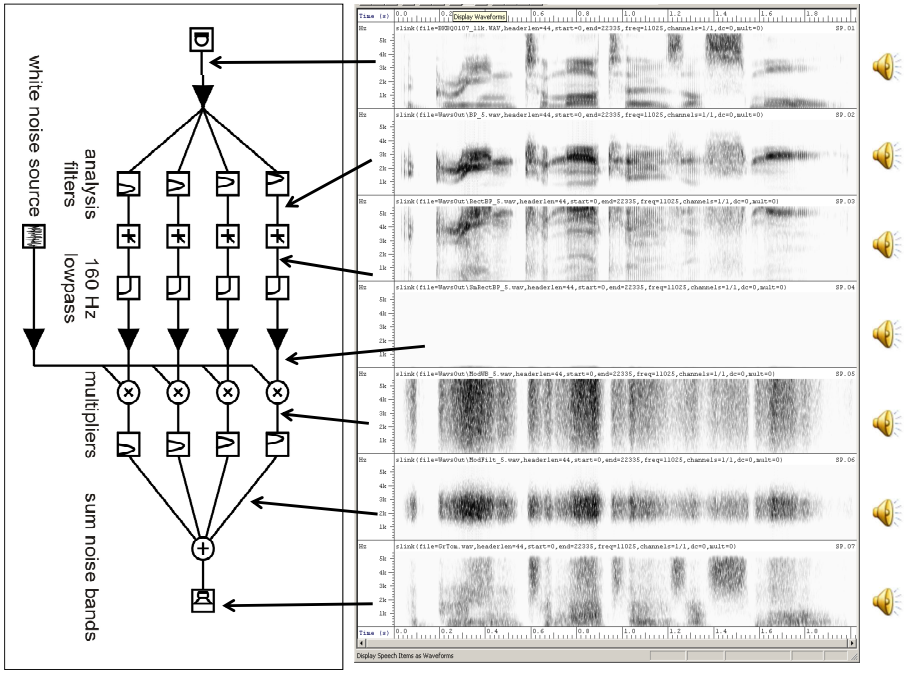
Proof that envelopes are sufficient: Noise-excited vocoding



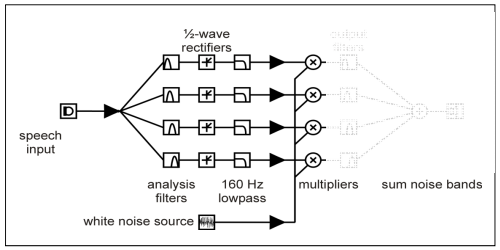
more or less preserves envelopes, destroys TFS

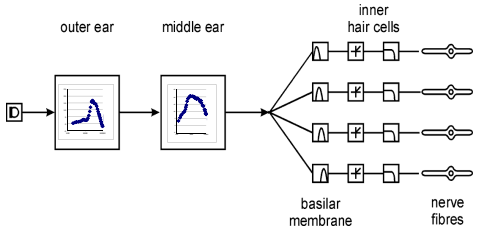




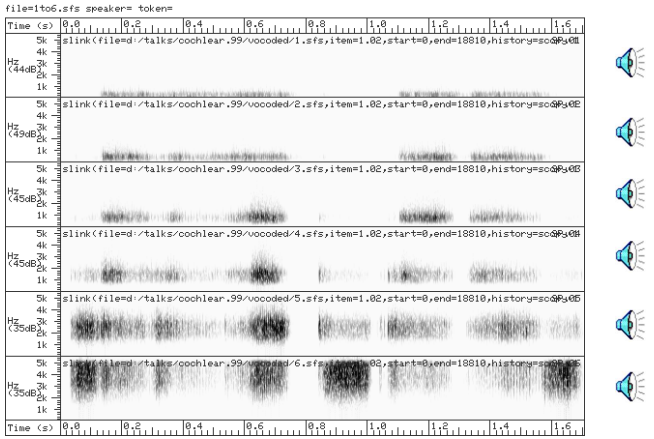


Note similarity to normal cochlear processing

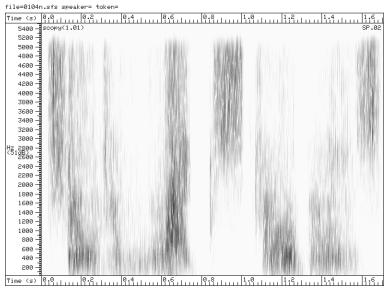


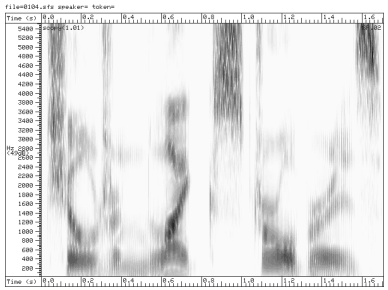


Separate channels in a 6-channel simulation

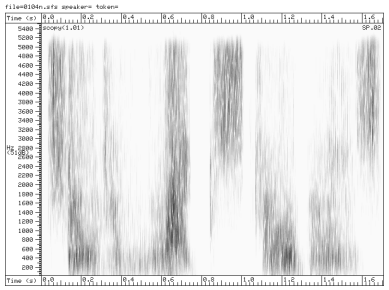


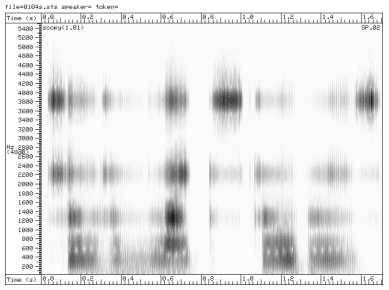
... and when summed together.



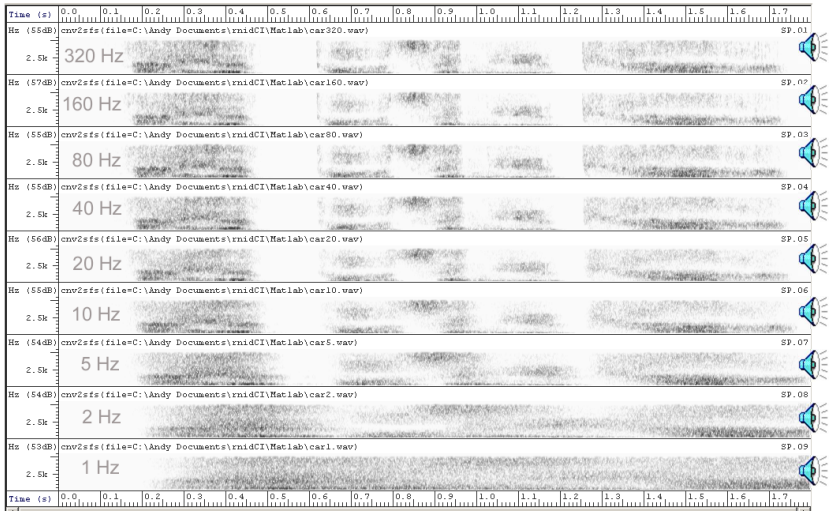


Never mind the quality... feel the intelligibility.





Effects of envelope smoothing on speech - modulations below 10 Hz are most important



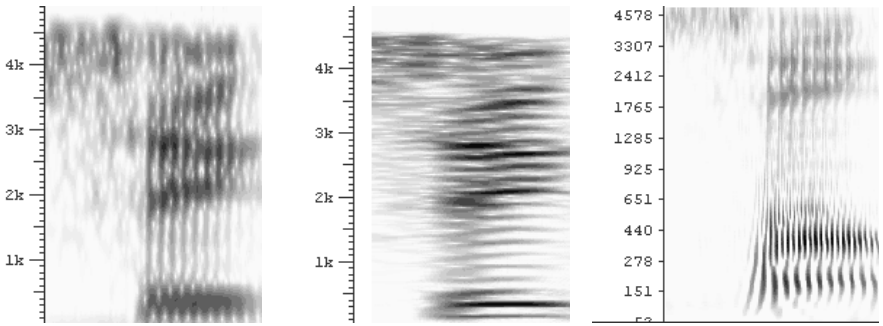
So what's missing in envelope?

- TFS *is* important for …
  - Localisation
  - Perception of melodic pitch
    Intonation and tone, for the TFS of a periodic sound
- In CI research, TFS often used as a code word for 'pitch perception'
  - Even though poor pitch perception may also arise from impaired frequency selectivity.

NHLs do use TFS for pitch

Types of Spectrogram

Wide-band Narrow-band Auditory

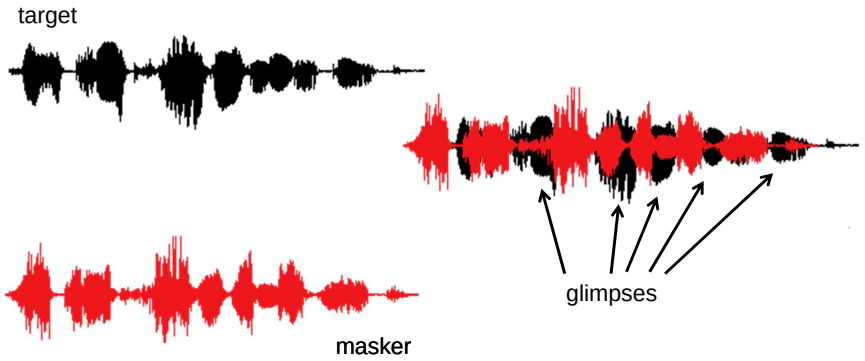


An auditory spectrogram looks like a wide-band spectrogram at high frequencies and a narrow-band spectrogram at low frequencies (but with more temporal structure).

So what's missing in envelope?

- TFS *appears* to be important for …
  - binding together uncorrelated envelope variations across frequency (when periodic)
  - listening in noise generally
  - 'glimpsing' (or 'dip listening') in noises that fluctuate over time (controversial!)

Fluctuating maskers afford 'glimpses' of the target signal



Does TFS have a role in glimpsing?

- CI users (with a very weak sense of pitch) do not appear to be able to glimpse,
- Nor do NHLs in simulation studies...
- And there is speculation that HI listeners (impaired in glimpsing) are also impaired in perception of TFS
- So perhaps TFS is necessary
  - by allowing an efficient auditory scene analysis
  - because it's hard to tell what to listen to when two noises are added together
- But periodicity *per se*, whether in envelope or TFS, may also be crucial
  - Periodicity is strongly cued in TFS at low frequencies which are relatively unimportant for speech intelligibility
  - in the mid-frequency region essential for speech intelligibility, periodicity is reflected strongly in *envelopes*

Summary

- Waveforms (after any filter bank/spectral analysis) can be decomposed into the product of
  - An envelope (something fairly slow)
    - o often divisible into slower and faster components
  - A TFS (something fast)
- Envelope is necessary and sufficient for speech perception in quiet
- One serious limitation of CIs (and HI listeners) especially for speech in noise may be poor access to TFS information
  - But the representation of TFS also depends upon frequency selectivity, so it is not necessarily easy to separate out their effects