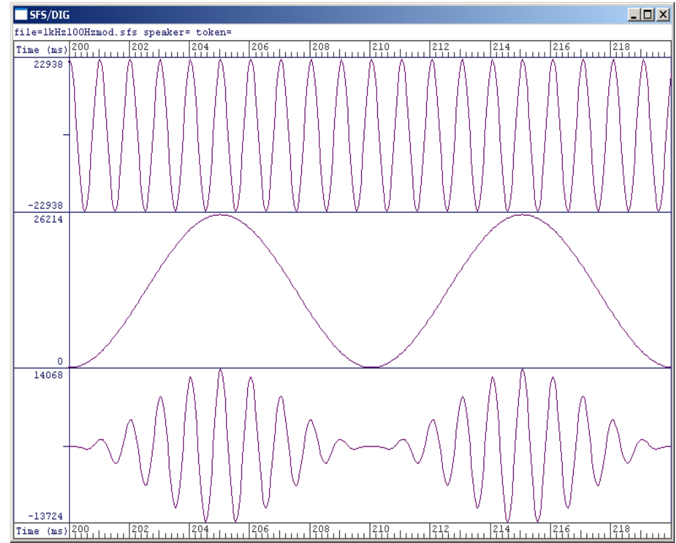
Temporal resolution

Modulating a sinusoid



carrier
(fine structure)

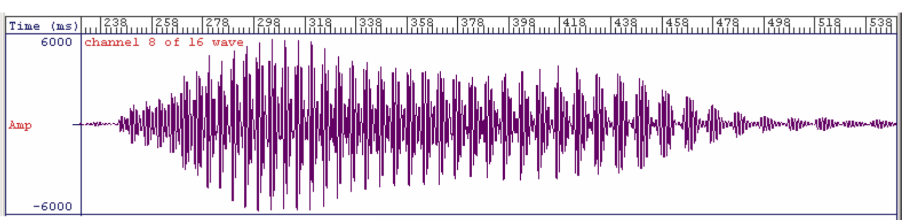
x

modulator
(envelope)

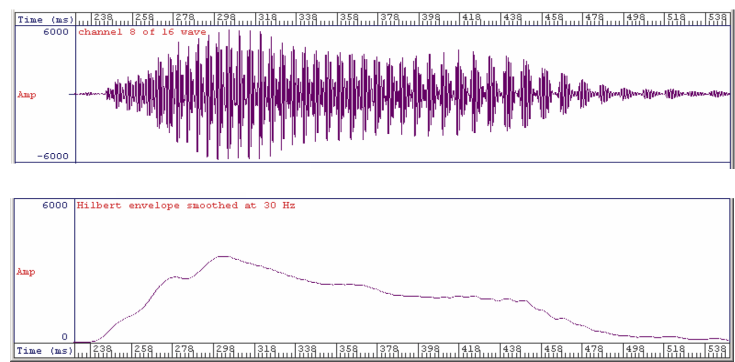
=
amplitude-
modulated wave

Domain of temporal resolution

- Fine structure and envelope
  - fine structure – relatively fast – reflects spectral components of sounds in the sound waveform, and periodicity (in some definitions)
  - envelope is the slower stuff
  - think of all waves as being made by multiplying an envelope against a carrier



Fine structure and envelope



Envelope – reflects changing amplitude of signal e.g., over multiple cycles for periodic sounds

Caveat about ‘temporal resolution’

- Typically defined as reflecting perception of variations over time in …
  - *envelope* (and there are different ways to define envelope)
  - rather than *fine-structure*
- But at least in theory, could concern temporal variations, for example, in frequency of a sinusoid

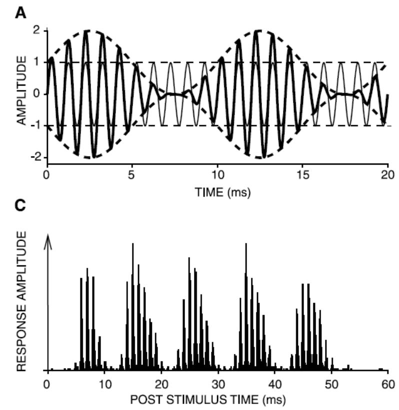


FIG. 1. *A*: superimposed waveforms of an unmodulated 1,000-Hz tone (thin line) and the same tone sinusoidally amplitude modulated (AM) (thick line) at 100% with a modulation frequency of 100 Hz, according to *Equation 1*. Dashed lines indicate the envelope. The amplitude is referenced to the peak amplitude 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 ± 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.

Both kinds of temporal features preserved in the auditory nerve

Joris *et al.* 2004

Limits to temporal coding of fine structure

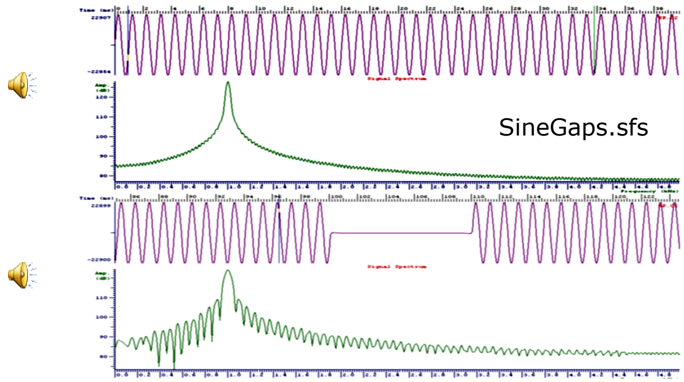
- Frequency coding by phase-locking
  - Declines in precision from 1.5 kHz (700 μs), absent above 5 kHz (200 μs)

Temporal Resolution for envelope most often tested in two ways

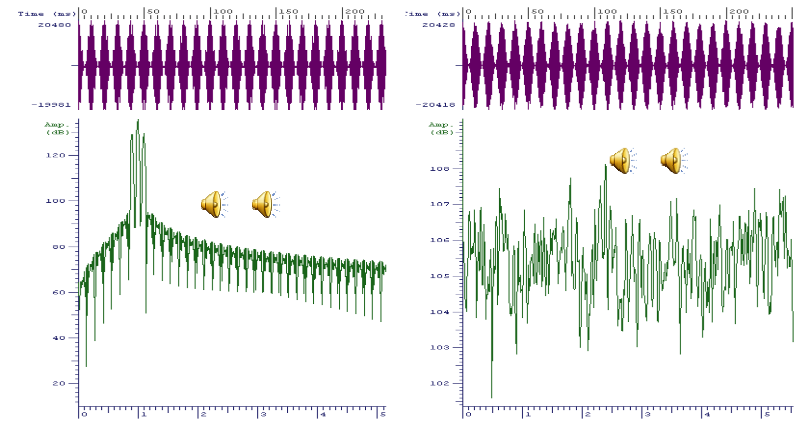
- Both involve *modulation* of the amplitude of waveforms …
  - Gap detection
  - Amplitude modulation
- but this almost always results in spectral changes.
- In other words, you usually cannot change the temporal (envelope) properties of a signal without also changing its spectrum
  - leading to a difficulty of interpretation unless special measures are taken

The need to eliminate spectral cues

- Modulating signals in envelope usually results in spectral changes (broadening, known as *splatter*)
  - e.g., effect of 10 ms gap in spectrum of 1 kHz sinusoid
- Need to avoid listeners hearing spectral changes



Effects of AM on spectrum



100 Hz AM of 1 kHz sinusoid

Spectral sidebands at 900 and 1100 Hz

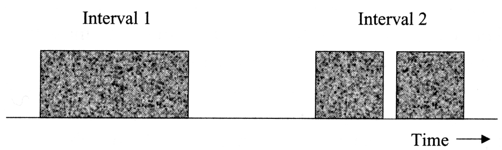
100 Hz AM white noise

Spectrum remains flat

Three possibilities

- Modulate wideband noise stimuli
- Minimise audibility of spectral changes by
  - keeping any sidebands in the same auditory filter as the original signal – allows use of low AM rates with sine carriers
  - and/or adding masking noise to make spectral changes inaudible
- Modulate wideband noise stimuli and filter into bands afterwards
  - but can change extent/form of modulation

Gap thresholds



- Pick the sound with the gap – vary the gap duration to find threshold
- Thresholds for wide-band noise are around 3 ms

Effects of noise spectrum on gap detection

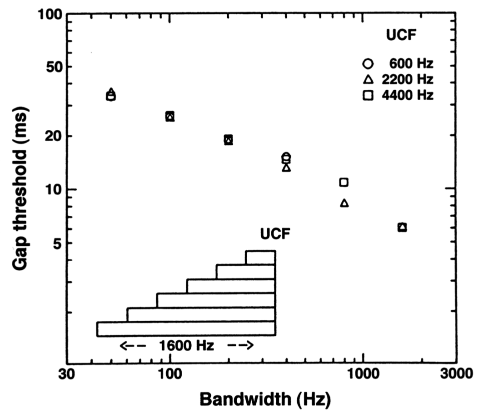


FIGURE 5.4 Gap thresholds for noise bands plotted as a function of the bandwidth of the noise bands. The upper cutoff frequency (UCF) of the noise bands was fixed at one of three values: 600, 2200, and 4400 Hz. The inset bars illustrate schematically how the bandwidth was varied keeping the UCF fixed. Gap thresholds decrease progressively with increasing bandwidth, but are almost independent of UCF. The data are from Eddins *et al.* (1992).

Wider noise bandwidth gives smaller gap thresholds

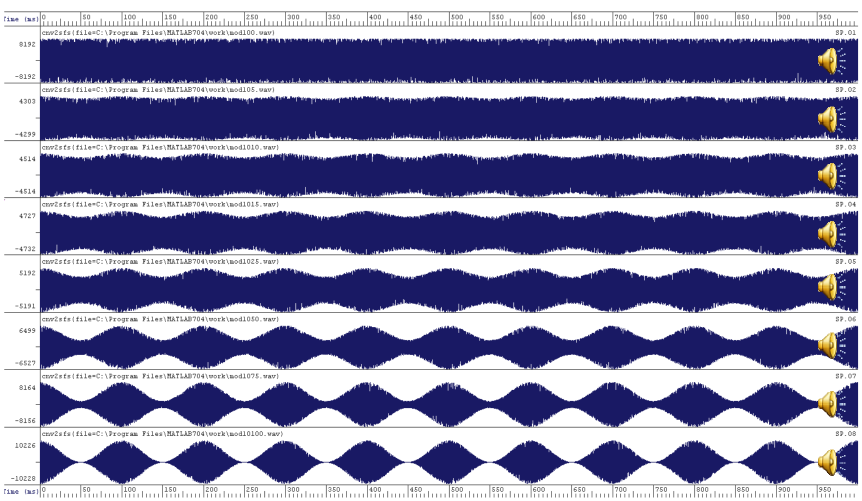
Frequency location of noise (UCF parameter) has little effect

May be because wide bandwidth allows listeners access to information from large numbers of filter channels

AM detection - TMTF

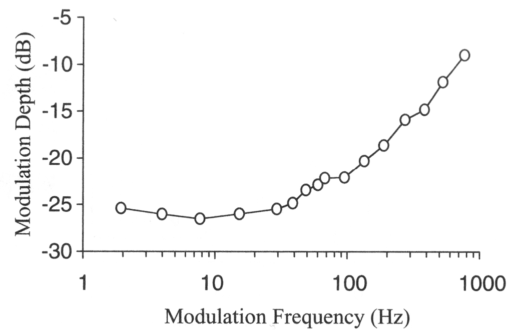
- TMTF – temporal modulation transfer function
- Analogous to an ordinary transfer function or frequency response
  - dealing with frequencies of *modulation* rather than frequencies of a sinusoidal waveform directly
- Analytic approach to temporal resolution
  - Considers temporal modulation across different frequencies of sinusoidal AM
  - As for gap thresholds, wide-band noise is an ideal signal because of the lack of spectral changes.
  - Fixed modulation rate – vary depth of modulation to determine minimum detectable depth

10 Hz modulation rate



TMTF data

- Thresholds expressed in dB as 20 log(m) where m is modulation index



m = 1 gives 0 dB

m = 0.05 gives -26 dB

The function looks very much like a low-pass filter (here inverted)

Upper limit of amplitude modulation detection between 500 and 1000 Hz

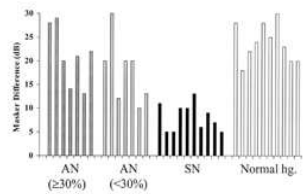
Translating to the clinic: Auditory neuropathy

Temporal resolution in Auditory Neuropathy (AN)

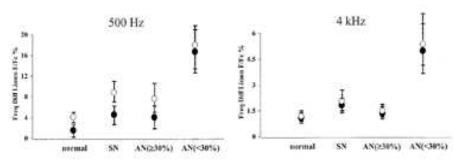
- AN defined by intact OHCs and normal OAEs but lack of CAP and ABR responses.
- Near normal audiometric thresholds but often severe problems with speech perception
- Retro-cochlear impairment
- Likely to involve disruption of phase-locking in auditory nerve

Rance, McKay and Grayden, 2004 (Ear & Hearing)

- Compared children with normal hearing, SNHL, and AN
- Measured
  - Frequency selectivity (simple notched noise method)
  - Sinusoid frequency discrimination
  - TMTFs
  - CNC word phoneme recognition



SNR difference for thresholds in wide-band and notched noise: 1 kHz probe, 500 Hz notch



Frequency discrimination thresholds at 500 Hz and 4 kHz

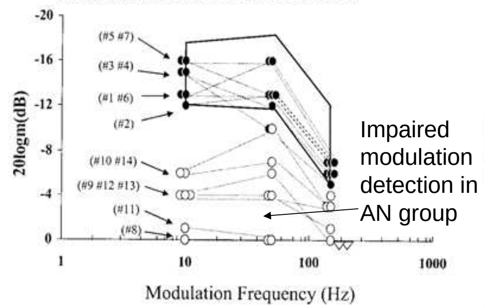


Figure 3. Amplitude modulation detection thresholds (AN subjects). Closed circles represent children in the AN ≥ 30% group, and open circles represent the children in the AN < 30% group. Open triangles show the findings for children in the AN < 30% group unable to detect a modulation depth of 0 dB. The enclosed area shows the mean ±2 SD range for the normal-hearing group.

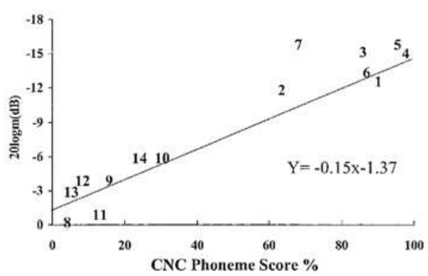


Figure 4. Amplitude modulation detection threshold (10 Hz MF) plotted as a function of CNC phoneme score (AN subjects). The data point for each child is represented by the subject identification number.

Temporal resolution and temporal frequency coding seems impaired in AN

- And both correlate highly with speech scores
- While auditory filtering seems near-normal in many of the AN subjects

A model of temporal resolution – the temporal window

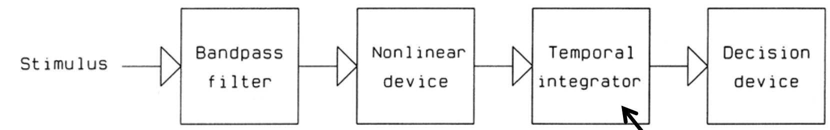
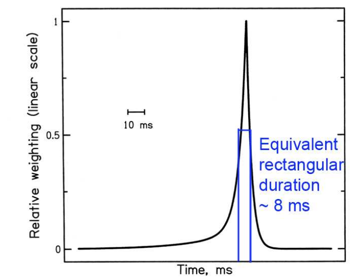


FIGURE 5.9 A block diagram of a model of temporal resolution.

impulse response (reversed in time)



LTI system characterised by a frequency response or … ?

FIGURE 5.10 The "shape" of the sliding temporal integrator (window). This is a weighting function applied to the output of the nonlinear device. It performs a weighted running average of the output of the nonlinear device. The shape is plotted on a linear scale as a function of time.

Effects of temporal window on signals

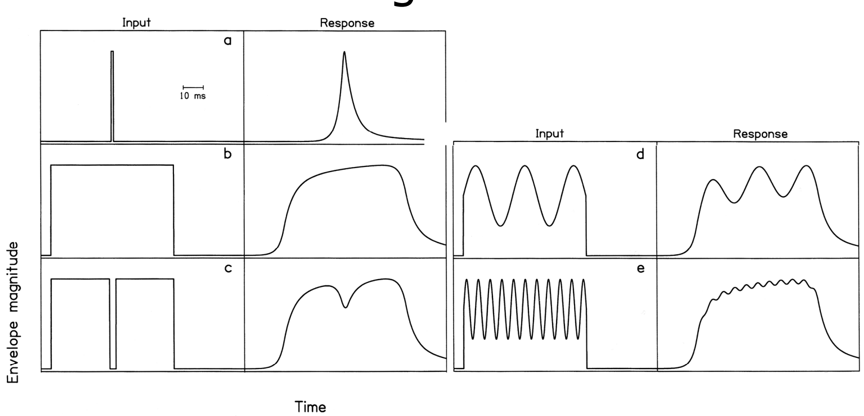
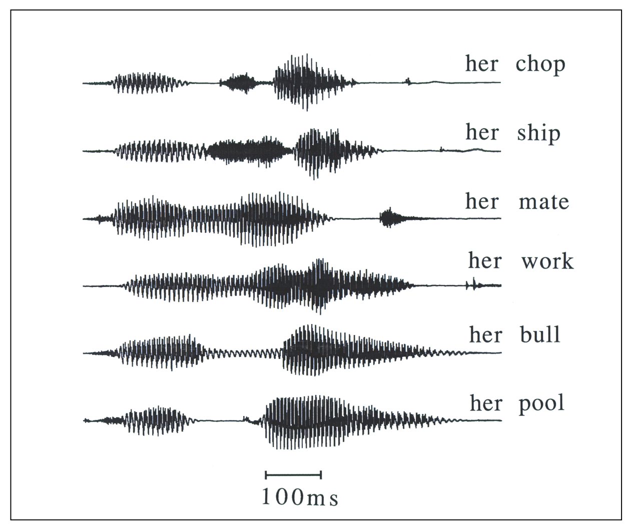


FIGURE 5.11 Examples of the influence of the sliding temporal integrator on the envelopes of sounds. The panels on the left show inputs to the sliding temporal integrator. The panels on the right show the corresponding outputs.

Decision device looks at evidence of level changes at output – a model of *within-channel* temporal resolution

Envelope in speech – one source of cues to consonants



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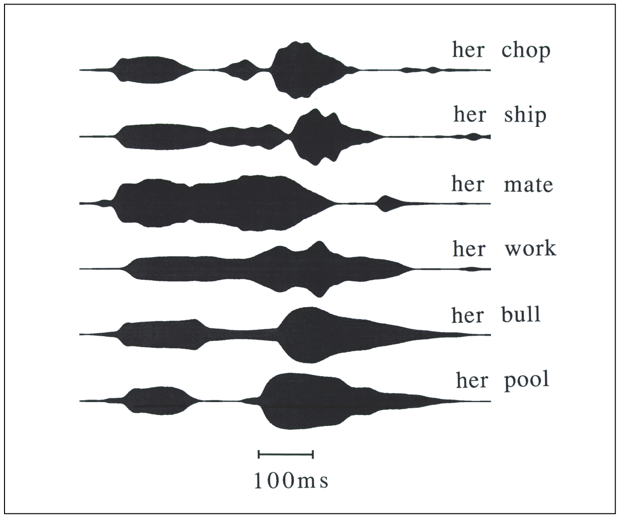
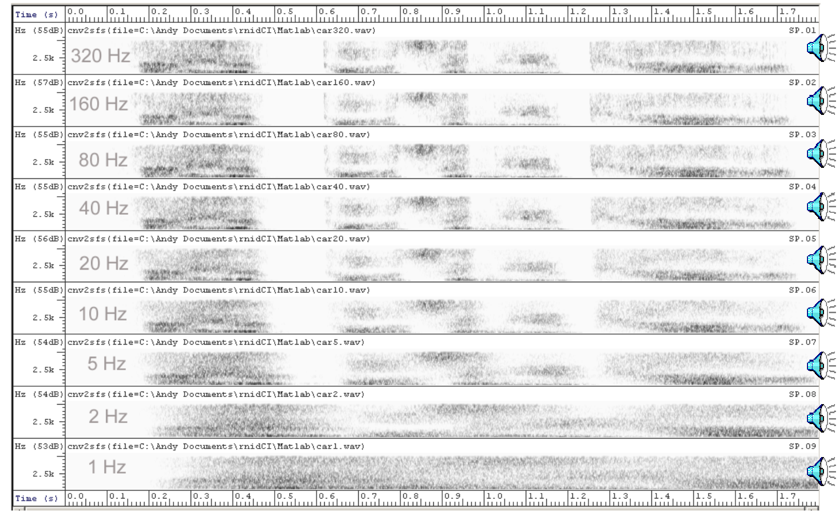
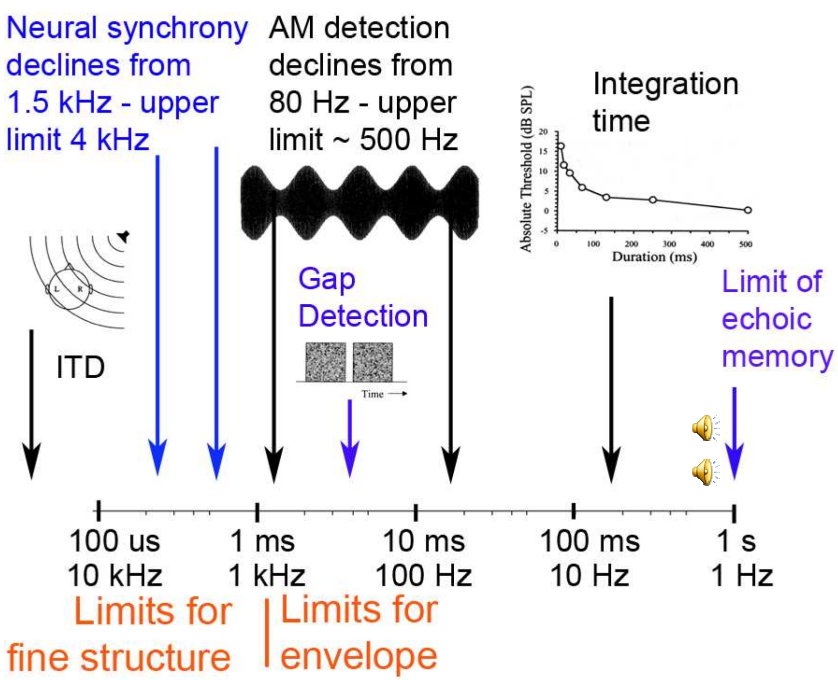


Effects of envelope smoothing on speech - modulations below 10 Hz are most important





Key Points

- Measures of temporal resolution relate to signal envelopes
- Measures must control spectral artefacts
- Gap detection and TMTF main measures
  - Both indicate limits in region of 1 to 3 ms in normal hearing
- Temporal window model can account reasonably well for within-channel temporal resolution