How Many Loudspeaker Channels are Enough?

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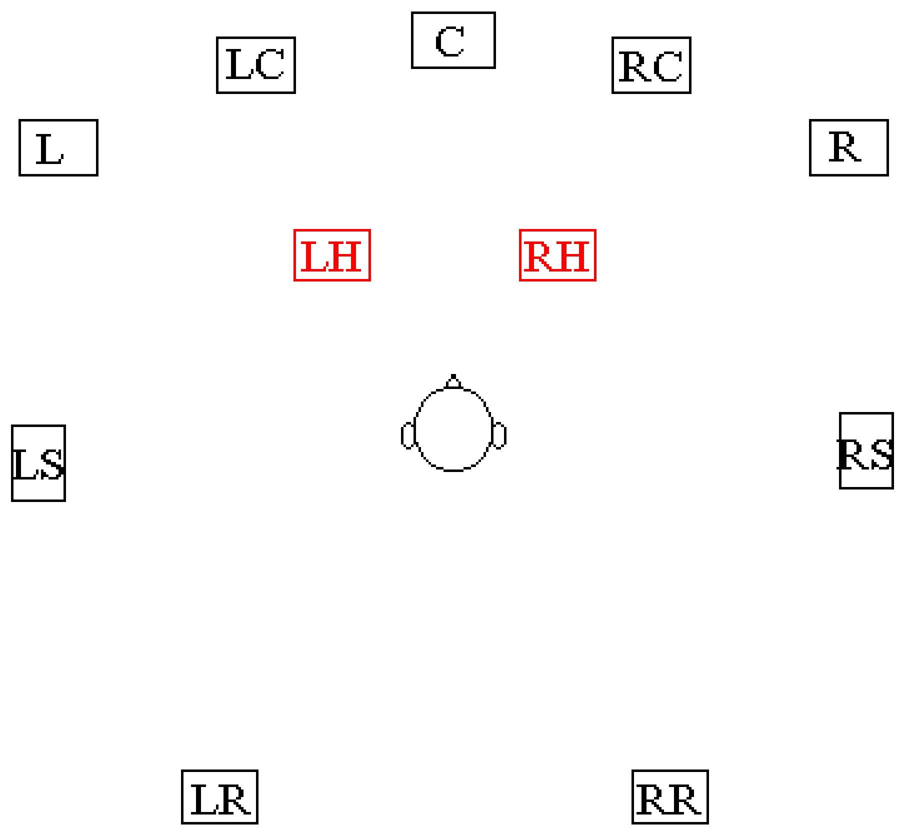
How many Loudspeakers vs How Many Recorded Channels?

- DSP can be used to generate loudspeaker drive signals from available input channels
- The success of this synthesis depends strongly on the intended use of the system
- We will look at this problem in detail later

How many Loudspeakers?

- Two major perceptions
  - sound direction
  - envelopment
- How will the system be used?
  - For forward music reproduction
  - For film with frontal dialog and occasional rear sound effects
  - For multimedia presentation with dialog in all directions and continuous multidirectional sound effects

Author's ideal system for music



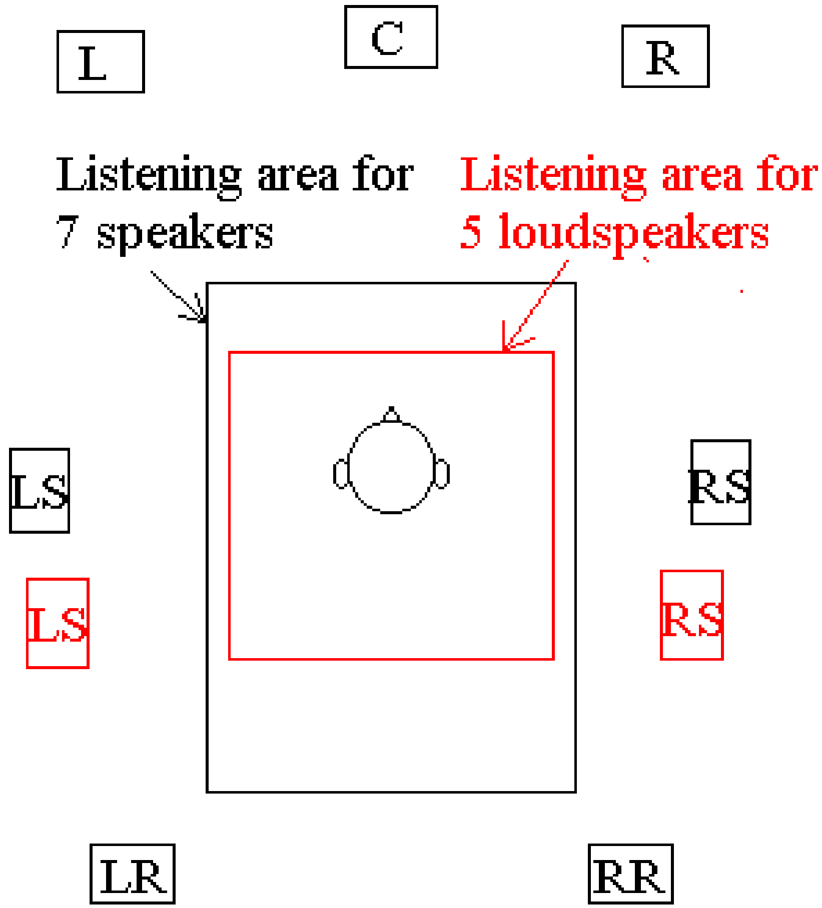
System description

- 5 front loudspeakers - similar to SONY
  - wider front image, conductor’s perspective, large listening area
- two side speakers
  - stable side images
  - best LF envelopment
- two rear speakers
  - HRTF functions different from fronts
    - gives more exciting sound effects
  - better high frequency envelopment

Height loudspeakers

– HRTF has a treble maximum at about 70 degrees elevation
– Reverberation that lacks these spectral components sounds unnatural
– Two height loudspeakers work much better than one
– Level is approximately equal to the level of the ceiling reflection from the main speakers
– Frequencies above 1000Hz are needed - loudspeakers can be small - good WAF factors.

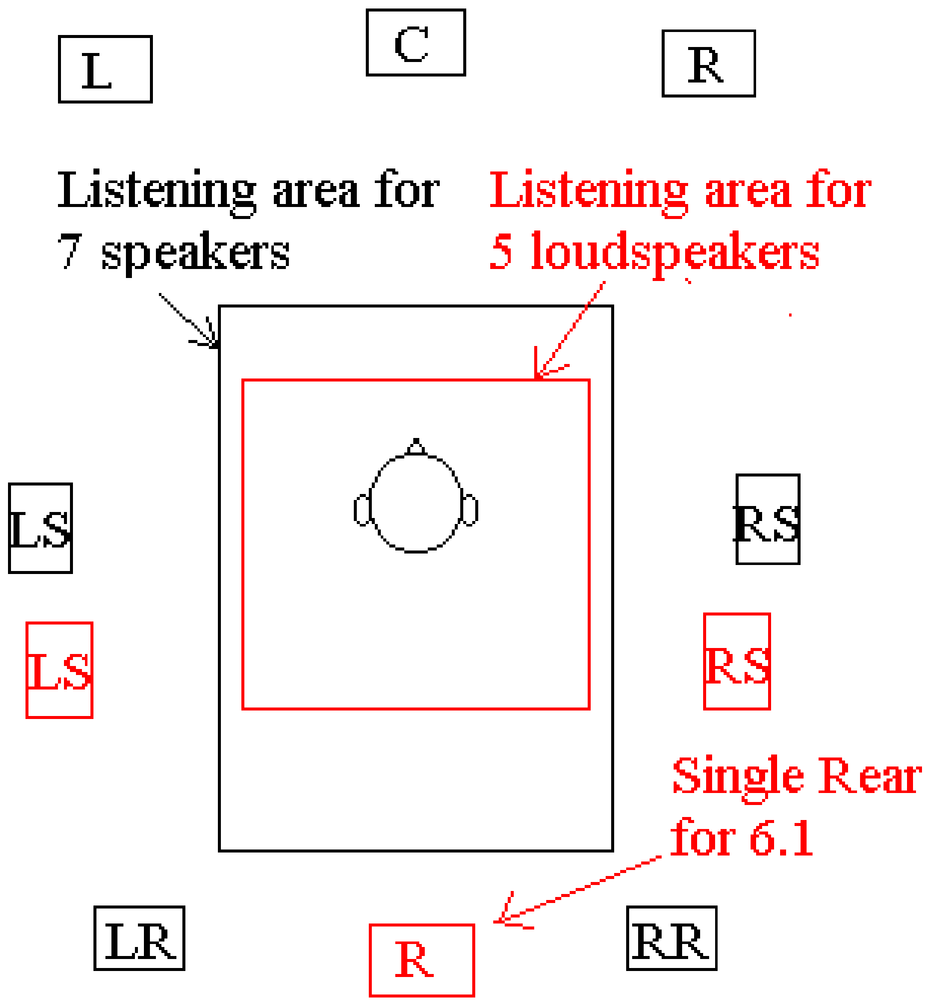
Let's be practical!



A practical system has:

- 3 front speakers spaced a little wider than +- 30 degrees
  - “pretty good” front localization
- Two side speakers - for image and envelopment
- Two rear speakers - for excitement and HF envelopment

6.1 vs 5.1



L
C
R
Listening area for
7 speakers
Listening area for
5 loudspeakers
LS
RS
LS
RS
Single Rear
for 6.1
LR
R
RR

6.1 vs 5.1

- single rear speaker suffers from
  - front-back reversals
  - poor envelopment
  - difficult to place in practice
  - (comment from Tom Holman) a dipole in the back works better than a monopole

What Kind of Loudspeaker?

- The author's experience with dipole speakers has not been good.
  - Most have poor power response, on-axis response, or both
  - But the idea is interesting - 1/r squared is problematic in rooms
- possible compromise - line radiators. Loudness increase is 1/r, not 1/r^2
- similar to DeVries and Boone's holography system - also a line source.

How many subwoofers?

- At least two
- Best at the sides, not the front
- Bass management should be Stereo, or two channel
- (comment from Tom Housain) In many rooms putting the SW in front gives a flatter frequency response. (answer from dg) In that case, put them in the front, but use two, and drive them in stereo.

Conclusions on Localization (discrete channels)

- If you need “the voice of god” you better put a speaker where you want it.
- An eleven loudspeaker system meets most psychoacoustic criteria
- A seven speaker system - with two loudspeakers at the side - has a smaller listening area than an eleven channel system.
- A five loudspeaker system has a smaller listening area than seven.

How many Channels?

- Three for the front
- two for the rear - 5-7 matrix works well.
- synthesize the height - MXP 100 will do.
- So… 5.2 ought to do!
  - Maybe 5.1 if the LFE was 40Hz down,
  - or is really used only for effects
  - (Tom Holman - "It is always used only for effects!" dg - "seems unlikely")
- How about a steerable effects channel?

END

- of the “how many loudspeakers” part of the talk

Envelopment in Small Rooms

- Several perceptions:
  - “room impression” Early Spatial Impression (ESI)
  - inside the head localization (Externalization)
  - Non - localization (continuous sound or tones)
  - True envelopment - Background Spatial Impression (BSI)
    - requires a syllabic input
    - requires time delays > 150ms
    - In small rooms BSI must come from the recording

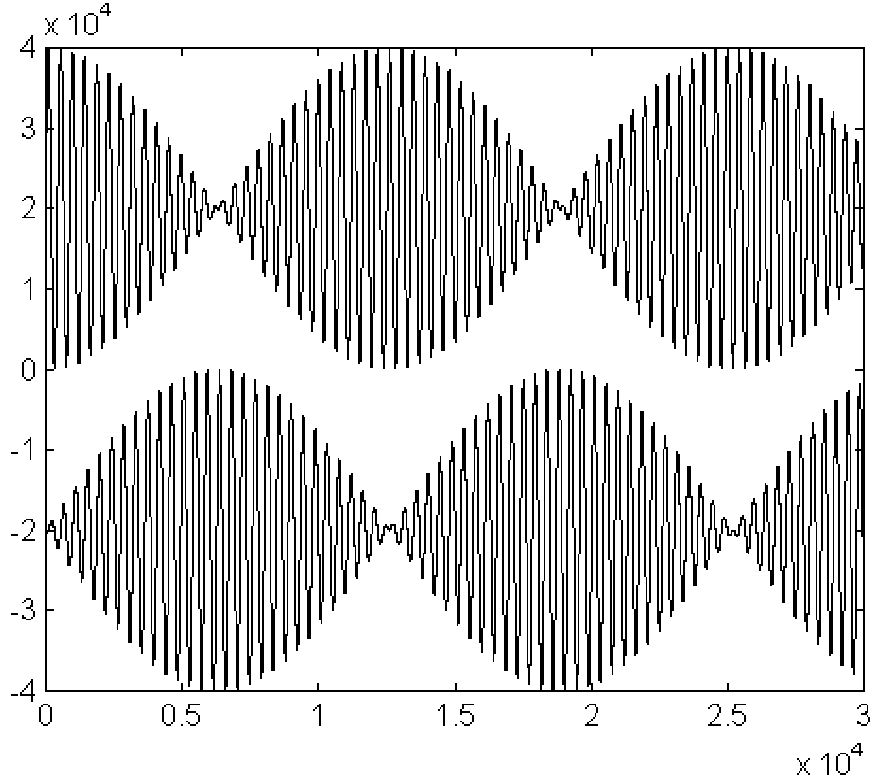
Personal Experience

– Author observed that two speakers sounded better than one - even at low frequencies.
– Experiments show tones are not localizable with either array.
– Pink noise (even 1/3 octave bands) sound spacious with a single speaker in small rooms.
– A string bass sounds non-spacious, in a small room, as does a single loudspeaker reproducing it.

Why does a string bass sound spacious in a large room, and flat in a small room?

- Why does a stereo recording of the string bass sound spacious in a small room when you use two speakers
- what makes a large room large, and a small room small?
- Answer - it’s the TIME CONSTANT of the room, and the BANDWIDTH of the music!

Demonstration of Low Frequency Envelopment



– we can design a beat frequency signal

Demo Signal

- Demo signal is made by taking the sum and the difference of two tones. One tone is about 3Hz higher than the other in frequency, so there is an obvious beat, 6 times a second.
- The tone pans from left to right and back at 6Hz.
- The phase alternates from in phase to out of phase at a 6Hz rate.

Comments on the demo

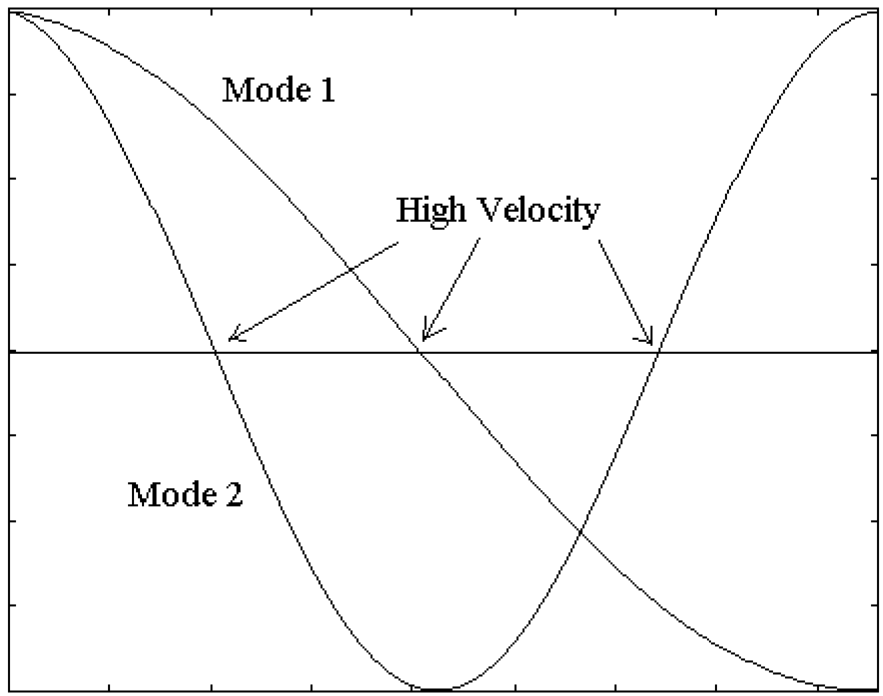
- When you play just one channel the sound gets louder and softer but does not move around the head.
- Play both channels and the sound moves around.
- In some places and for some frequencies only L+R is heard, and the sound is pure tone.
- In this lecture room the sound does not move around, but sounds outside the head and spacious. This is envelopment.

And use it to test rooms

- envelopment is clearly audible whenever the listener is near a velocity maximum of a lateral mode
- envelopment is nearly inaudible when the listener is near a pressure maximum

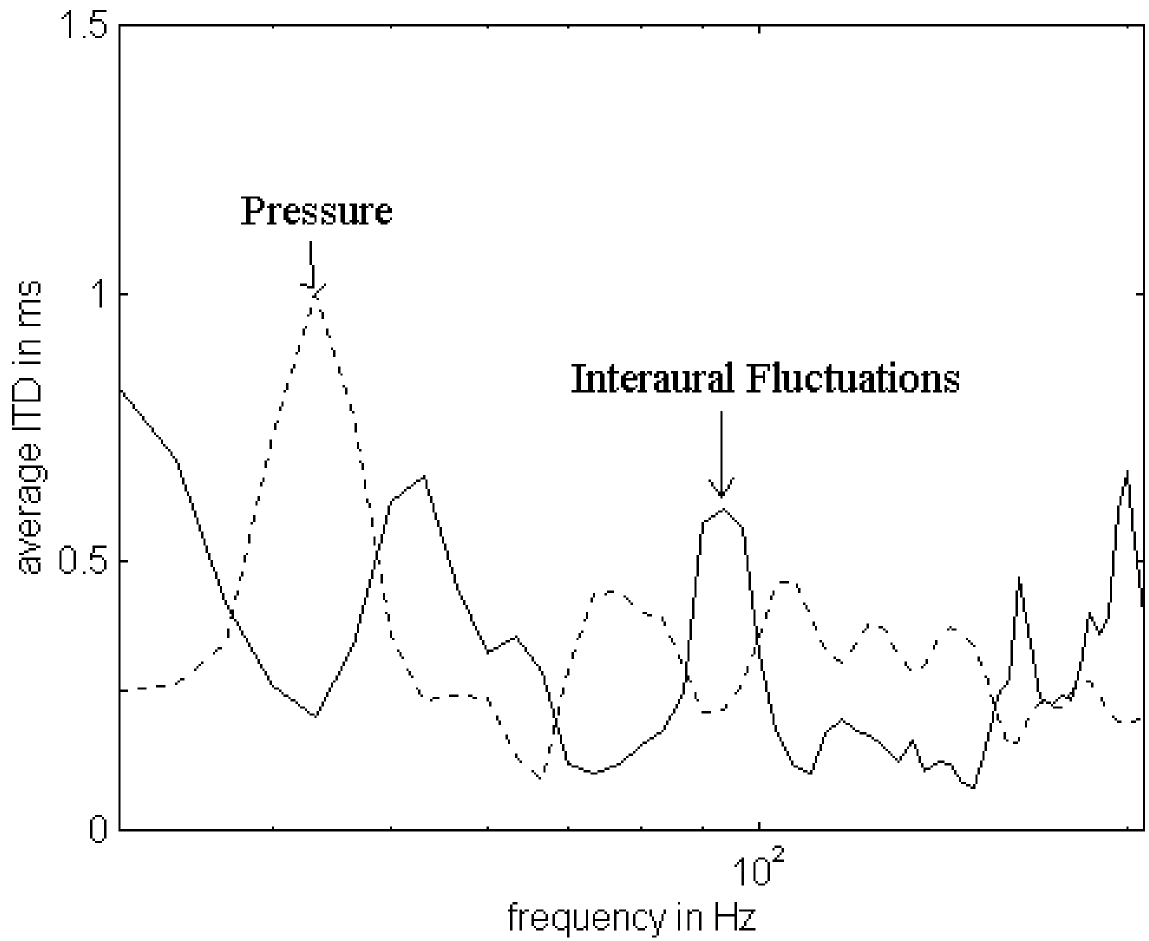
Example: Standing waves

– plotting pressure



– A listener at a velocity maximum will hear high envelopment

Measurement Results



Measurement comments

- note the minimum of interaural fluctuations occurs at the pressure maxima. Clearly the lateral modes have a minimum velocity where the lateral mode pressure is maximum.
- Apparently in this room over these frequencies the lateral modes dominate the room response.
- In general, the amount of interaural fluctuation depends on the interaction between lateral and medial modes. If you heavily damp the lateral modes the room will not be spacious.

Short Summary

- Low frequency envelopment in listening rooms depends on the ratio of lateral modes to medial modes
- and on the decorrelation in the recording

Measurement and Modeling

- You don’t understand anything
  - unless you can make a machine that measures what you perceive.
- A sound level meter measures loudness - (more or less)
- We need a machine that can measure our spatial perception of enclosed spaces.

OK - so build a machine!

- The method is clear - true envelopment is created by apparent motion of the reverberation from a syllabic source, created by fluctuations in the ITD and the IID
- We have to detect the ITD and the IID the way the ear does
- Details of how the ear detects localization are not well known
  - and details are where it is at...

It’s all in your head

- To understand perception we must:
  - understand the physics of the sound detector
  - understand how the brain processes the detected stimulus
  - build a model that includes both.
- To understand rooms we must couple the room properties to the perception.
- Frequencies below 200Hz behave quite differently than higher frequencies

Interaural Time Delay (ITD)

- Interaural Cross Correlation a traditional measure
  - IACC cannot be easily calculated from the basilar membrane data
  - IACC combines Interaural Intensity Differences (IID) and ITD
  - Perceptual experiments show IID and ITD are separately perceived.

ITD and single reflections

- spatial properties of single lateral reflections depend on the delay
  - the delay dependency is different for cues based on ITD, IID, and IACC
- measured data show that below 200Hz ITD is the primary cue for spatial properties.
- Below 200Hz ITD is also the primary cue for localization.

Spatial perception and ITD

- ITD during a fast rise is perceived as source azimuth.
- A rapidly varying or randomly varying ITD is perceived as a stationary source in the presence of envelopment.
  - An absence of variation in the ITD in the presence of head motion results in in-the-head localization.
  - (constant - non syllabic - signals can also localize inside the head)

TWO spatial perceptions

- Envelopment
  - the perception that room sound - particularly reverberation - surrounds the listener.
  - most small rooms provide no envelopment of their own.
  - Envelopment must come from the recording
- Externalization
  - low frequencies are perceived as inside the head in many playback rooms.

How does the ear detect the ITD?

- ITD of sine waves seems easy to detect
  - but these are only weakly localized!!
- There are inherent ambiguities in the ITD of monochromatic signals
  - beyond a certain ITD the lead or lag of phase becomes ambiguous
- Steady tones are weakly localized
- Phase of steady signals is not detected above 500Hz.

And the localization depends strongly on the source

- plucked string bass produces strong localization and high envelopment.
- Bowed (arco) string bass does not.
- High source dependence makes the measurement of envelopment directly from an impulse response unlikely to be successful.

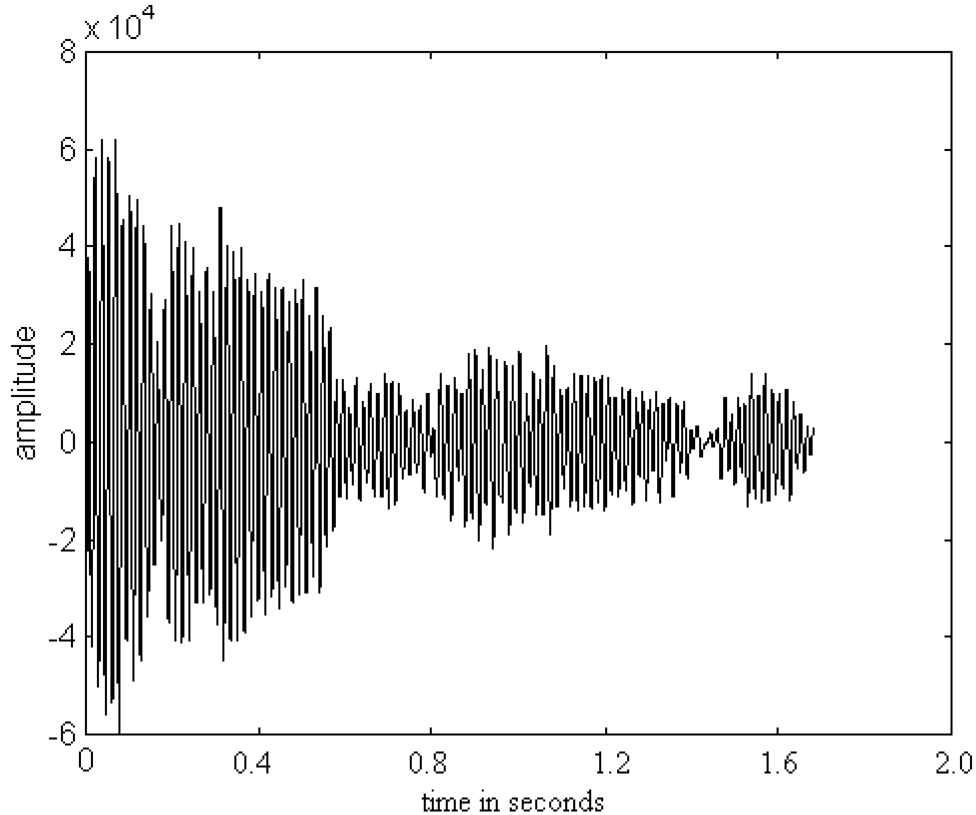
Human hearing detects the IDT during signal rise-times

- Most musical signals are NOISEY
- level and phase fluctuate rapidly
- The ear is always looking for ITD differences during the rising edge of signals
- IDTs during dips in the level (of either ear) are inhibited
- IDTs during steady tones are also inhibited

Some ideas for further experiments

- 1. How quickly does a signal have to rise to be strongly localized?
- 2. What is the difference between an unlocalized sound and a (syllabic) sound that is enveloping by virtue of high fluctuation in the ITD?

Example - decay in Boston



63 Hz stopped tone

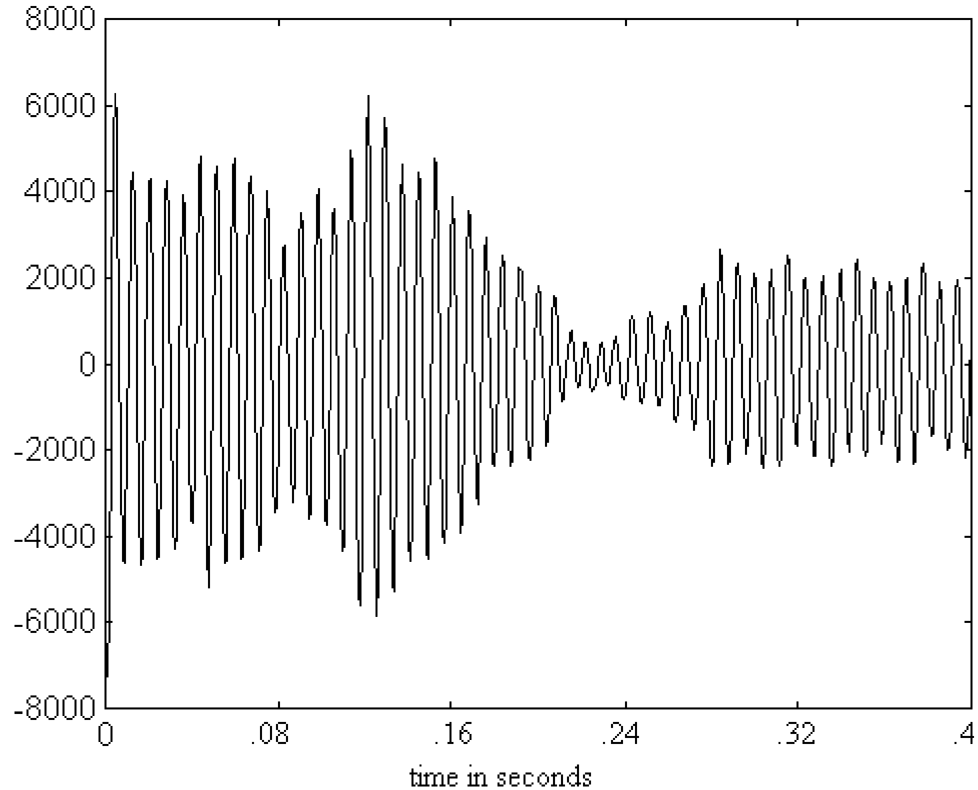
Envelopment

- envelopment is the Holy Grail of concert hall design
- when reproducing sound in small spaces envelopment is frequently absent
- sound mixing rooms with low reverberation times are often particularly poor
- In rooms where envelopment can be heard the strength of the perception depends on the recording technique.

How do we measure envelopment?

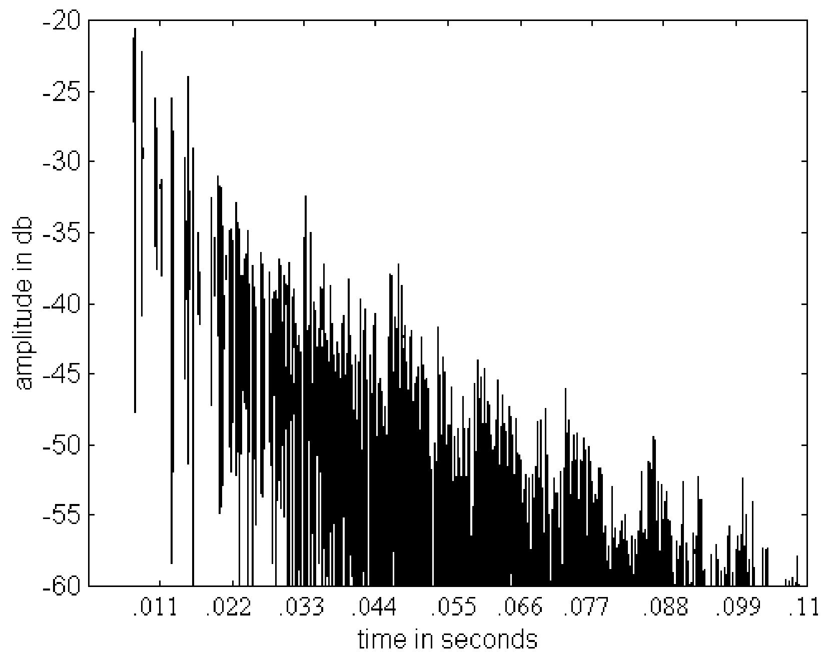
- ITD Fluctuation in the range of 2-20Hz is perceived as envelopment
- Fluctuations during the reverberant component of the signal stream are particularly important.
- Reflected sound causes ITD fluctuation
- The amount of fluctuation depends on the properties of the source music.

Reflected sound causes ITD fluctuation



- Large spaces can produce fluctuations even with narrow band signals.

The impulse response of a small room is short



- 12’x15’x9’ room , RT ~0.2sec, TC ~ 30ms
- If the music signal varies slowly the room will always be steady-state

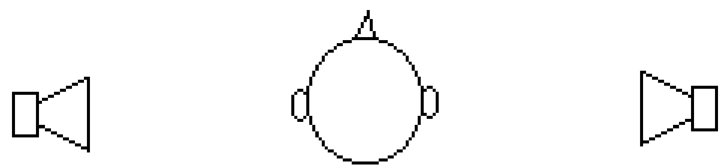
Steady state is not enveloping

- If the room is steady state the 3Hz - 20Hz fluctuations in IDT are not produced. The ITD is constant unless there are two incoherent sources.

Small spaces - listening rooms

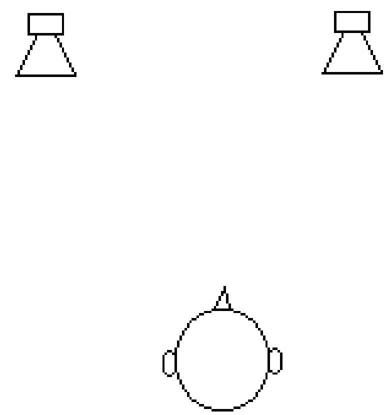
- Small spaces produce fluctuations in the 3-20Hz range ONLY if the sound source is broadband.
  - Broad band signals vary quickly enough to prevent steady-state.
- For narrow band signals a fluctuating ITD can still be produced
  - IF the recording has fluctuating phase
  - AND there are multiple drivers.

Anechoic spaces



- envelopment can be created by reproducing sound from two decorrelated loudspeakers
- envelopment at LF is maximum when the loudspeakers are at the side
- a single loudspeaker gives no envelopment

Anechoic space - standard stereo

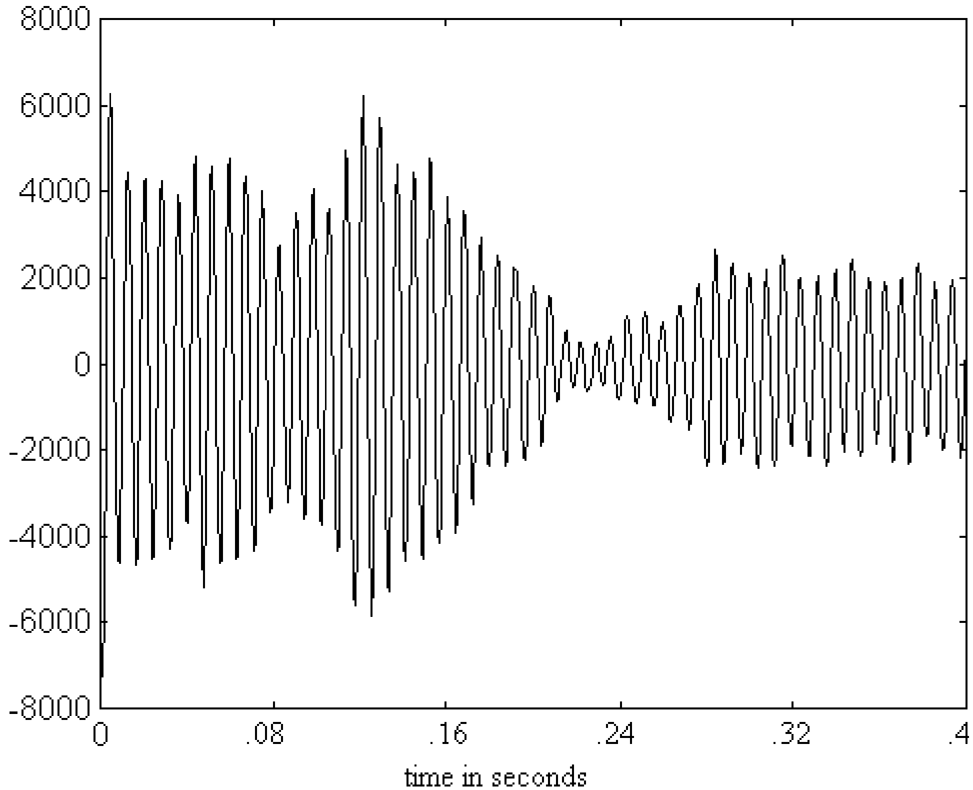


- Standard stereo gives little envelopment because the speakers are not lateral - even with decorrelated material.

Reflective spaces

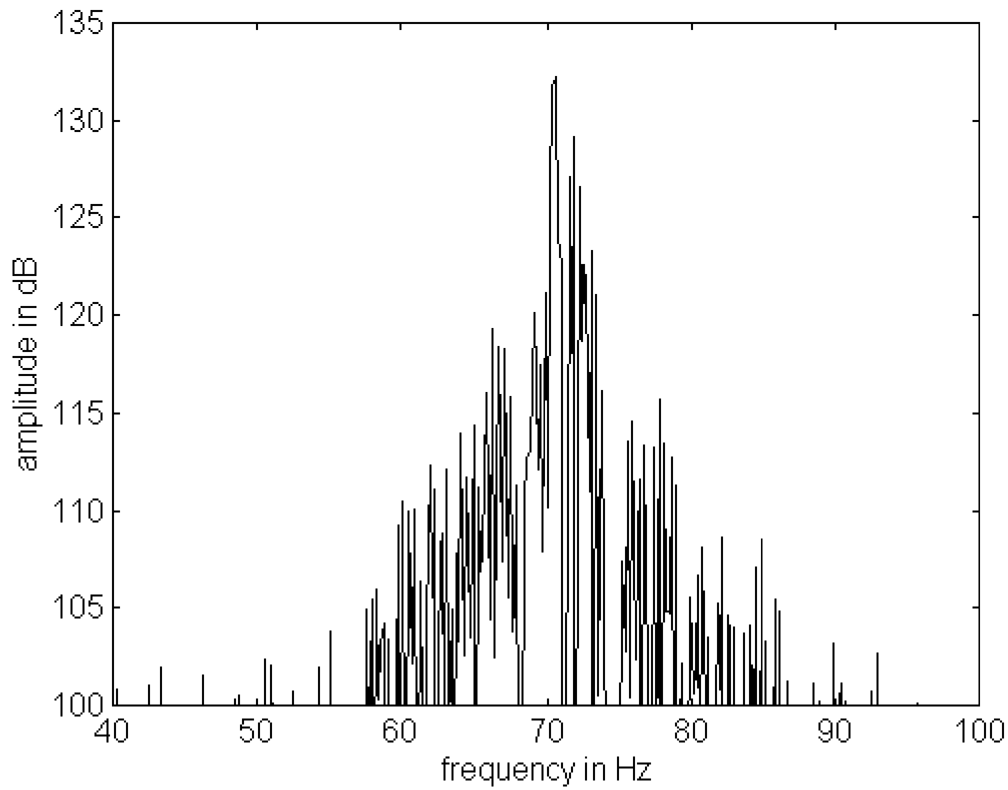
- can create envelopment directly ONLY
  - if the reverberation time constant is larger than the inverse bandwidth of the stimulus
    - reverb time constant ~= RT/7
  - or if there are multiple drivers reproducing material with fluctuating phase.

Recorded reverb has narrow bandwidth and slow variation



- A small room cannot produce a fluctuating ITD from a single driver.

Bandwidth of sound decay



Decay of a held sine tone in Boston Symphony

Note the bandwidth is 3Hz or less

A measure for Envelopment

- Must measure zero in an anechoic space
- Must measure low values when a single driver is used
- DG has not found a clever way of doing this directly from the impulse response or its Fourier transform!!
- But we can use convolution to probe the effects of the impuse response on signals.

Brute force works for DFT

- To find the Diffuse Field Transfer Function (DFT) we model:
  - (or measure) the room, to find the binaural impulse response from multiple drivers
  - the musical signal - to convolve with the impulse response
  - the head-pinnae system, to calculate the ITD
  - calculate the fluctuation in the ITD
  - The average magnitude of the fluctuations is our measure

Conclusions on Envelopment at low frequencies

- Two or more LF drivers are essential for music
- A single LF driver anywhere in the front does NOT create envelopment in a room with lateral reflectivity < 0.6
- LF drivers are (marginally) better at the side.
- Recorded reverberation must be decorrelated

Envelopment at High Frequencies

- Above 200Hz most music is no longer monochromatic
- Many (at least the best) playback rooms can be well damped
- Loudspeakers tend to be more directional
- Thus the reverberation radius can be larger than the source to listener distance

Above 200Hz room modes become less important

- Although a live room could produce substantial envelopment, rooms in common use do not.
- Above 1000Hz front/back differences begin to be noticeable.
- At 1500Hz just the front speakers can produce envelopment
- Between 200 and 500Hz the loudspeaker arrangement and the method of driving these loudspeakers become critical.

Above 700Hz

- The angle for maximum interaural fluctuations moves toward the medial plane.
- At ~1500Hz two speakers at +-30 degrees from the front can create a completely surrounding sound field.
- Try an experiment with decorrelated applause in a dead room. The sound can be completely surrounding.

Morimoto - the front/back ratio

- Morimoto showed that for solo violin music reflections coming from behind the listener are perceived as more enveloping than those from the side
- This is partly a simple consequence of the frequency range and the head sensitivity to envelopment
- But it is also likely to be a learned psychological response
- We need speakers behind the listener for best HF envelopment

Success is elusive with a fixed listening position

- many experiments with a fixed measuring head did not yield results that agreed with subjective impressions.
- People are seldom facing directly forward, and they move their heads.
- It is necessary to measure both lateral and front/back envelopment.

2-5 and 2-7 Matrices

- Matrix systems are capable of greatly increasing both subjective and measured envelopment in most rooms
- However most matrix systems were developed to enlarge the sweet spot for dialog and sound effects, not to increase envelopment

A successful matrix increases envelopment by:

- reproducing reverberation from the sides of the listener with maximum decorrelation
- reproducing low frequencies from the sides of the listener wherever possible
- reproducing enveloping sound effects - such as crowd noise or applause - with full separation to the sides and the rear of the listeners.
- Maintaining a wide front image

Not all matrix systems are the same

- Several 2-5 matrix systems are currently on the market
- These systems differ markedly in their subjective and measured envelopment
  - in general, image width and envelopment from the front speakers are reduced compared to two channel stereo
  - rear channels are not optimally decorrelated
- These differences are particularly noticeable in cars

Conclusions 1

- spatial properties of small rooms are determined by
  - the interaction between lateral and medial room modes
  - the bandwidth and syllabic properties of the source
  - the orientation of the listener

Conclusions 2

- small rooms develop their own sense of space if
  - the room time constant is greater than the inverse bandwidth of the source
  - the listener is not near a lateral velocity minimum for the source frequency
  - there are at least two drivers on opposite sides of the listener
  - the source material contains decorrelated reverberation

Conclusions 3

- most if not all the low frequency spatial properties of small rooms are measurable with a swept wobble tone, a binaural microphone, and a detector for interaural fluctuations
- A measurement system for higher frequency room properties is under development.
- (check the author's web page for updates)