The Perception of Distortion

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What do we seek?

Why do we make loudspeakers?

What are the goals?

How do we evaluate our progress?

Why do we make loudspeakers?

- Loudspeakers are an electro-acoustical transducer – they convert electrical signals (which we cannot hear) into acoustical ones (which we can hear)
- For the most part (and there are widely varying applications) the loudspeaker is meant to reproduce a recorded signal or reinforce an original one
  - In a few instances the loudspeaker is actually part of the original creation of the sound such as in a guitar amplifier
    - In this case the notions of this presentation have no relevance

Reproduction

- In this situation the loudspeaker is expected to reproduce, at the ear, the equivalence of the electrical signal at its input.

Reinforcement

- In this situation the loudspeaker is expected to reinforce, by making louder, a signal which is too low in level to be heard throughout the venue at the desired level.

Reproduce or Reinforce

- For the most part, the role of the loudspeaker in these two situations is the same
- The goal is to recreate, at the listener, an accurate facsimile of the electrical input signal
- These two situation likely differ in the venue in which they are used and the levels of sound that they create, but for the most part the goal is the same

An accurate acoustical reconstruction of the electrical input signal

Recreation of the input signal

- Note that there is nothing subjective about this goal
- The goal is not to create “good sound”
  - What if the recording is bad or the performance poor, can the loudspeaker ever hope to correct these situations?
- The loudspeaker CAN make the recording or the performance worse, but it can never make it any better than it was originally.
- So the ideal is a perfect or faithful reproduction of the original – not simply “good sound”

Achieving the Goals

- When the loudspeaker does not accurately reproduce the electrical input signal it is said to “distort” it
- Distortion takes two form
  - Linear distortion – most notably frequency response
  - Non-linear distortion – when the signal is changed in ways that depend on factors other than its frequency
- This talk is concerned with Non-linear distortions.

Linear Distortion

- The perception of linear distortion has been well studied and pertinent references to the work of Dr. Floyd Toole at Harman International are the most significant
- Basically it is well know that a flat response is desired and that peaks tend to be audible depending on the area under them and that dips are not as audible as a peak
- In a real room situation the mixture of direct sound to reverberant sound is a critical factor and this has strong implications to the loudspeakers directional response

Nonlinear Distortion

- Nonlinear distortion has not been as well studied as linear distortion.
- Its subjective effects are widely believed to be anywhere from extremely important to unimportant
- It therefore become essential to develop some criteria regarding the audible importance of loudspeaker nonlinear distortion.

The Perception of Nonlinear Distortion

- In 2003, Dr. Lidia Lee and myself presented two papers "On The Perception of Nonlinear Distortion"
- These papers presented a theory for a new paradigm for nonlinear distortion assessment along with the results of a comprehensive test of audibility of distortion
  - From now on I will mean nonlinear distortion when I talk of distortion.

Theory

- The first paper hypothesized that the ear could not detect harmonics of a signal as readily as an instrument might because of the called masking.
- Masking is a central characteristic in the development of perceptual coders, ala MP3, MA, etc.

Masking

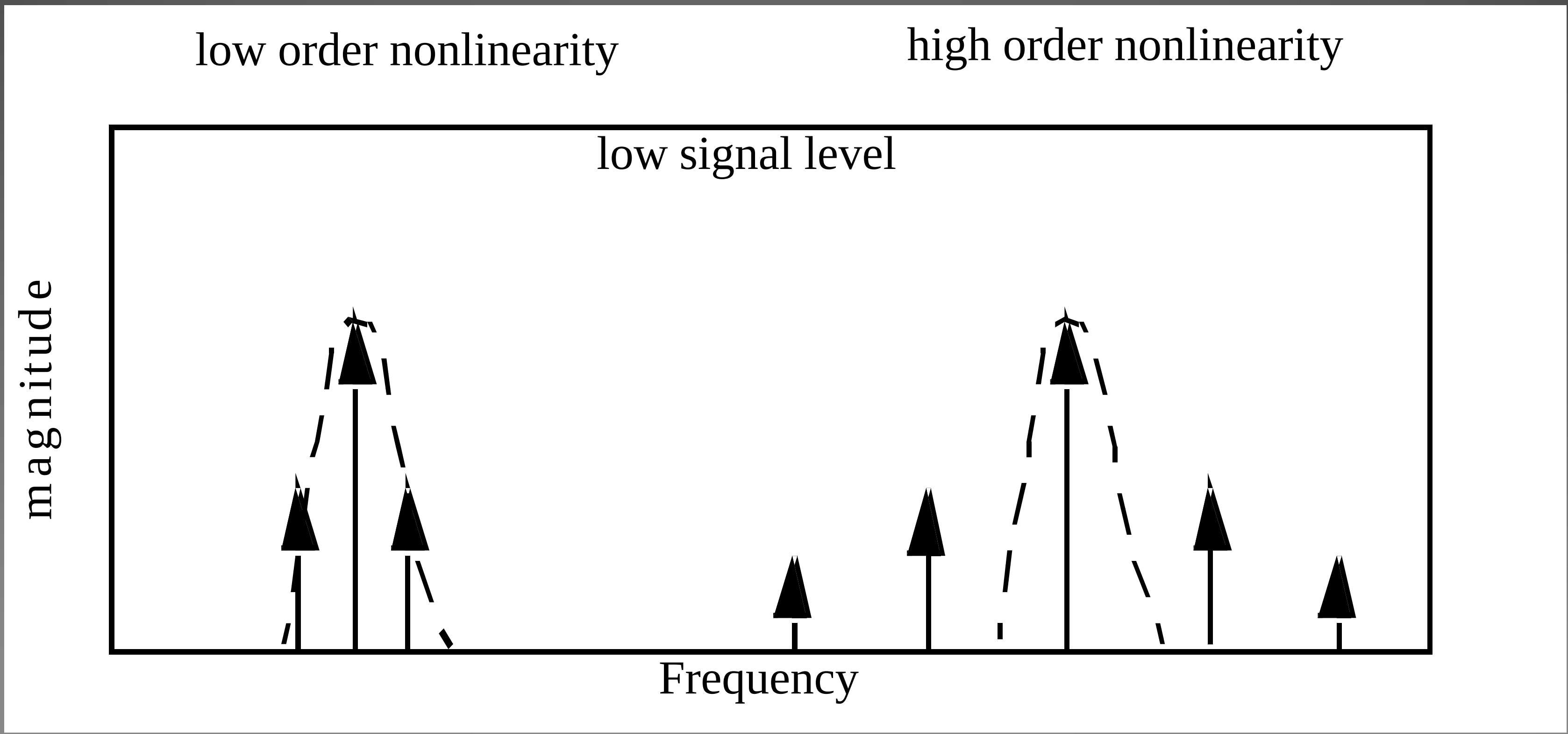
- A topic in itself, the main features that we are trying to incorporate are:
  1. Masking is predominately upward toward higher frequencies, although masking does occur in both directions.
  2. The masking effect increases – masking occurs further away from the masker – at a substantial rate with excitation level.

Implications to distortion perception

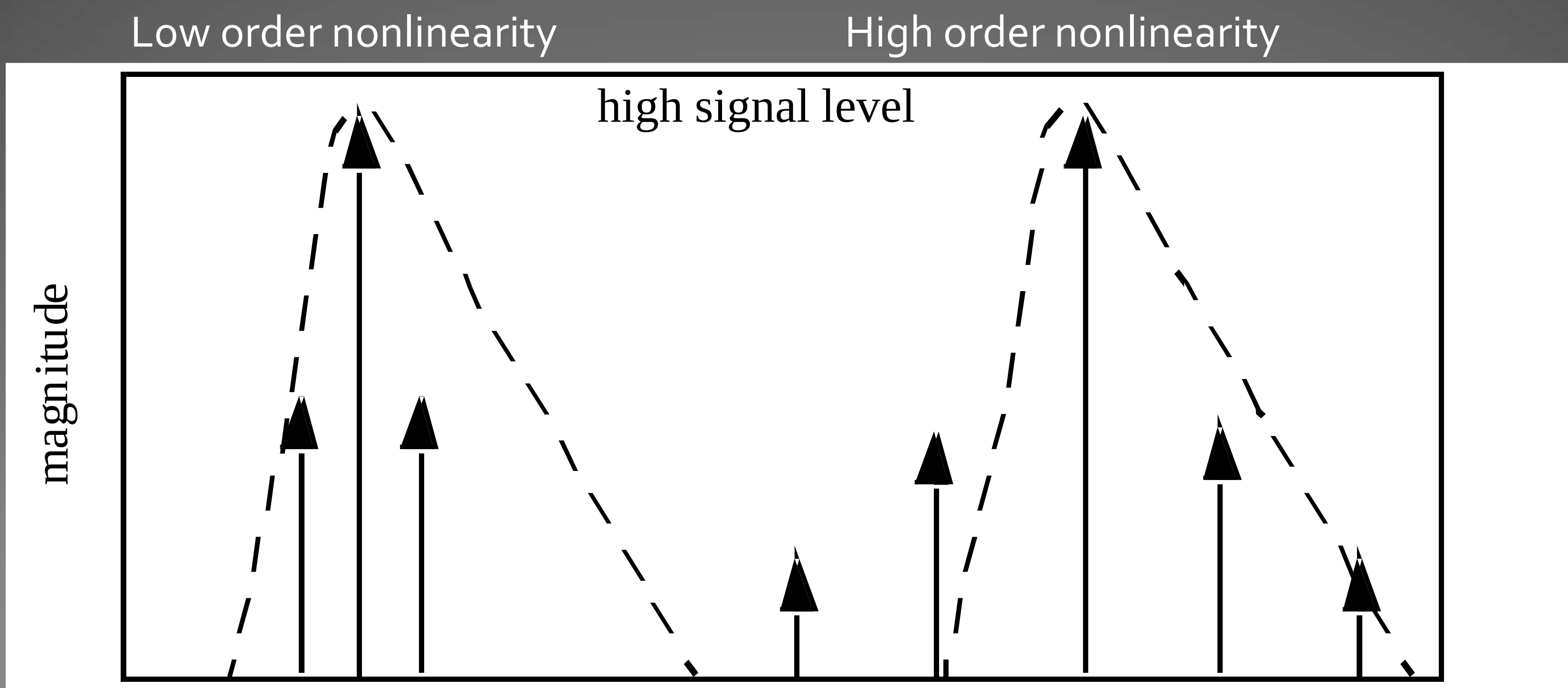
Distortion by-products that are created upward in frequency are likely to be less perceptible (masked to a greater extent) than those that fall lower in frequency.

2. Distortion by-products that lie closer to the excitation are less likely to be perceived (they are masked) than those that lie farther away (masking is a localized effect – it mostly occurs in the vicinity of the masker).
3. Distortion by-products of any kind are likely to be more perceptible at lower signal levels than at higher signal levels. (Less masking occurs at lower signal levels)

Example at low signal level



Example high signal level



Hypothesized principles

1. The masking effect of the human ear will tend to make higher order nonlinearities more audible than lower order ones.
2. Nonlinear by-products that increase with level can be completely masked if the order of the nonlinearity is low.
3. Nonlinearities that occur at low signal levels will be more audible than those that occur at higher signal levels.

Problems

- A sound systems quality is often judged (but not exclusively) by its THD and/or IMD numbers.
- In the context of the perception of distortion, it is not unreasonable to question the validity of these numbers for several reasons.

The validity of THD and IMD

- They are purely mathematical relationships without consideration for the characteristics of the receiver – the human ear.
- The recent application of psychoacoustics to problems in audio data compression clearly indicates that masking plays an almost dominate role in hearing acuity.
- Perceptual coders, MP3, etc. can have very high THD numbers while possessing readily accepted signal quality.

The test assumptions

- The limiting assumption used in this test is that the nonlinearities have no frequency dependence.
- Real systems can have frequency dependent nonlinearities, most notably loudspeakers, but some systems can be approximated as having no frequency dependent nonlinearities – some amplifiers.

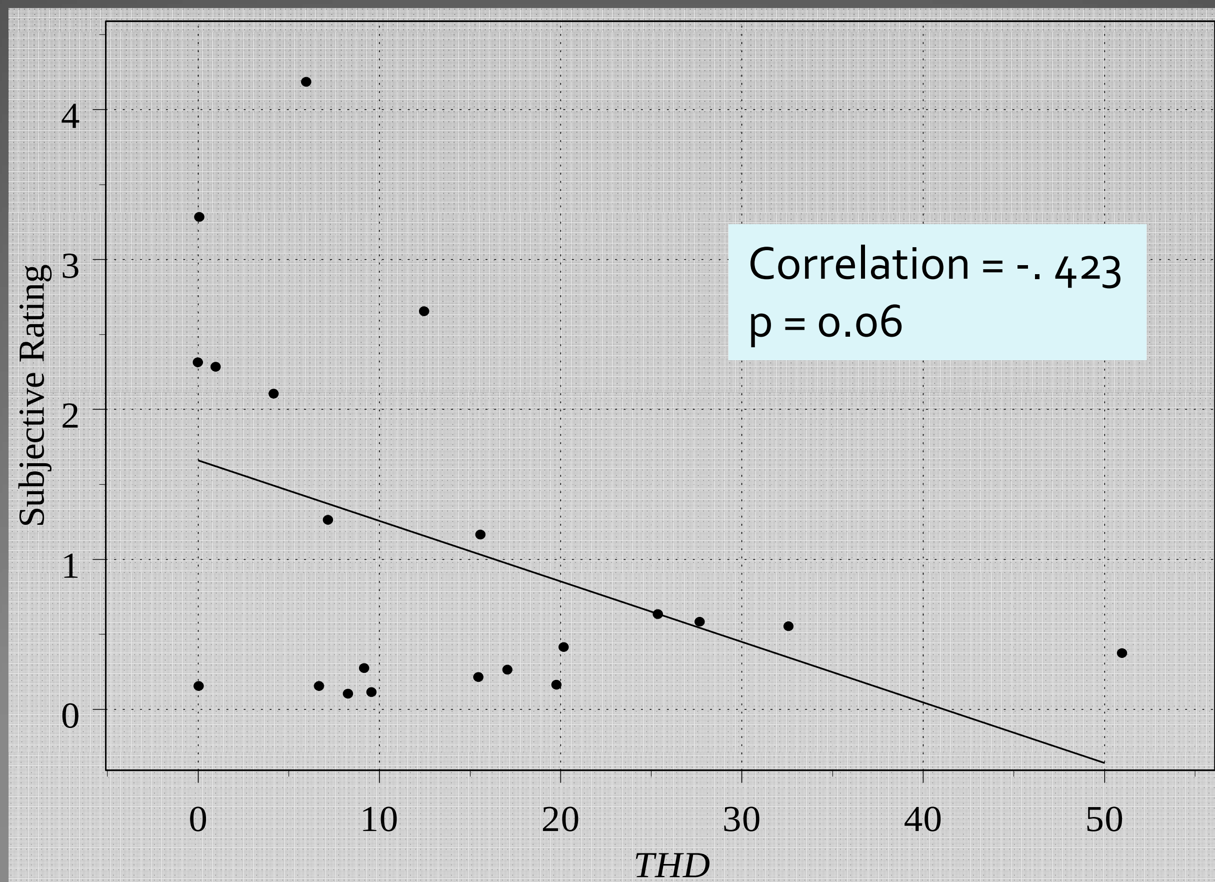
Participants

- The test involved 42 individuals with normal hearing sensitivity
- Each participant took a hearing test just prior to the testing
- The participants ages ranged from 19 – 39 (mean = 21)
- Participants were paid for their participation

The test apparatus

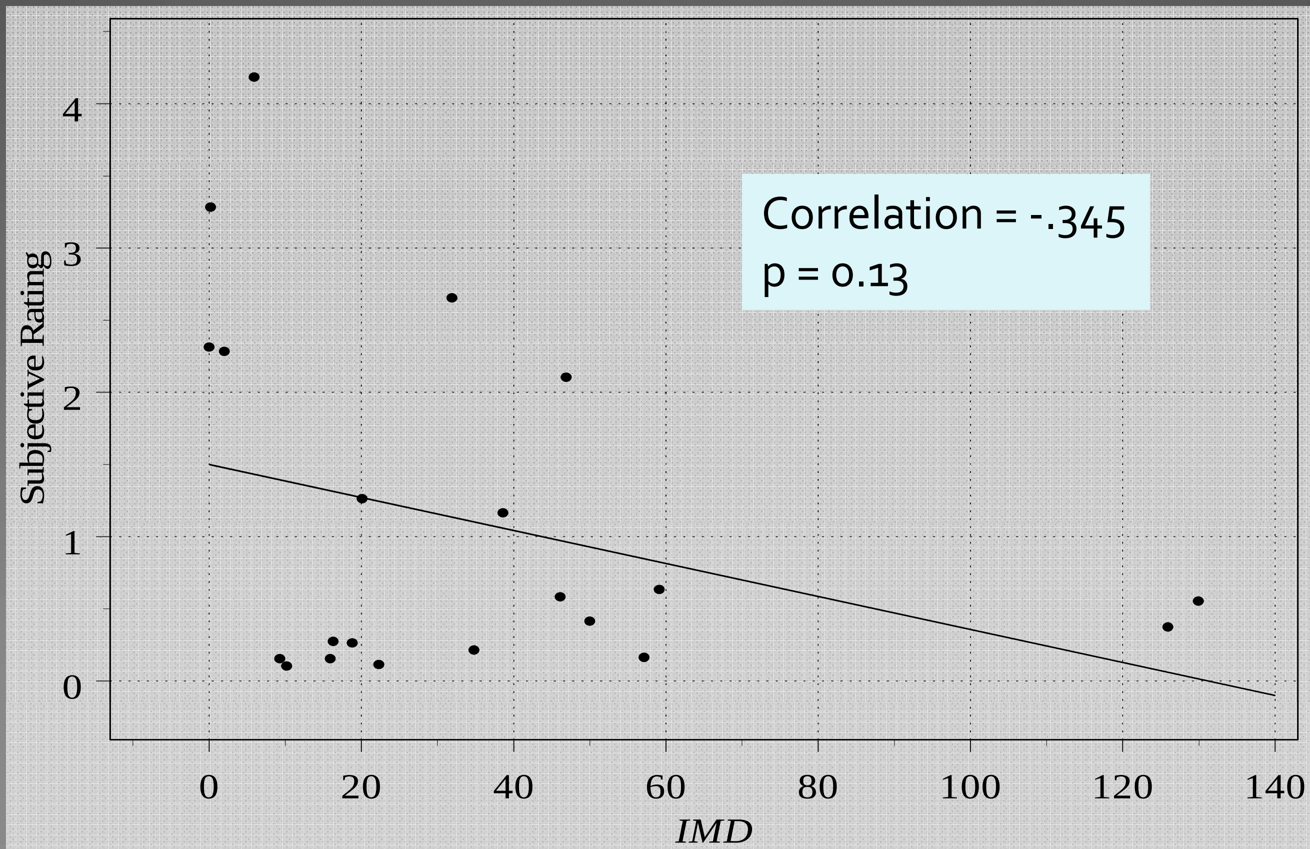
- The source was recorded directly from the CD into a wav file which became the reference.
- Twenty one distorted wav files were created using MathCad.
- The wav files were all 16 bit, 44.1 kHz. files.The output transducers used for the study were Etymotic ER-4 MicroPro insert earphones.

Results THD



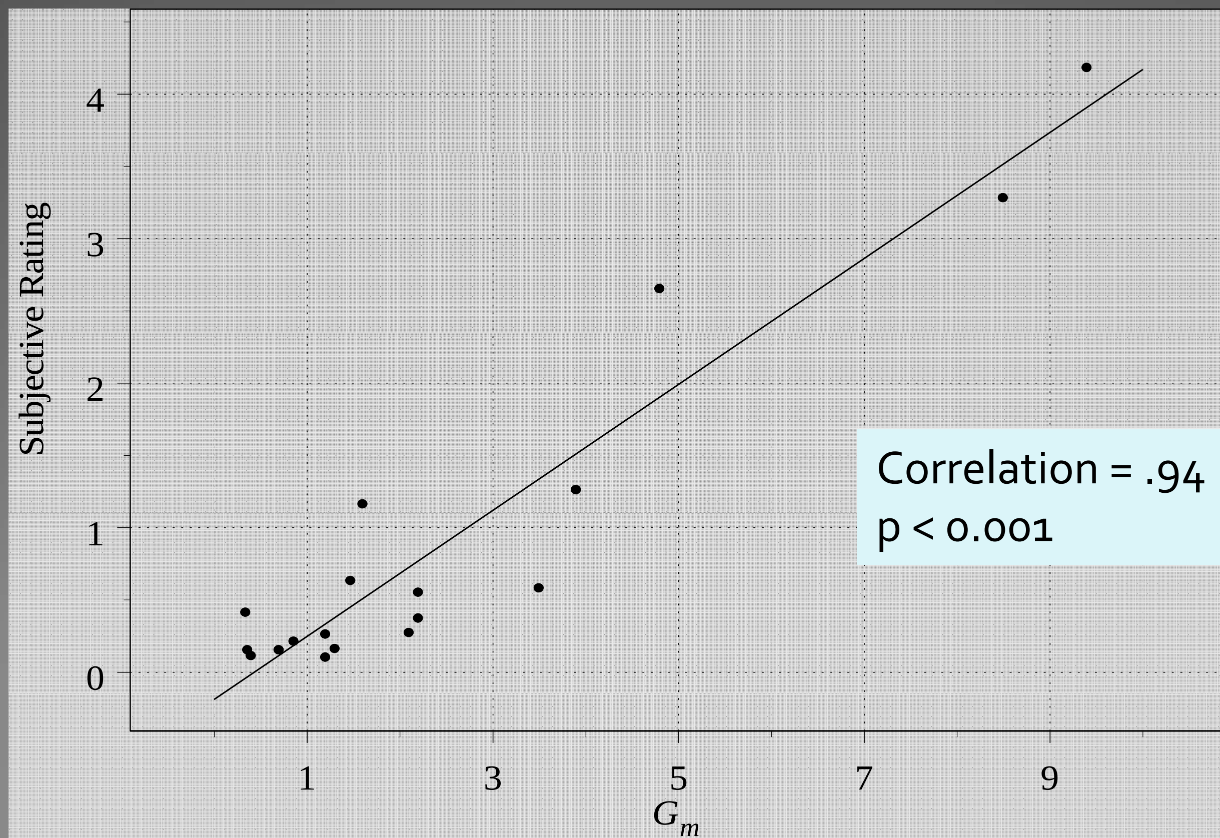
Correlation = -. 423
p = 0.06
Subjective Rating
THD
0
1
2
3
4
0
10
20
30
40
50

Results IMD



Correlation = -.345
p = 0.13
Subjective Rating
IMD
0
1
2
3
4
0
20
40
60
80
100
120
140

G_m (values < 10.0)



Implications

- THD and IMD have no correlation to the perception of the distortion that they are intended to represent.
- Correlation is possible with a metric that takes into account the way the ear actually functions
- One of the most important implications is that distortion in loudspeakers could well be an insignificant factor

Distortion in Loudspeakers

- Loudspeakers tend to have very low order nonlinearities
  - Higher orders would require very large forces in a mechanical system
- Loudspeaker distortion tends to increase with output, but is generally low at lower levels
- These factors imply that loudspeaker distortion may be masked in the ear

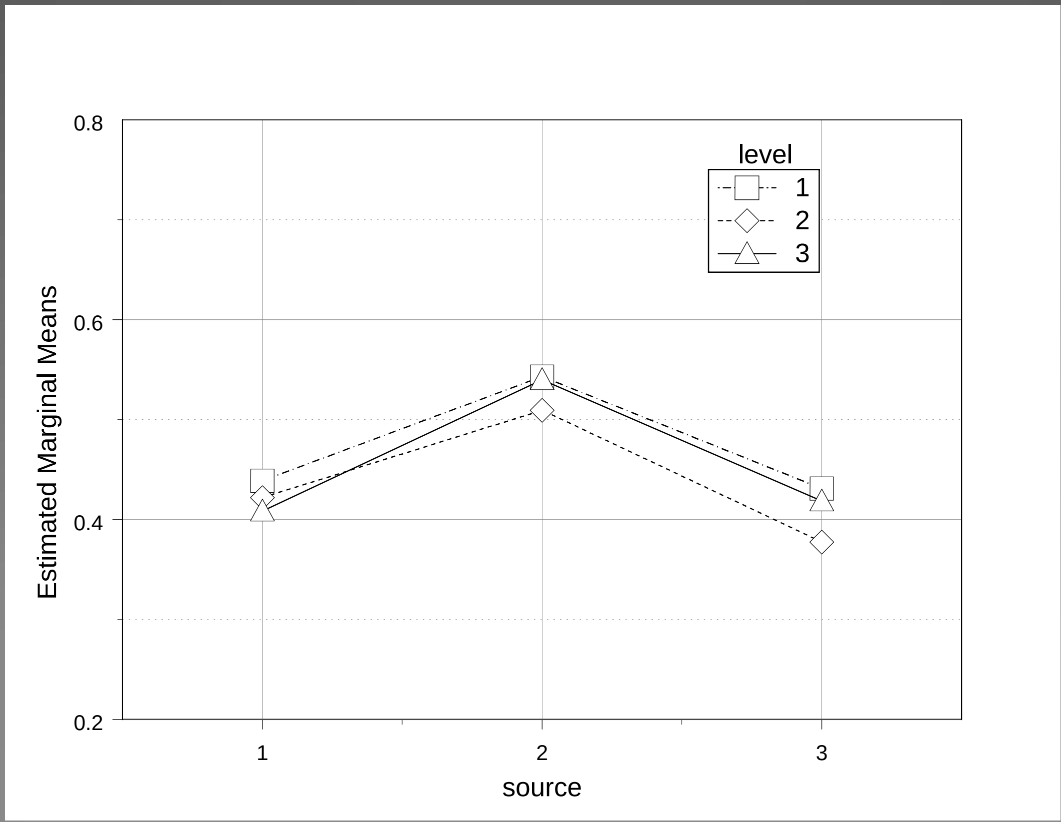
A Test

- A test was performed using compression drivers to test this hypothesis
- Three compression drivers were tested at three different output levels, but the test level was held constant
  - The THD levels varied from a few percent to about 20 percent at the highest level
- The drivers had linear distortion differences

Results

- If the drivers could be distinguished from one another then linear distortion is an audible factor
- If these differences are not a function of the level then nonlinear distortion is NOT audible

Results



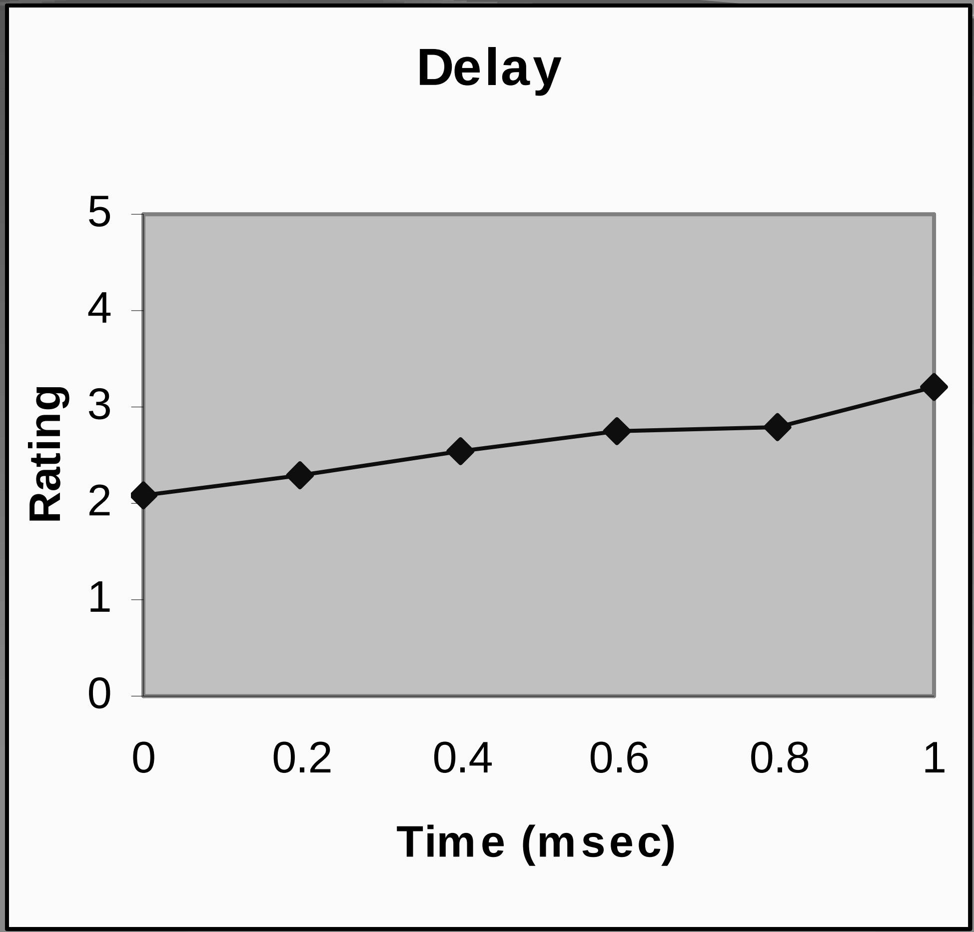
Implications

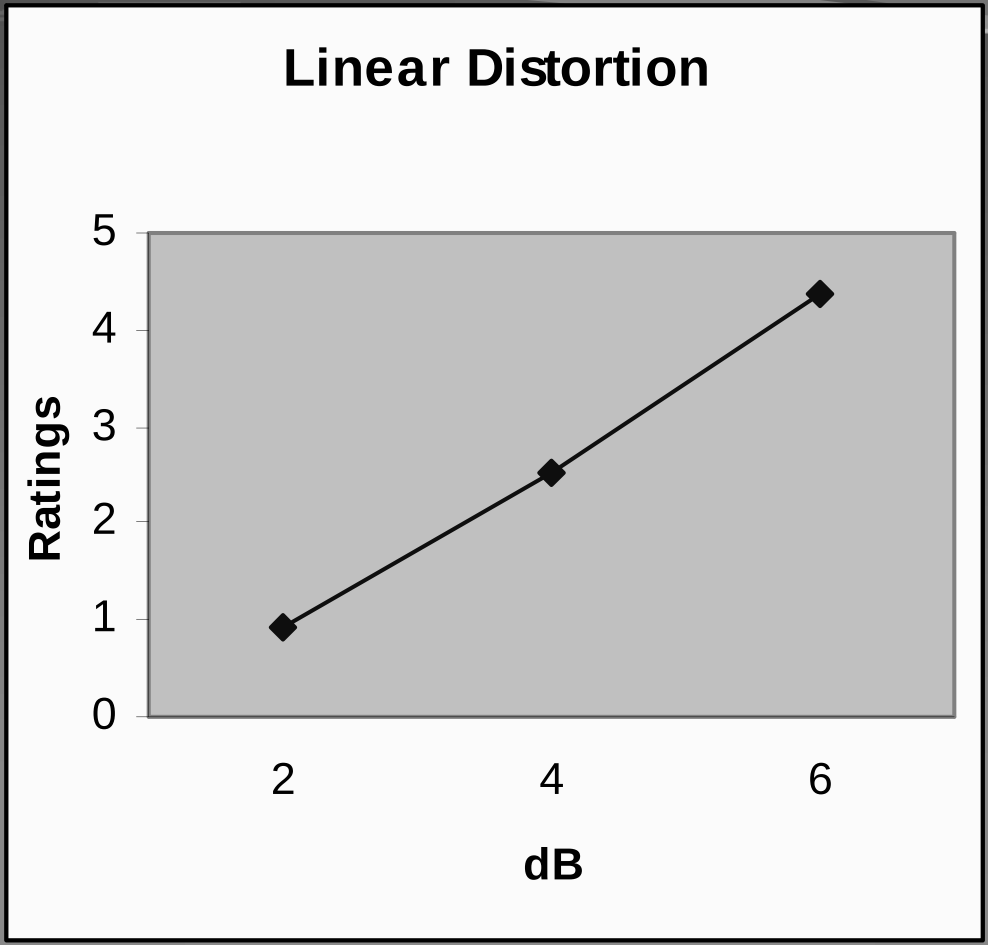
- Linear distortions can be audible although the data cannot be said to show that it is always audible
- Nonlinear distortion – in this test – was not audible
- This is consistent with the results of the previous test.

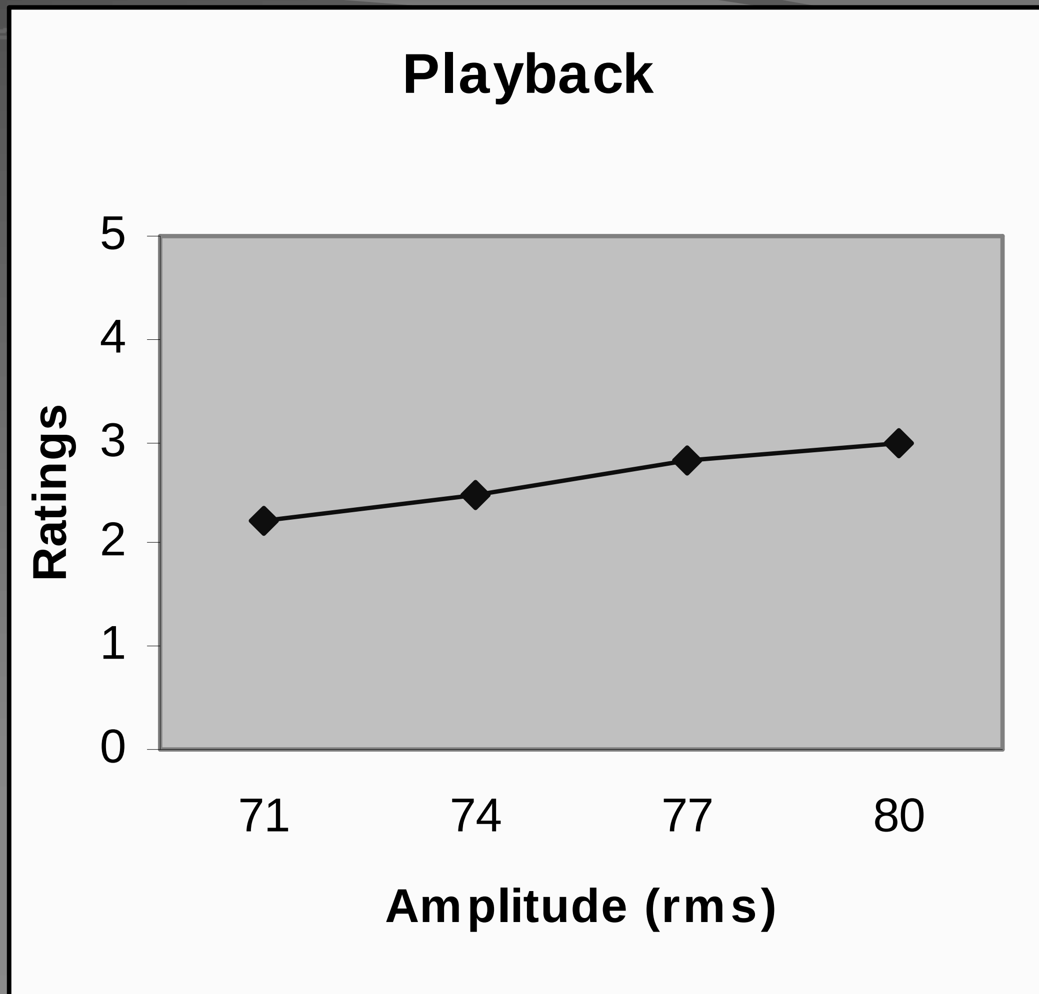
Another piece of data

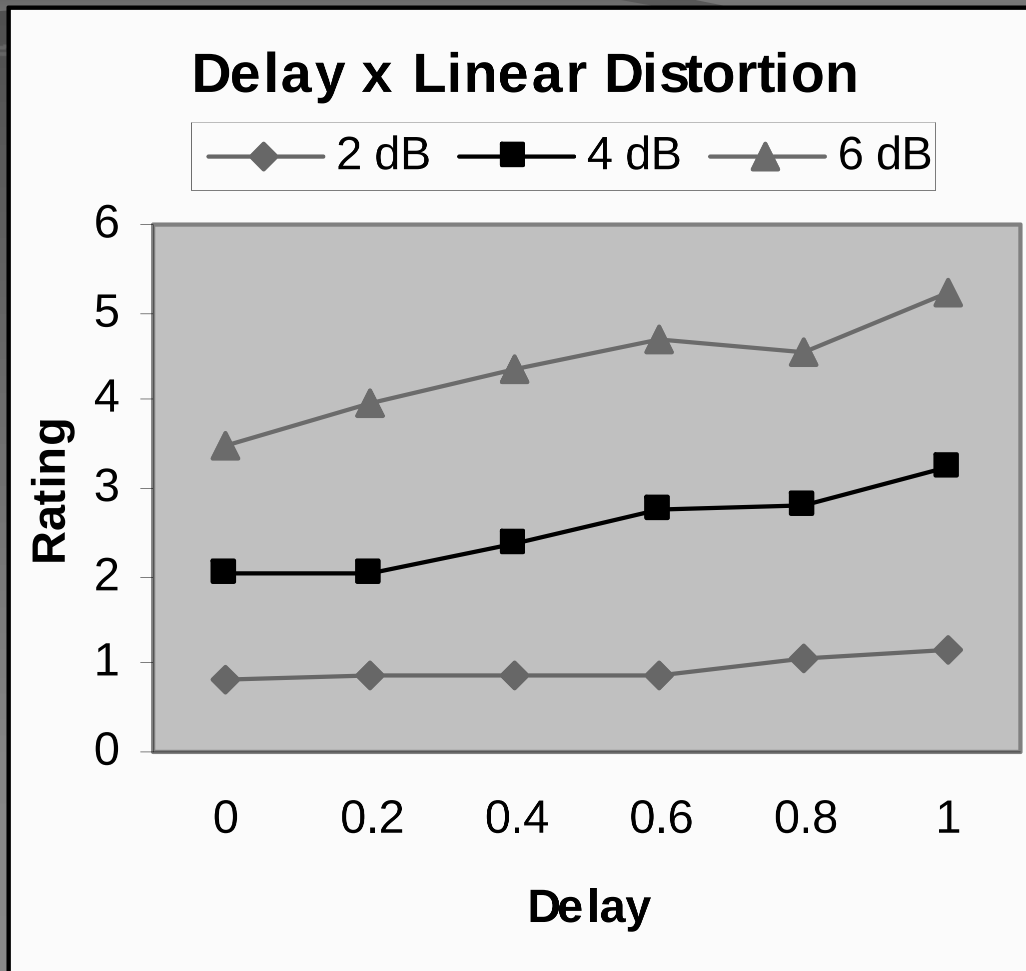
- In 2006 Lee and Geddes showed results for a test of purely linear distortions of a unique kind which were intended to simulate diffraction and acoustics effects found in horns
- In this test there were three control variables
  - Level of effect
  - Time delay of effect
  - Level of the playback

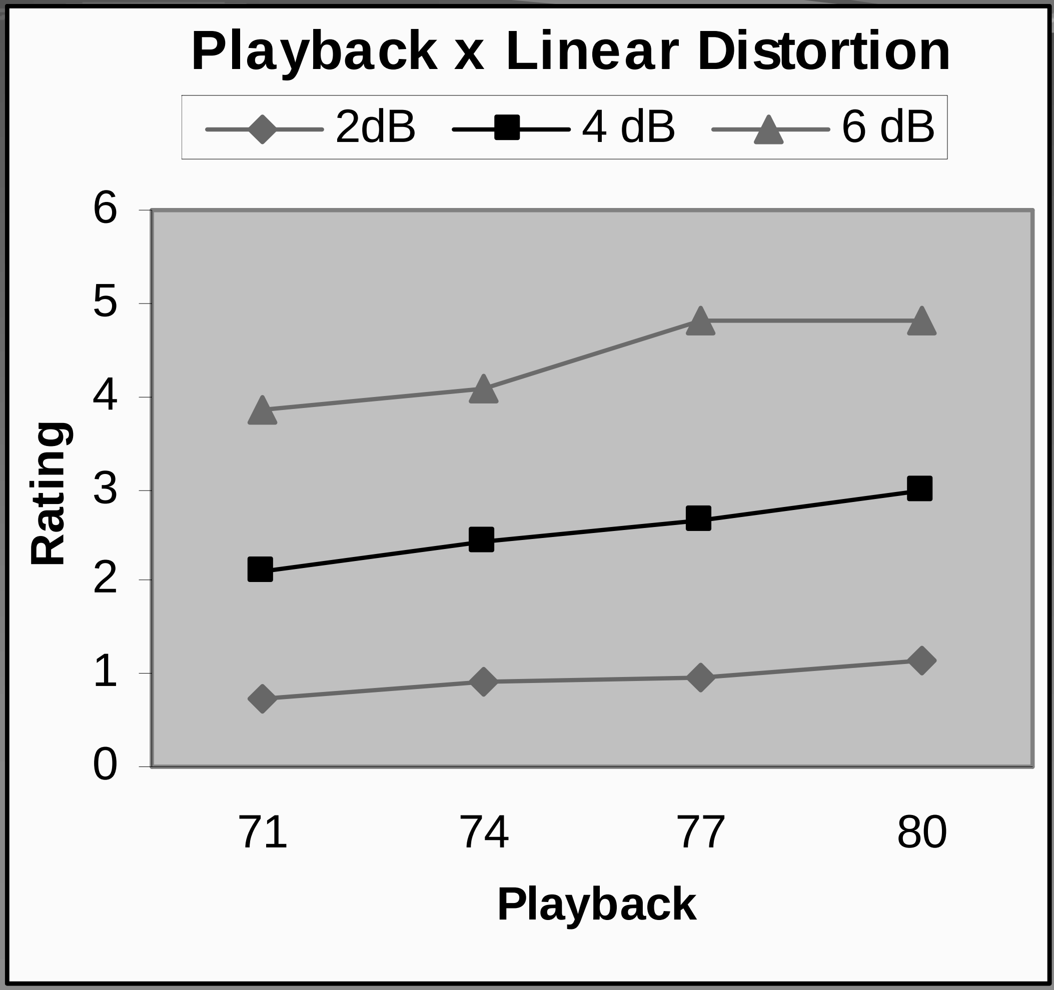
- Musical passages were modified by adding in a high-pass filtered signal which has variable amplitude and delay.
- The playback levels were varied
  - 80 dB (in the ear canal) – a fairly low level – was all the greater that could be tested because of clinical testing regulations. Many typical venues will exceed this amount quite substantially
- Ratings were 1 – 10 with 1 being inaudible and 5 being highly audible
  - Noise floor is expected to be at 1-2


Delay
Rating
5
4
3
2
1
0
0
0.2
0.4
0.6
0.8
1
Time (msec)


Linear Distortion
Ratings
5
4
3
2
1
0
2
4
6
dB


Playback
Ratings
5
4
3
2
1
0
71
74
77
80
Amplitude (rms)


Delay x Linear Distortion
2 dB
4 dB
6 dB
6
5
4
3
2
1
0
Rating
0
0.2
0.4
0.6
0.8
1
Delay


Playback x Linear Distortion
2dB
4 dB
6 dB
6
5
4
3
2
1
0
Rating
71
74
77
80
Playback

Implications

- Very small delayed signals, like diffraction from cabinet edges, etc. are likely to be audible
- The audibility increases with the amount of the linear distortion and its delay time
  - This is not surprising
- The most interesting effect is that the audibility increases with signal level

Implications con't

- This means that these effects are more audible at higher SPL levels than lower ones.
- This is in stark contrast to the audibility of nonlinear distortion which is less at higher SPL levels
- The nonlinearity in the ear is likely to be responsible for a loudspeaker to sound bad at higher levels and not the nonlinearities in the loudspeaker itself.

Conclusion

- Nonlinear distortion in a loudspeaker does not appear to be a strong factor in its perception
- Of course a loudspeaker could sound bad from nonlinearity, but it is likely that with proper design this factor can be made insignificant
  - There is simply no point in lowering the nonlinear distortion below some level

Conclusion

- In a completed system, with competent drivers, the high level sound quality is more likely to be limited by cabinet diffraction or similar effects than by driver nonlinearities.
- Recent designs at *Ai* have shown this to be the case
- Reduced diffraction designs can reach extremely high SPL levels without audible problems even though the measured THD can be as high as 20%

- Blind reliance on measurements can be misleading - one needs to tie those measurements back to subjective perception
- It is the perceived sound quality that matters not the measured quality – unless that measurement has been scaled and correlated to subjective perception through valid psychoacoustic tests.
- Unfortunately very few of our current genre of acoustic tests have had this kind of introspection