

Acoustical Measurement of Sound System Equipment according IEC 60268-21

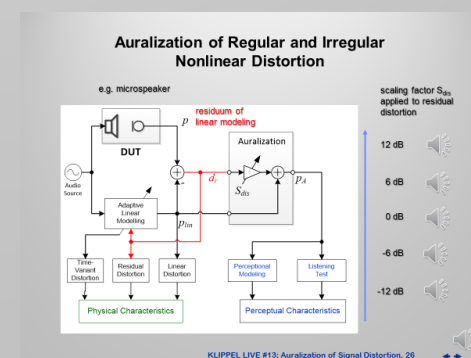
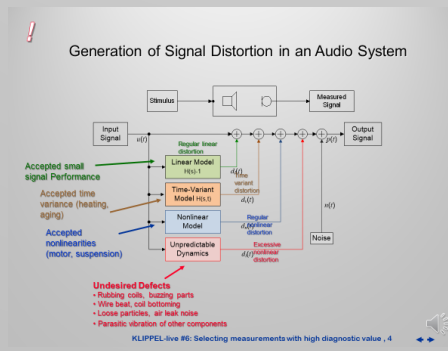
KLIPPEL LIVE

a series of webinars presented by

Wolfgang Klippel

Previous Sessions

1. Modern audio equipment needs output based testing
2. Standard acoustical tests performed in normal rooms
3. Drawing meaningful conclusions from 3D output measurement
4. Simulated standard condition at a single evaluation point
5. Maximum SPL – giving this value meaning
6. Selecting measurements with high diagnostic value
7. Amplitude Compression – less output at higher amplitudes
8. Harmonic Distortion Measurements – best practice
9. Intermodulation Distortion – music is more than a single tone
10. Impulsive distortion - rub&buzz, abnormal behavior, defects
11. Pitfalls in Testing Wireless Audio Devices
12. Benchmarking of audio products under standard conditions
13. Auralization of signal distortion – perceptual evaluation
- 14. Setting meaningful tolerances for signal distortion**
15. Rating the maximum SPL value for product



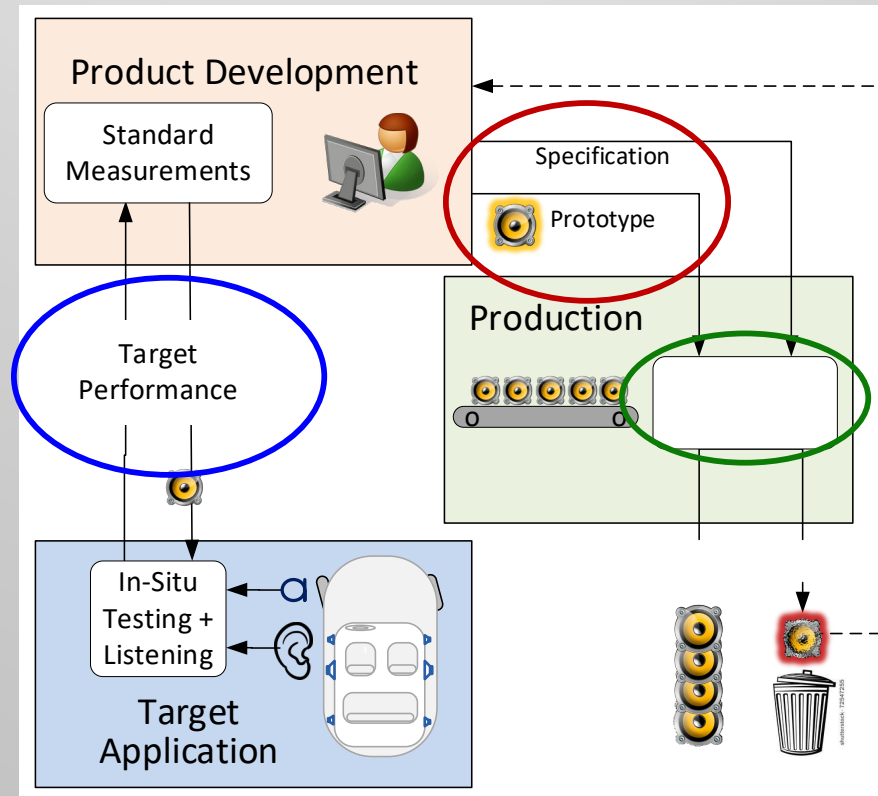
14th KLIPPEL LIVE: Setting meaningful tolerances for signal distortion

Topics today:

- Modeling the processing in our ears
- Audibility threshold under critical condition
- Perceptual audio quality measured with music
- Our brain decides about the audio quality
- Maximizing the end-user value

How to create a successful Audio Product?

Life cycle

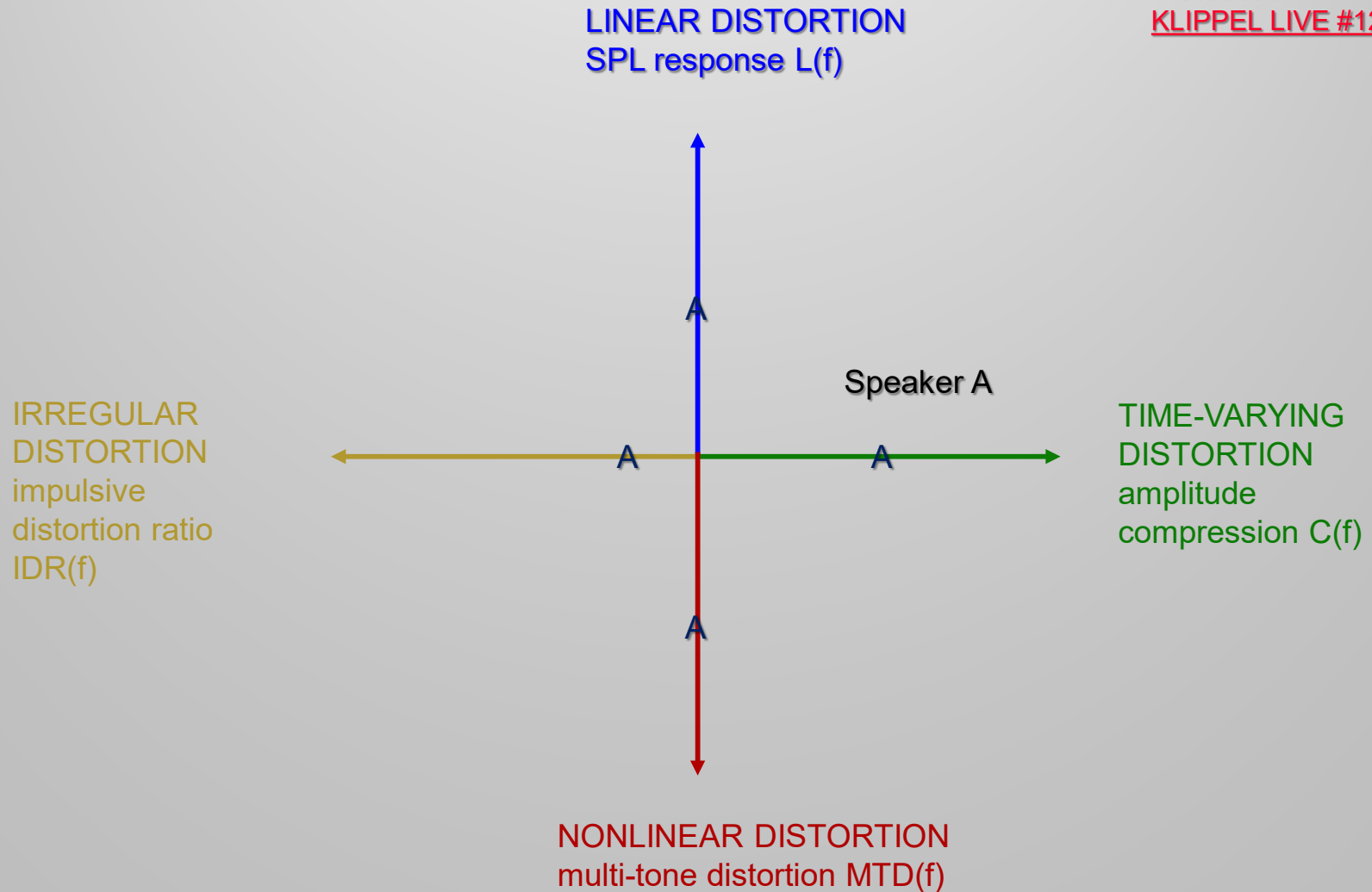


We need target values, limits and tolerances for our measurement data !

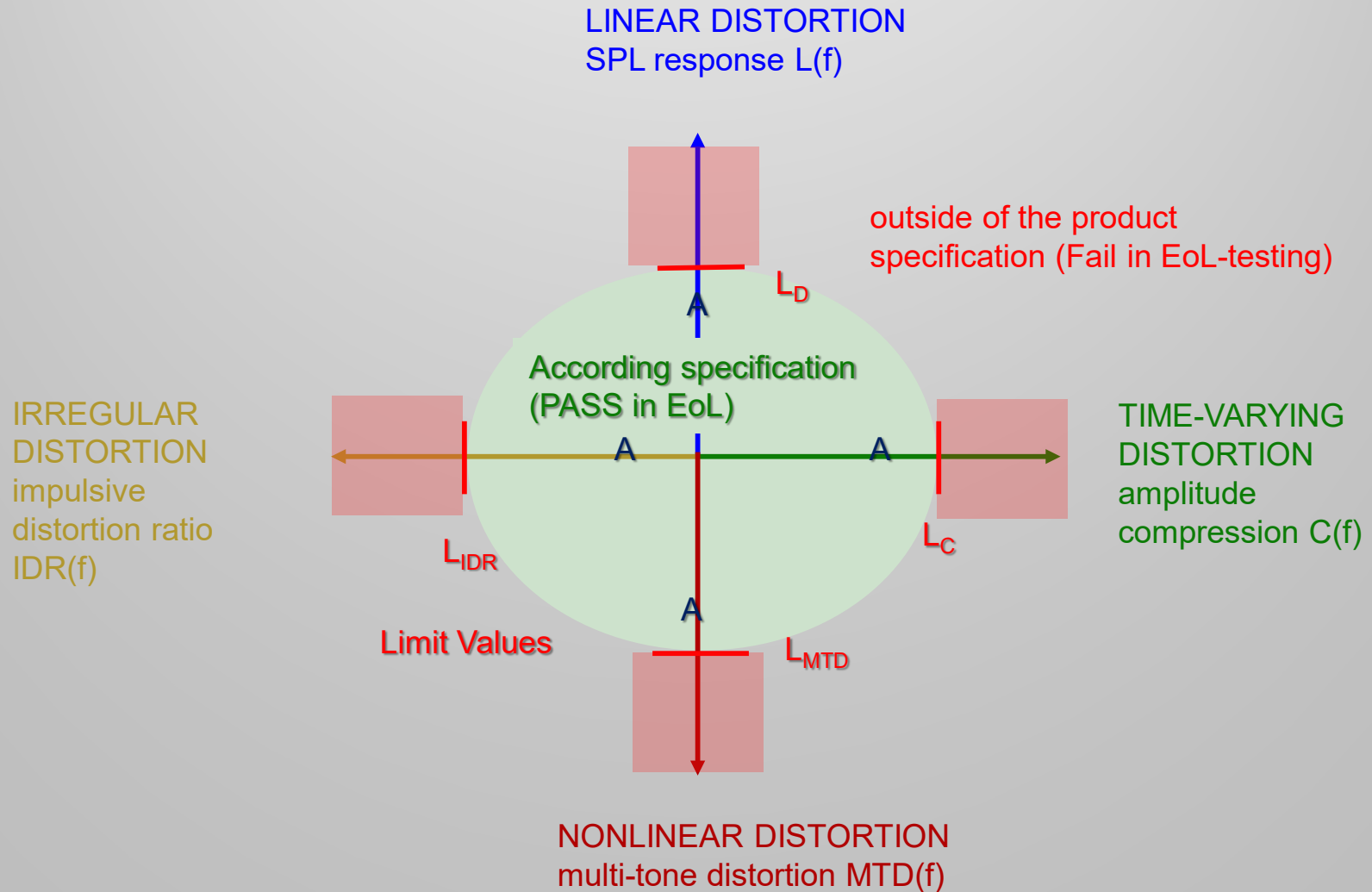
Essential Metrics for Benchmarking

defined in IEC Standards

Discussed in
KLIPPEL LIVE #12



Applying Limits to the Metrics



Poll:

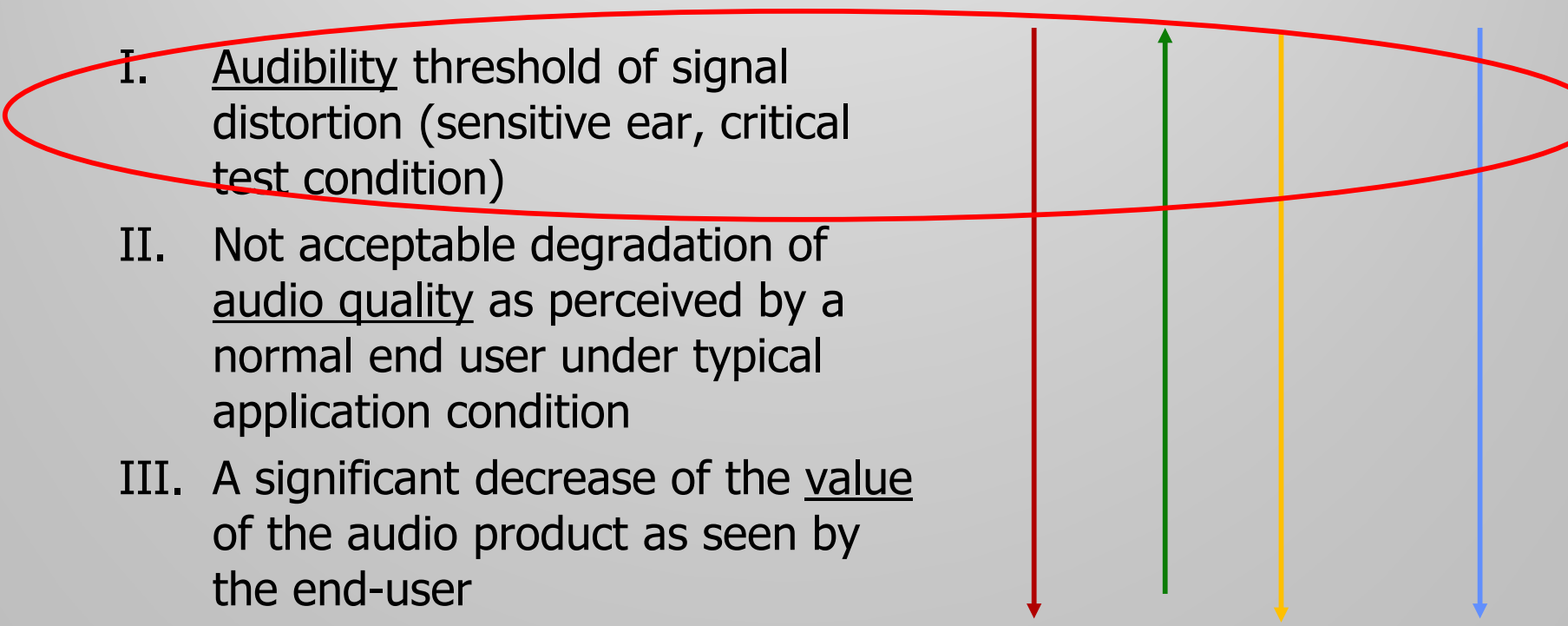
How would you set the limits for signal distortion ?

- A. At the limits, the distortion becomes just audible for a trained and experienced listener (GOLDEN EAR) under special critical conditions 6%
- B. At the limits the distortion can be detected by a normal user under typical conditions 24%
- C. The limits correspond to a small loss of perceptual audio quality as perceived by a normal user under typical conditions 24%
- D. The limits describe distortion which are unacceptable for some listeners 6%
- E. The limits describe the signal distortion that generates the best benefit-cost ratio for end user 41%
- F. Other 0%

Criteria for the Limits

Worst case scenario

Predictable
by modeling

- 
- I. Audibility threshold of signal distortion (sensitive ear, critical test condition)
 - II. Not acceptable degradation of audio quality as perceived by a normal end user under typical application condition
 - III. A significant decrease of the value of the audio product as seen by the end-user

complexity

economical
importance

Higher
limit value

Worst Case Scenario

Audibility under most critical condition

End-user: Experienced listener (e.g. sound engineer, musician, audiophile)

Most critical program material: two-tone signal with optimal amplitude, frequency setting and sufficient duration

Acoustical Environment: Anechoic room (dominant direct sound, no ambient noise)

Test Methodology: Double Blind AB-Test to find a just detectable difference

Limit: Identical with audibility threshold

Practical Relevance: High-quality products (e.g. Studio Monitor)

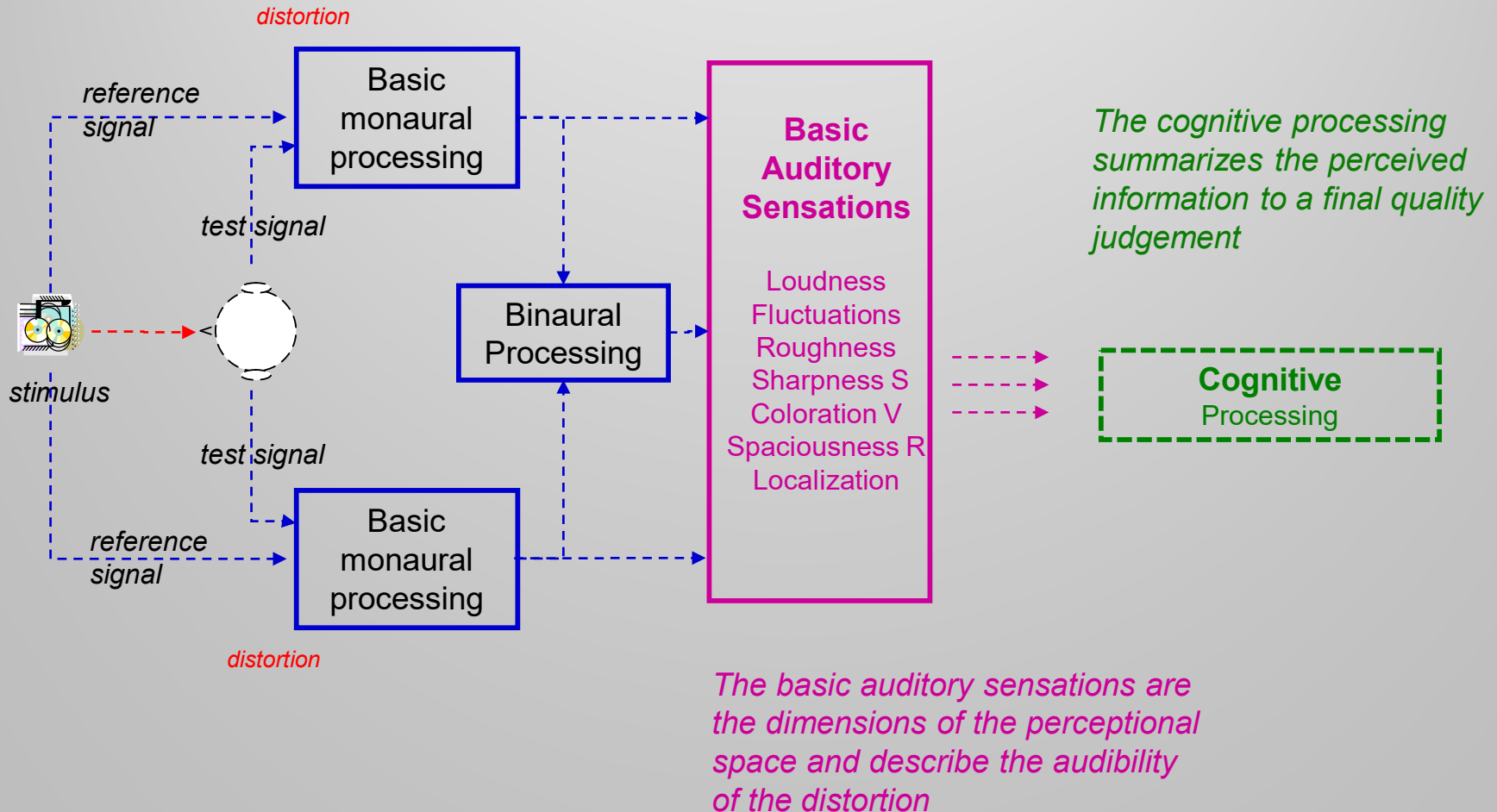
Audibility of Signal Distortion

Methods for Assessments:

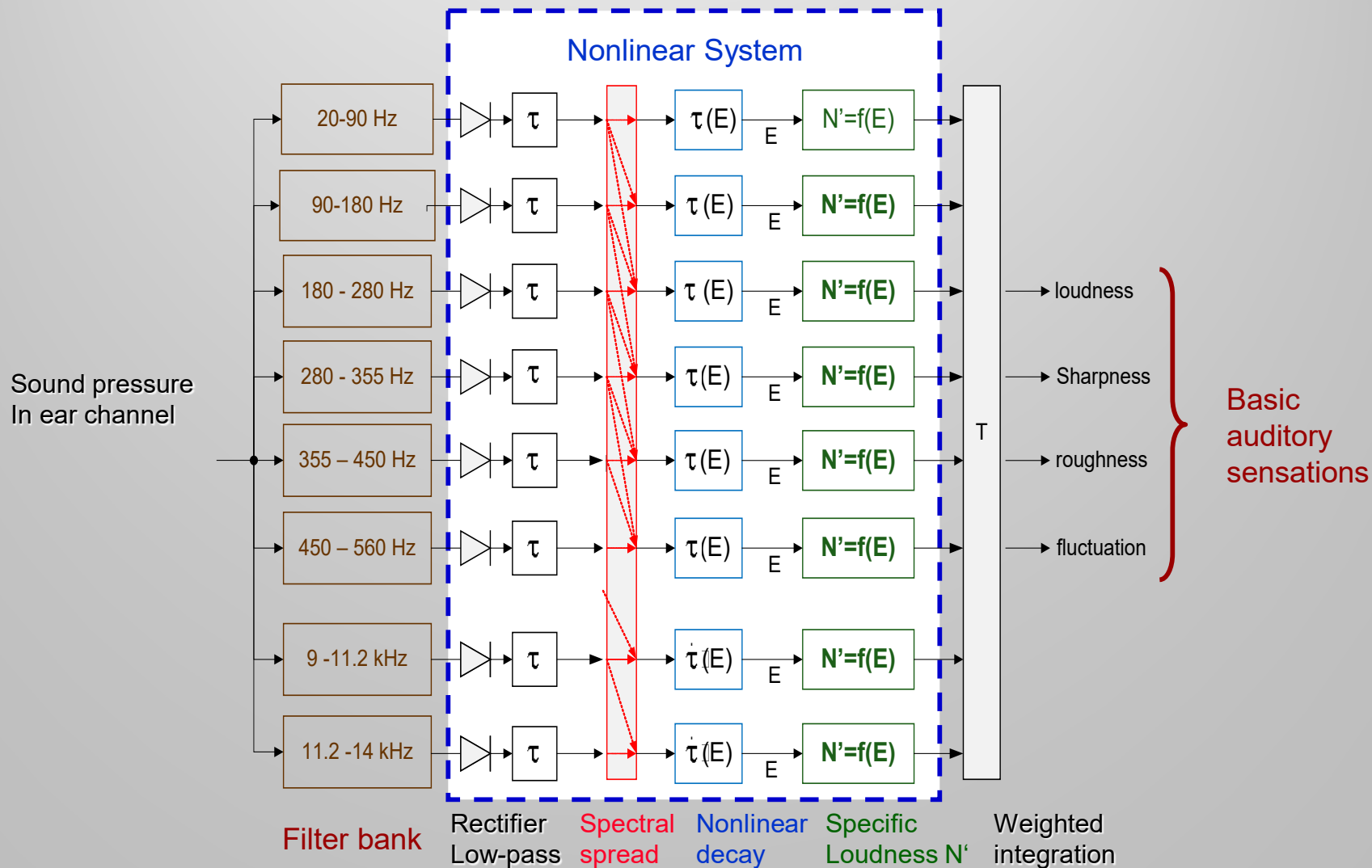
1. Modeling the perceptive and cognitive processing in ear and brain based on basic research
2. Listening to real products (selected participants, program material, listening room, double blind AB test, statistical analysis)
3. Systematic listening to a modified sound output (Auralization of signal distortion → [KLIPPEL LIVE #13](#))

Evaluation of Signal Distortion

based on Perceptual Modeling

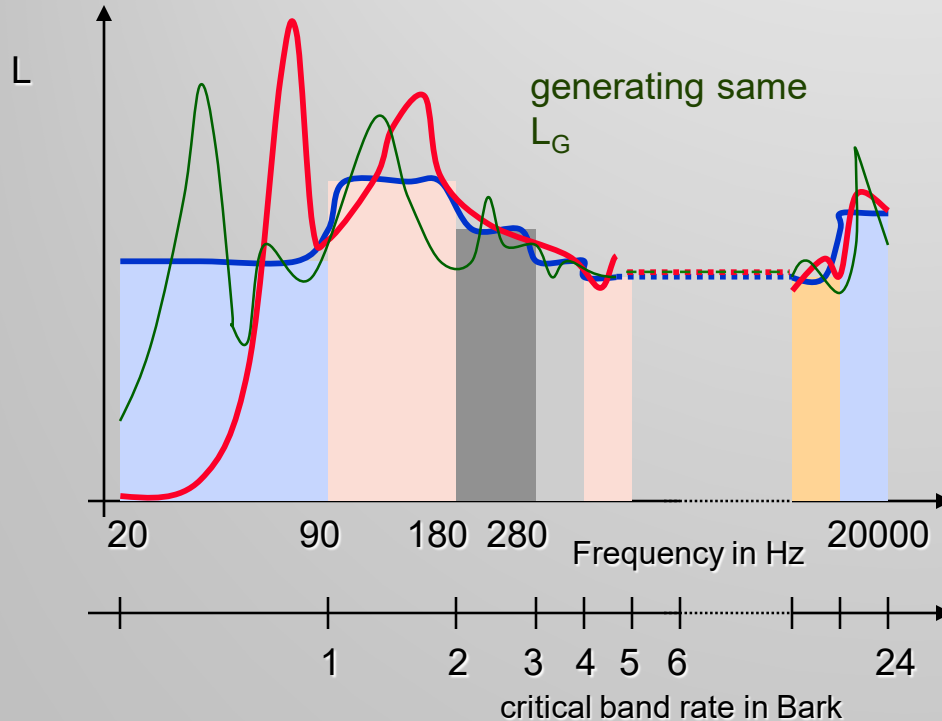


Basic Monaural Processing

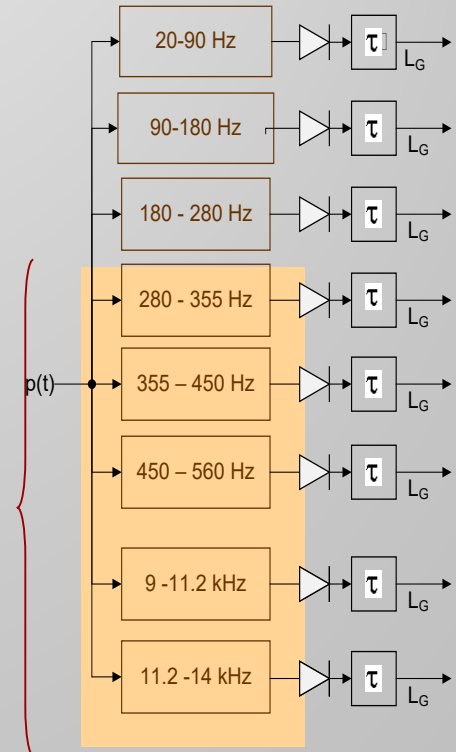


Transformation

SPL Spectrum → Critical Band Level L_G



Third-octave band passes

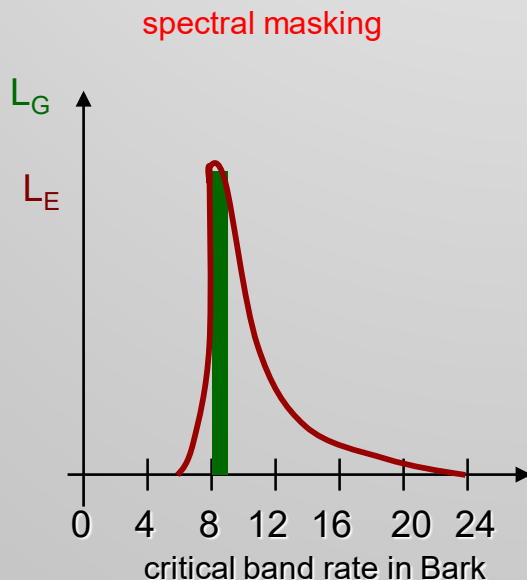
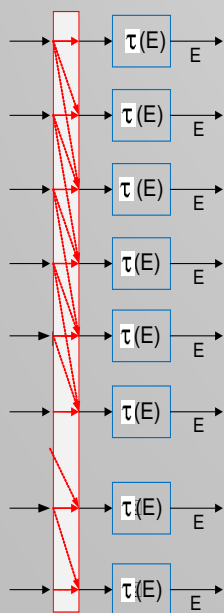


Consequences for the assessment of audio systems:

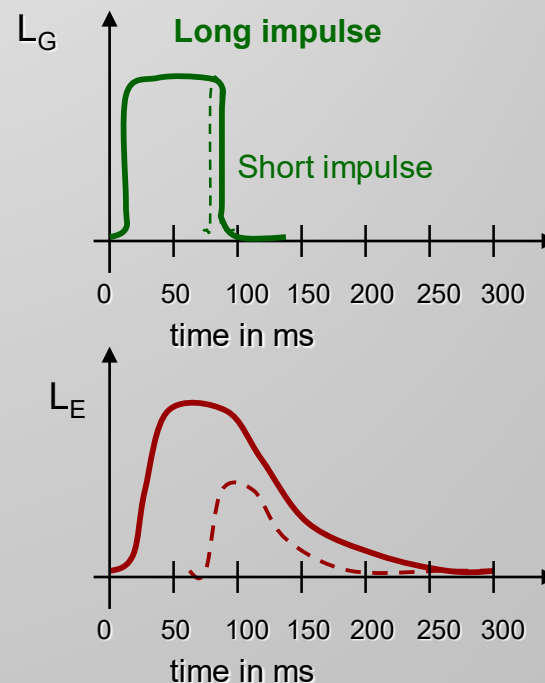
- third-octave spectral analysis of reproduced audio signal is useful for interpretation of coloration in audio-chain (stimulus-speaker-room-ear)
- bass sensations can be enhanced by increasing level of higher frequency components within the critical band
- 1 dB variation of the critical band level becomes audible

Transformation

Critical Band Level $L_G \rightarrow$ Excitation Level L_E



temporal masking

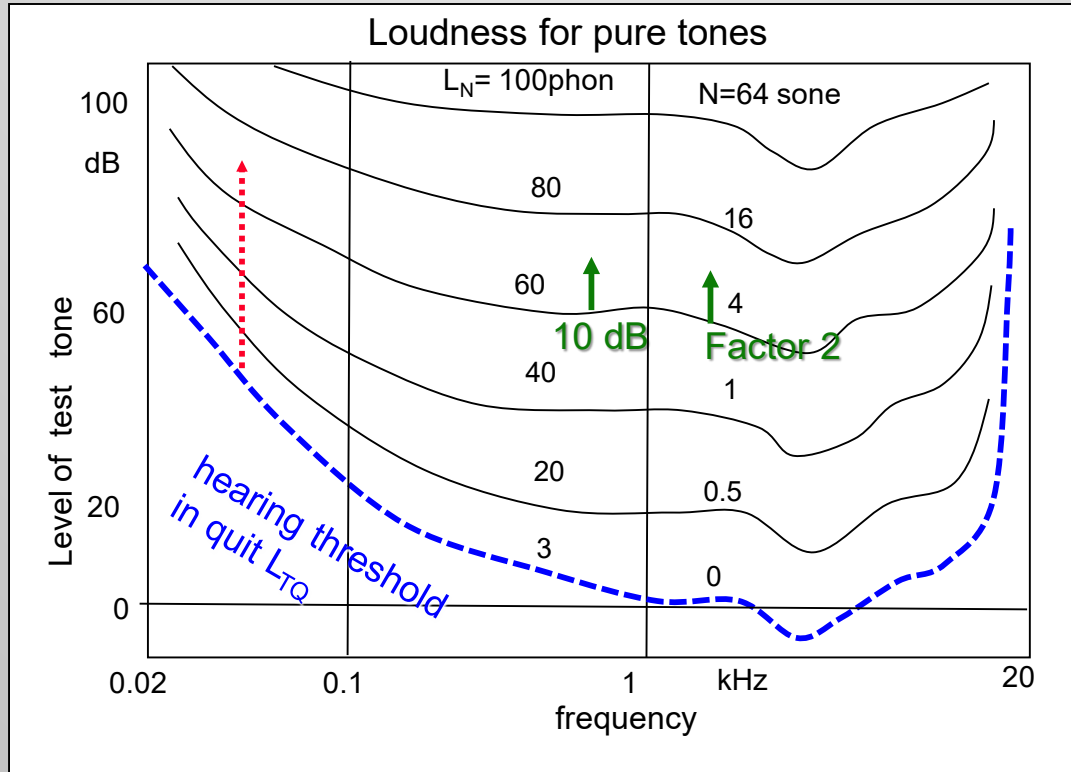


Consequences for assessment of audio systems:

- Peaks are more critical than dips in amplitude response
- Nonlinear distortion is masked by the fundamental component
- Fast modulation of the envelope is less audible

Transformation:

Excitation Level $L_E \rightarrow$ Specific Loudness N'



1. Specific Loudness
 $N'=0$ for $L_E < L_{TQ}$
2. Loudness doubles if excitation level rises by 10 dB for $L_E \gg L_{TQ}$

Consequences for assessment of audio systems:

- Bass signals are not audible if the listening level is too low
- Small differences in transfer response may cause significant differences in perceived bass sensation

Poll:

Which limit would you apply to Total Harmonic Distortion (THD) under most critical conditions ?

A. More than 10 %	5%
B. 10%	43%
C. 1 %	29%
D. 0.1 %	10%
E. 0.01 %	0%
F. Less than 0.01 %	0%
G. I don't know	14%

Audibility Thresholds under Critical Conditions

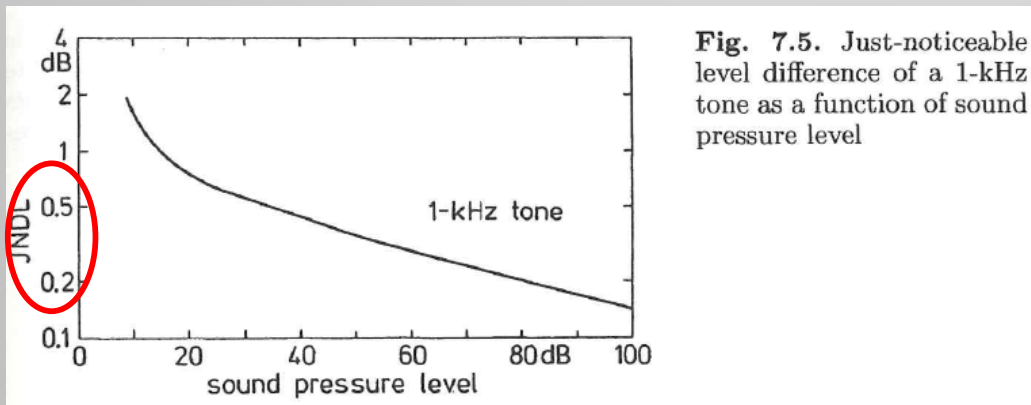
Distortion	Metrics	Audibility Thresholds
Linear Distortion	Variation of SPL frequency response $\Delta L(f)$	0.5 ... 1 dB
Time-variant linear distortion	Amplitude Compression C	0.2 ... 1 dB
Regular Nonlinear Distortion	$D_{THD}(f)$, $D_{2HD}(f)$, $D_{3HD}(f)$, $D_{2IMD}(f)$, $D_{3IMD}(f)$	0.3 ... 3 %
Irregular Distortion (defects)	Impulsive distortion ratio $IDR(f)$	-60 ... -40 dB

Audibility of Linear Distortion

most critical condition

Just-noticeable Changes in Amplitude

Reference: E. Zwicker, H. Fastl, Psycho-acoustics, Facts and Models, 2nd edition Springer



Impact on Audio Measurements:

- Variation of SPL response $L(f)$ versus frequency
- Amplitude Compression $C(t)$ versus time

Threshold for sinusoidal stimulus depends

- Frequency and level of the tone
- Duration of the tone (at least 0.5s)
- Pause between the tones (at least 0.2 s)
- Other factors

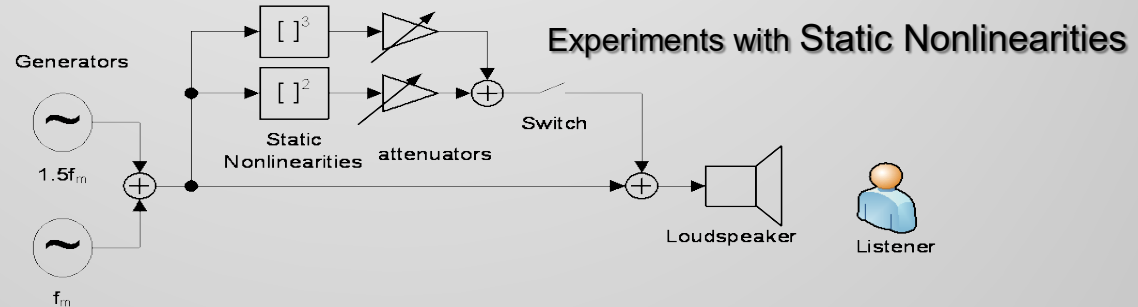
Critical scenario in practice:

- Glissando (continuous slide) in music with a sparse spectrum
- Just noticeable shift in localization of the sound event (lateralization)

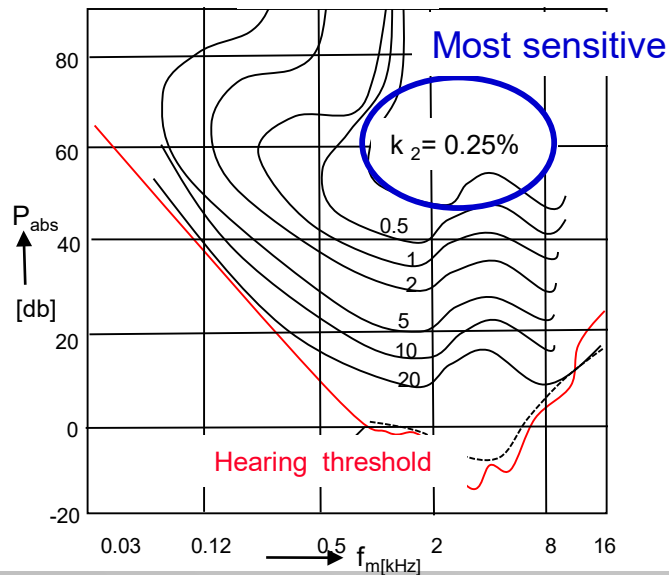


Audibility of Regular Nonlinear Distortion

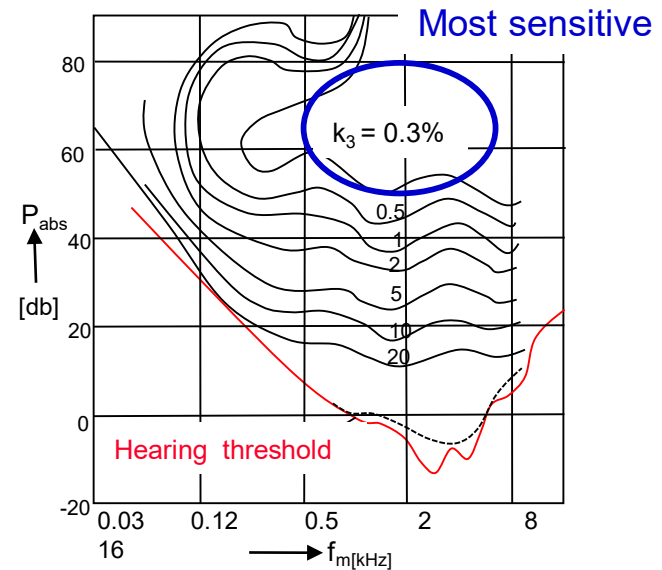
Two tones
(fifth interval)



Just- noticeable 2nd-order harmonic distortion



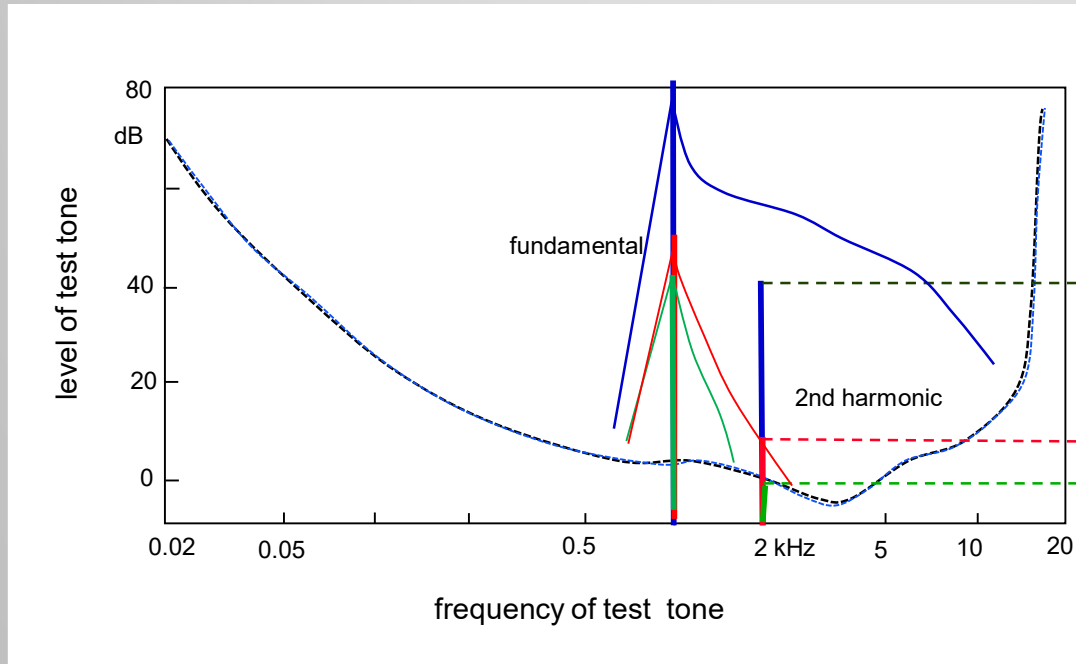
Just- noticeable 3rd-order harmonic distortion



Gäbler, G. Die Grenzen der Hörbarkeit nichtlinearer Verzerrungen bei der Übertragung von Instrumentenklingen. Frequenz 9, 15-25 (1955).

Spectral Masking of the Harmonic Distortion

Level of test tone masked by a tone at 1kHz of different levels



Reference: E. Zwicker, H. Fastl, Psychoacoustics, Facts and Models, 2nd edition Springer

$L_M = 80$ dB and
1% of 2nd harmonic is not audible

$L_M = 50$ dB and
1% of 2nd harmonic is clearly audible

$L_M = 40$ dB and
1% of 2nd harmonic is not audible

Consequences for audio reproduction:

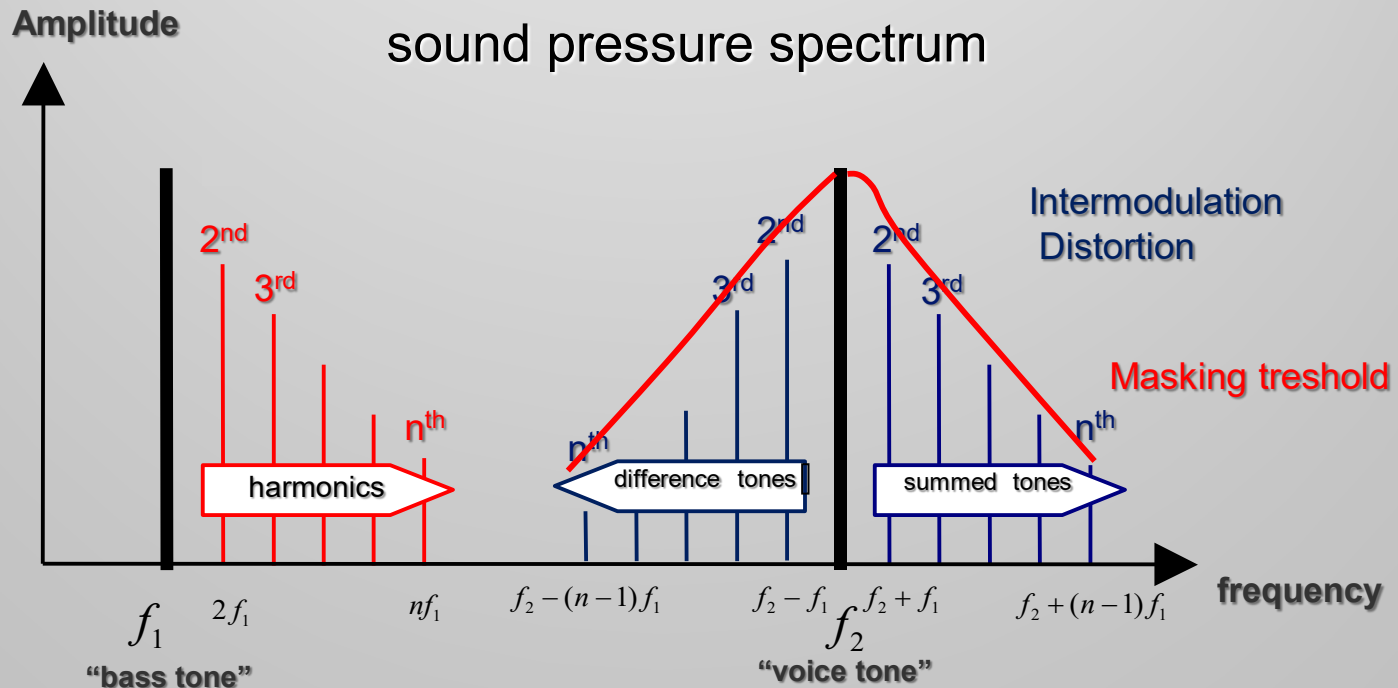
Low SPL: Distortion are masked by hearing threshold in quiet

High SPL: Distortion are masked by the fundamental and ear nonlinearity

Intermodulation Distortion

generated by Two-tone Stimulus

Discussed in
[KLIPPEL LIVE #9](#)

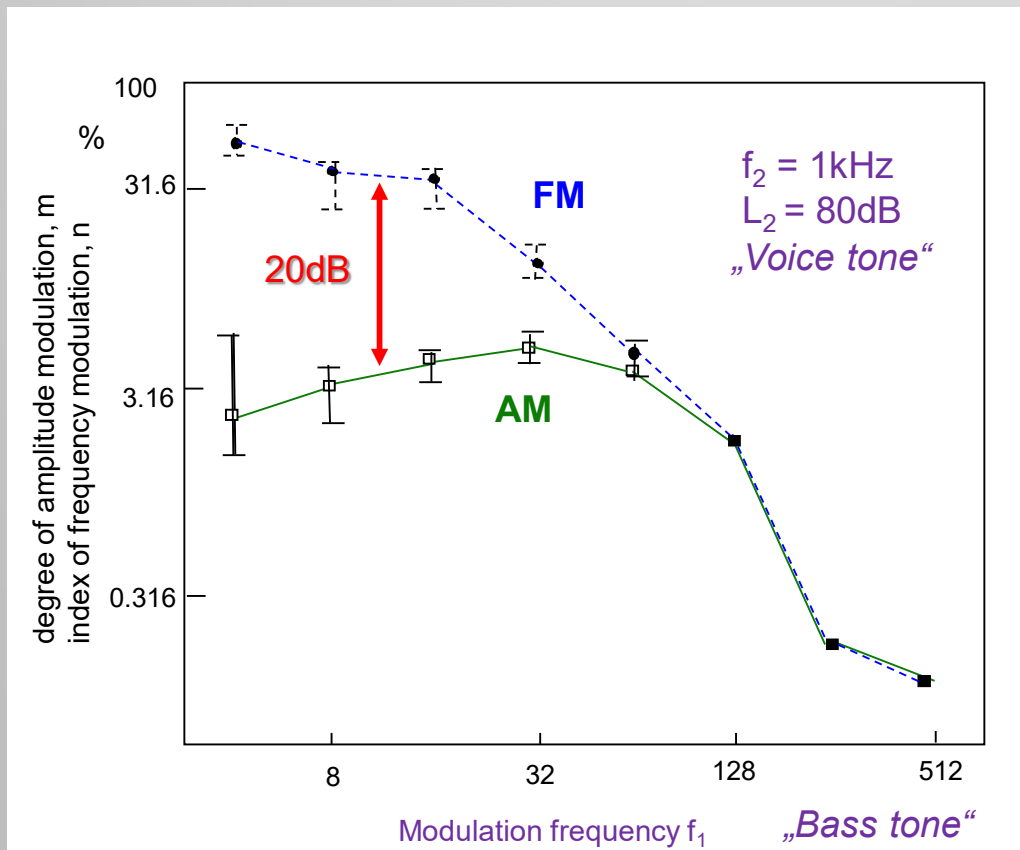


Are the intermodulation distortion components masked by the fundamental ?
It depends on the frequency of the bass tone f_1 !



Audibility of Intermodulation Distortion

Just-noticeable degree of amplitude modulation (AM) and just noticeable index of frequency modulation (FM) of a high-frequency tone $f_2 = 1$ kHz tone at 80 dB SPL, as a function of modulation frequency f_1



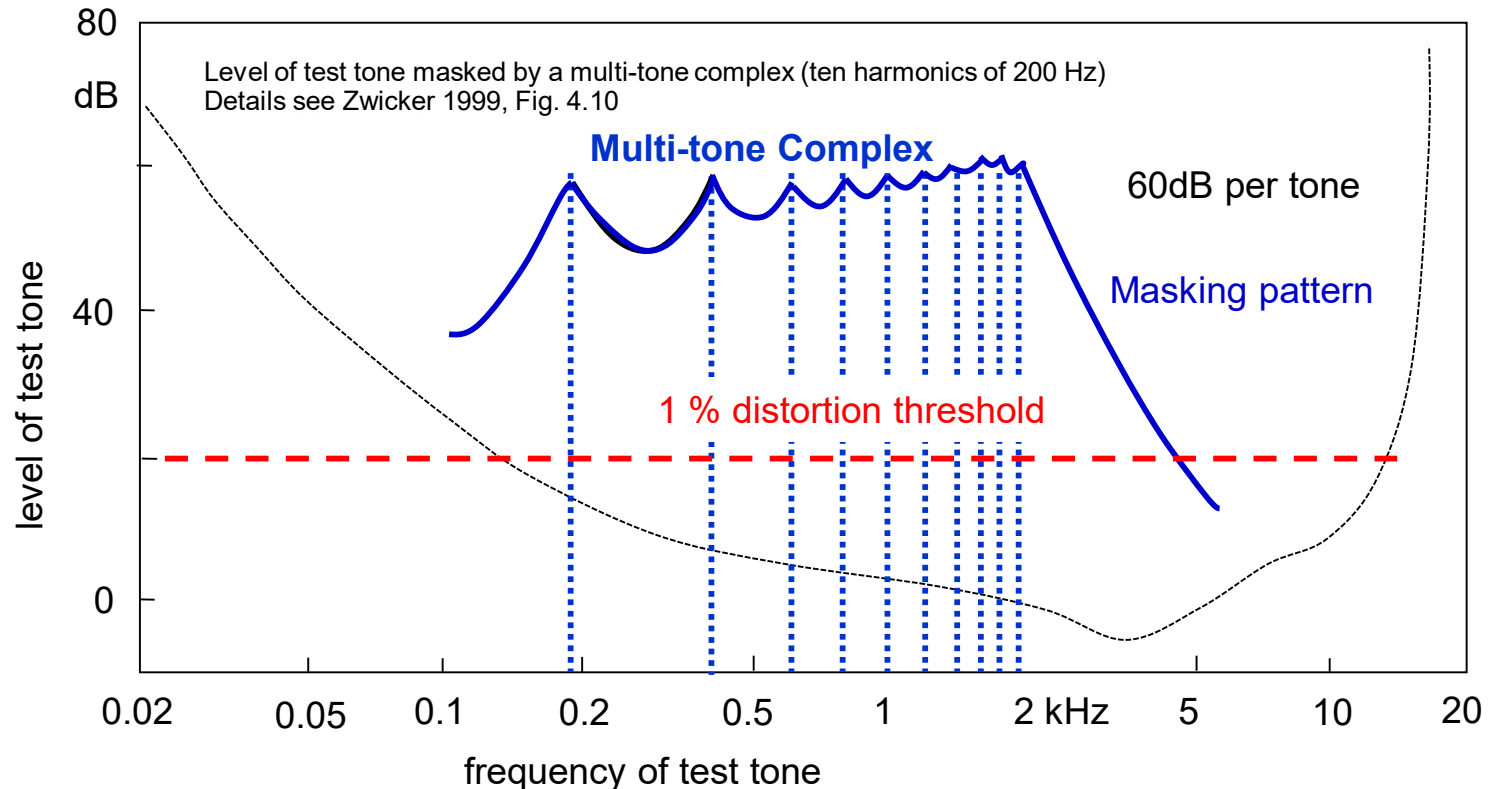
Conclusion:

- the intermodulation distortion is not masked ($f_1 > 200$ Hz)
- **AM modulation** (e.g. force factor distortion) is audible at 3% and perceived as roughness and fluctuation ($f_1 < 100$ Hz)
- Threshold of **FM modulation** is 20 dB higher ($f_1 < 30$ Hz)
- **Doppler** distortion is not critical



Masking Threshold

generated by a band-limited Multi-Tone Stimulus

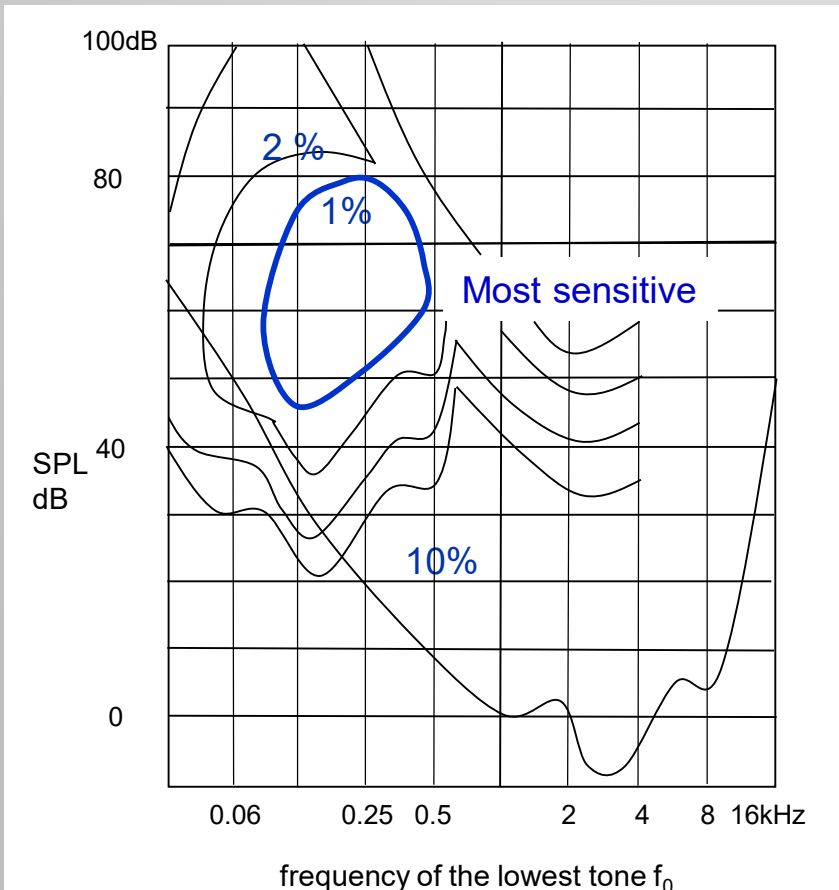


The fundamental components generate a high masking pattern.
The distortion at higher frequencies can be detected at 1 % threshold !

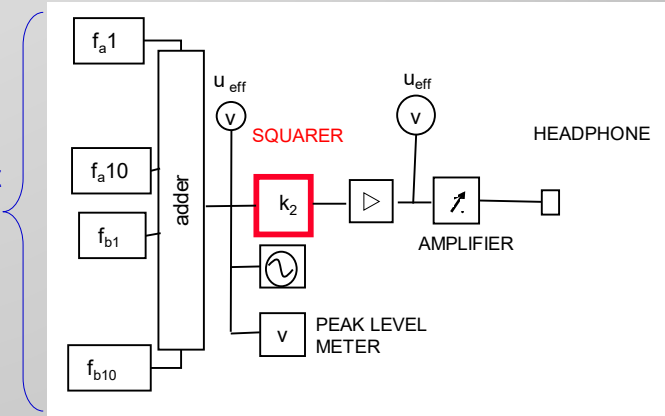


Audibility of Intermodulation

Multi-Tone complex via static nonlinearity



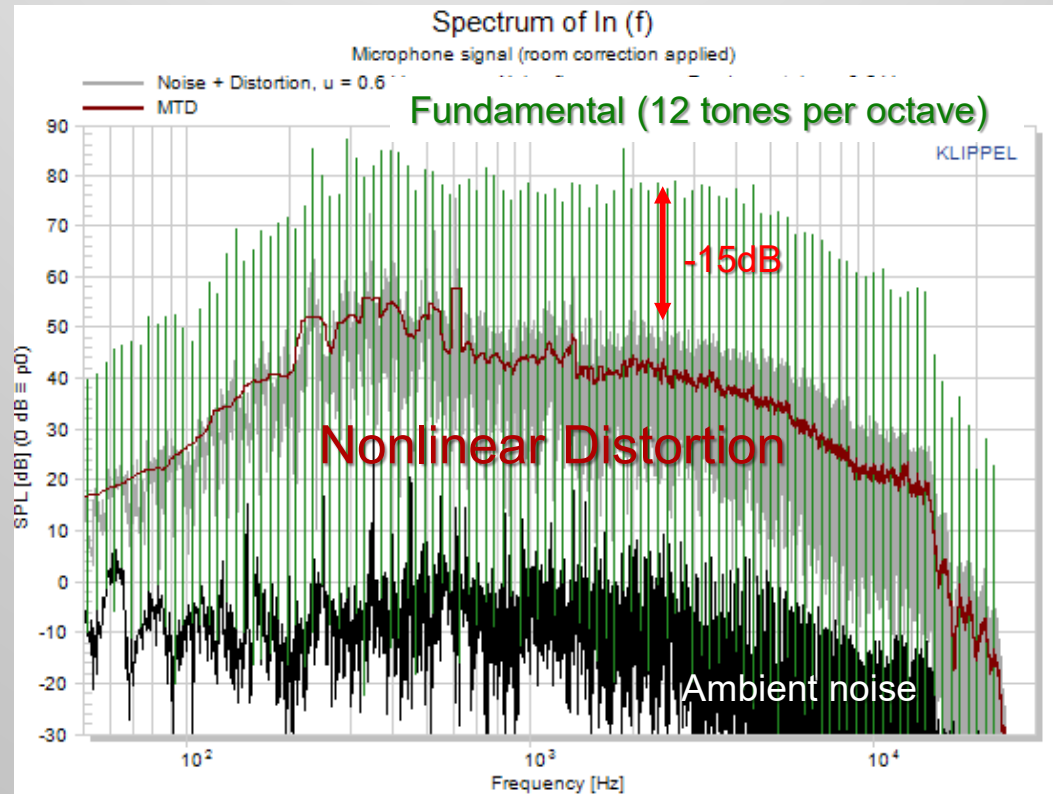
10 sinusoidal
Generators at
 f_0 and
harmonics



Gäbler, 1955

Threshold of audibility of a distorted multi-tone complex comprising fundamental f_0 and harmonics up the 10th order

Nonlinear Distortion in a Dense Spectrum



- Nonlinear Distortion are masked in the loudness and SPL spectrum !

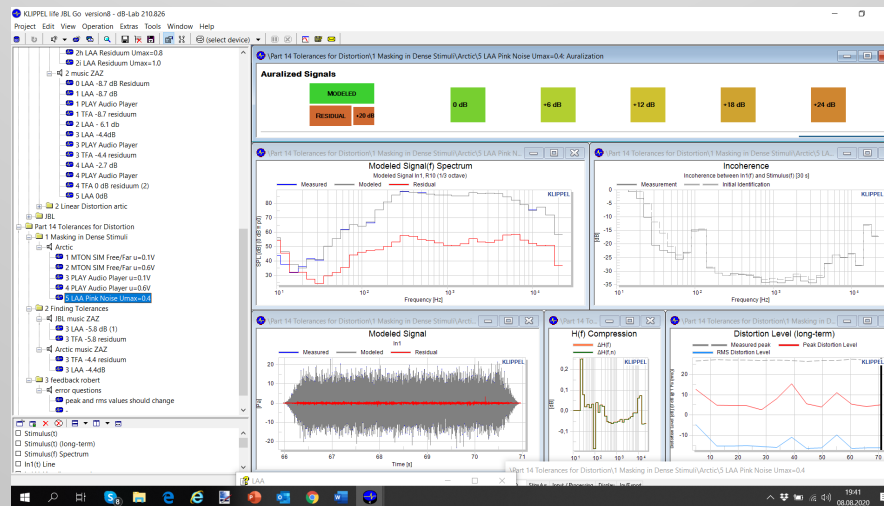
BUT

- Nonlinear Distortion can be detected in the time domain (as roughness and fluctuation)

Demo: Audibility of Amplitude Modulation

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- Live Audio Analyzer (LAA)
- Multi-tone Measurement (MTON)



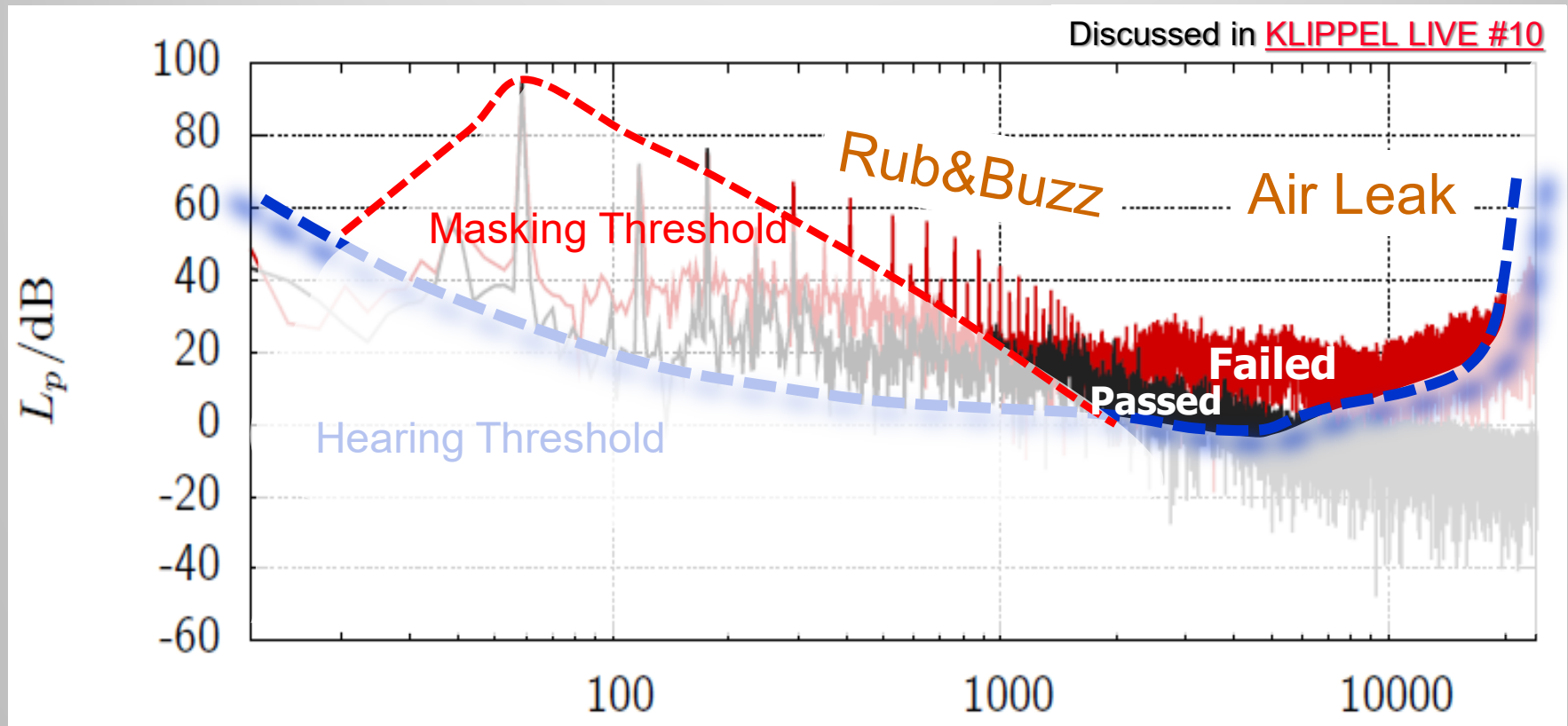
JBL
Bluetooth
Speaker
(one
channel)



Arctic Competitive
Bluetooth
Speaker
(stereo, only left
channel is used)



Masking of Loudspeaker Defects



- Fundamental component masks low-order harmonics
- Hearing threshold also masks irregular distortion at high frequency

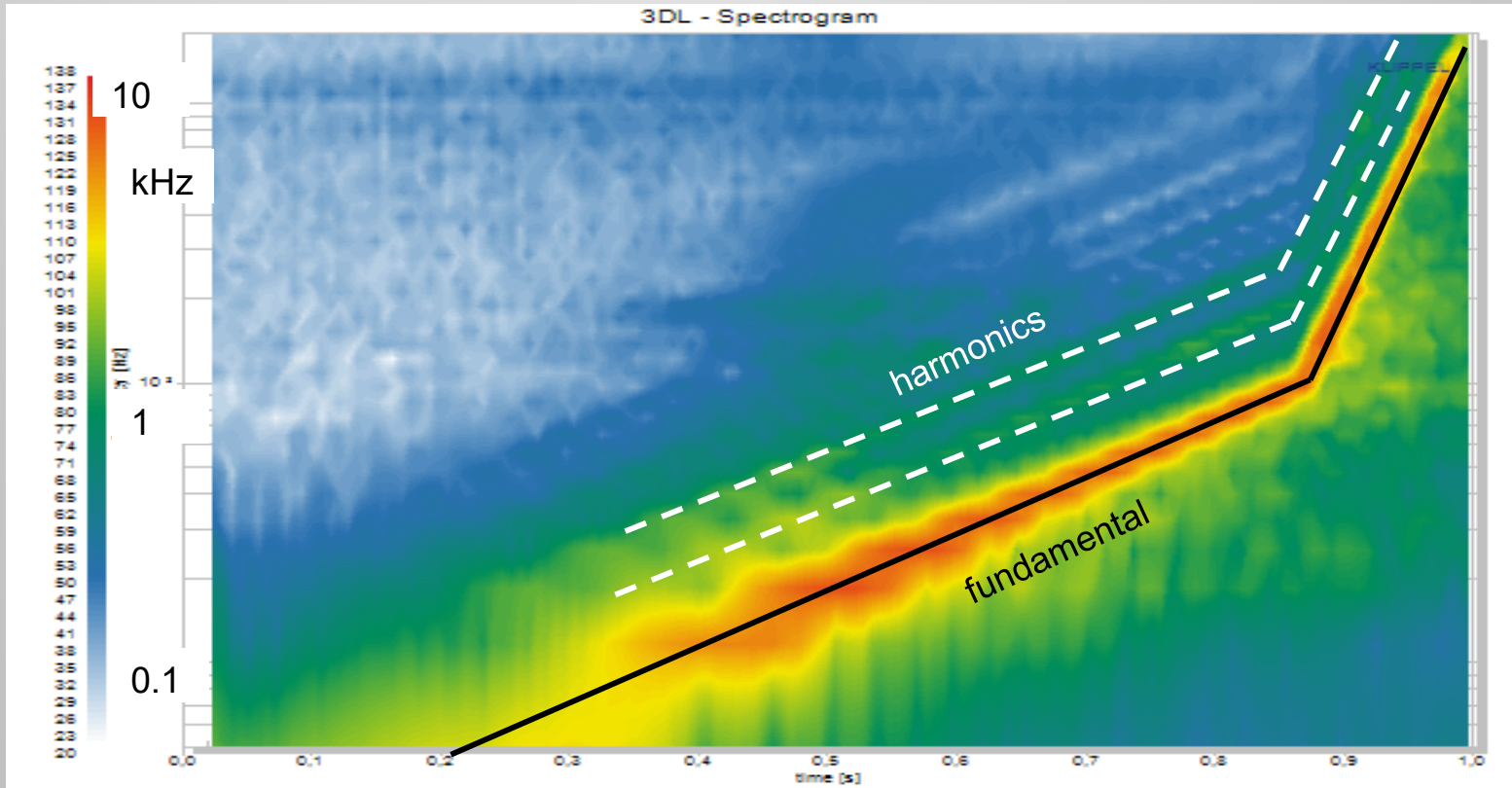
Questions: Which perceptual metrics reveal the loudspeaker defects ?

Spectrogram $L_{REF}(f_s, f_e)$ generated by an Auditory Filterbank

Discussed in
[KLIPPEL Live #10](#)

Spectral
frequency

f_s



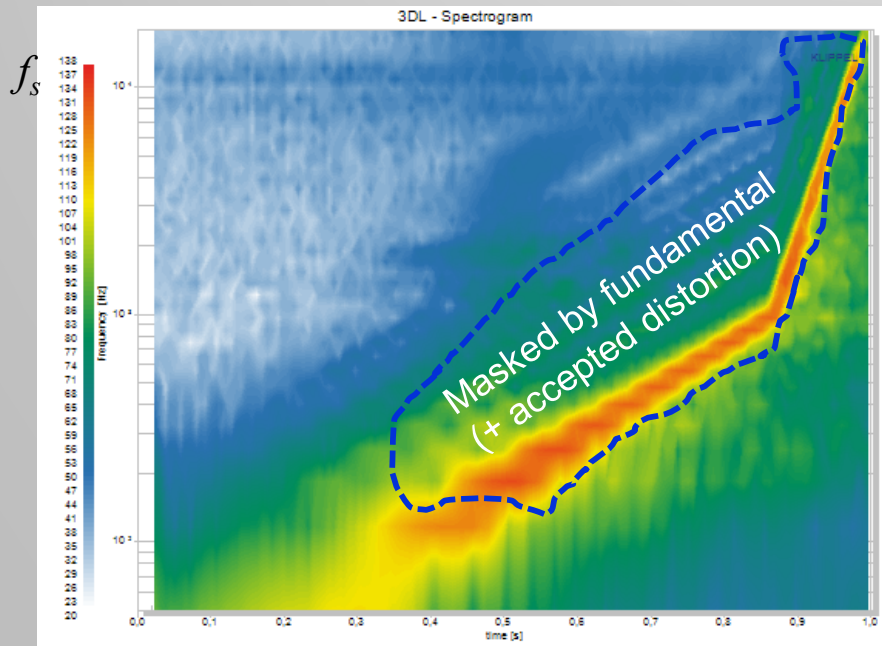
Instantaneous excitation frequency of the chirp

f_e

3D Disturbance to Mask Ratio

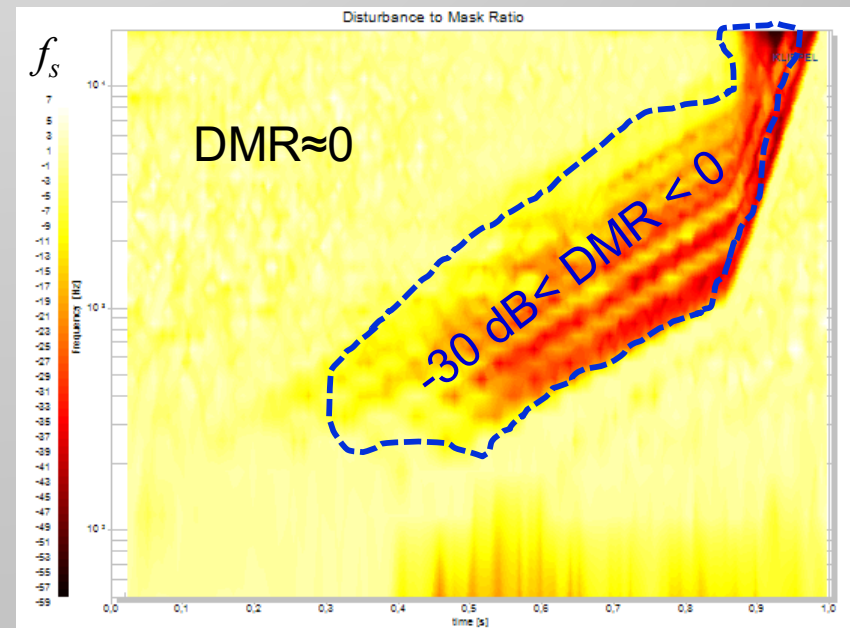
Disturbance Mask Ratio shows the difference between the spectrum $L_{\text{DUT}}(f_s, f_e)$ of the DUT and the masking threshold generated by the Golden Reference DUT !

Spectrum $L_{\text{REF}}(f_s, f_e)$ of the Golden Reference DUT



f_e

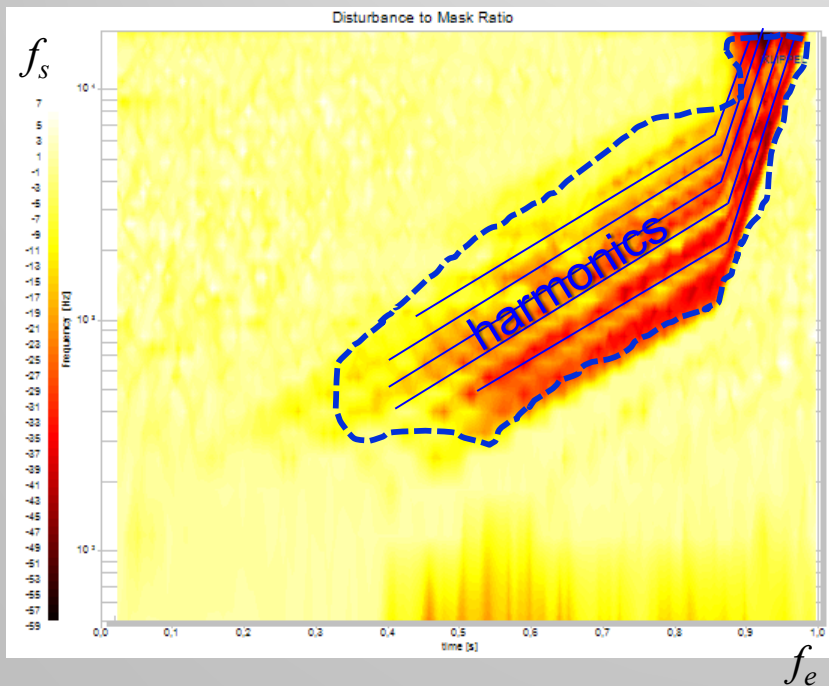
Disturbance Mask Ratio $\text{DMR}(f, t)$ of the Golden Reference DUT



f_e

Low Masking of Impulsive Distortion !

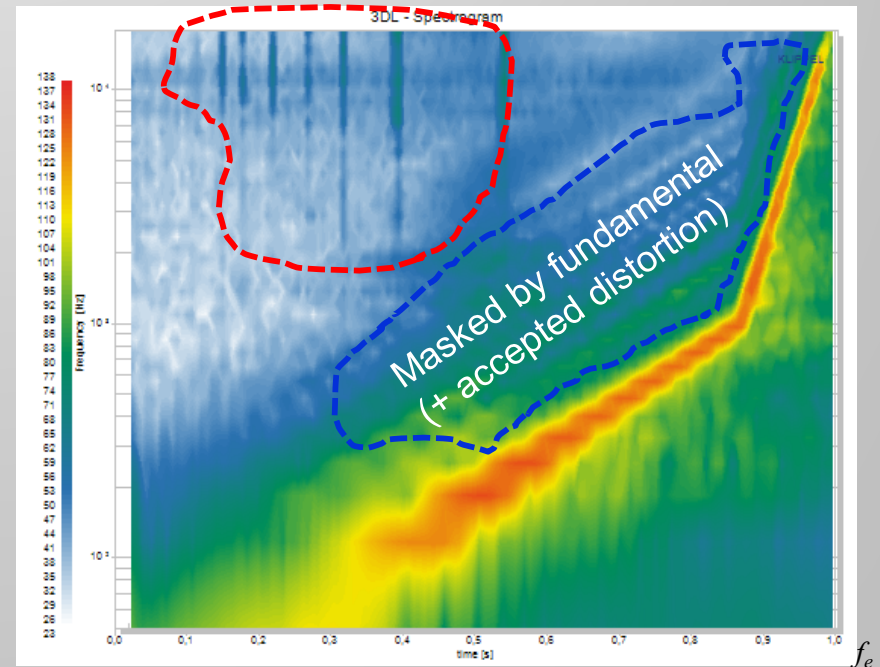
Disturbance Mask Ratio DMR(f, t) of the Golden Reference DUT



Low-order harmonic distortion (dominating THD) is masked by fundamental and accepted distortion

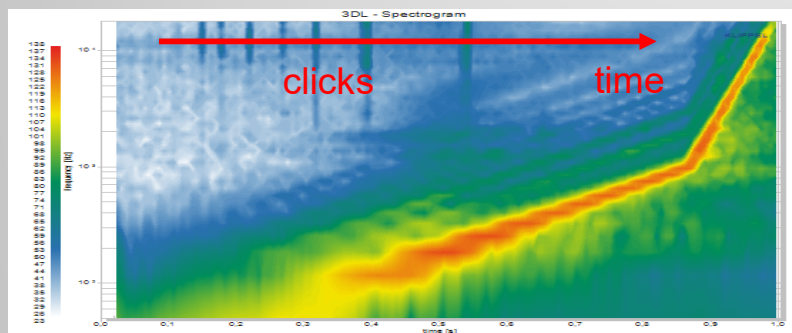
3D Spectrum of a Defective Speaker
(loose particles simulated by one grain of salt)

impulsive Distortion



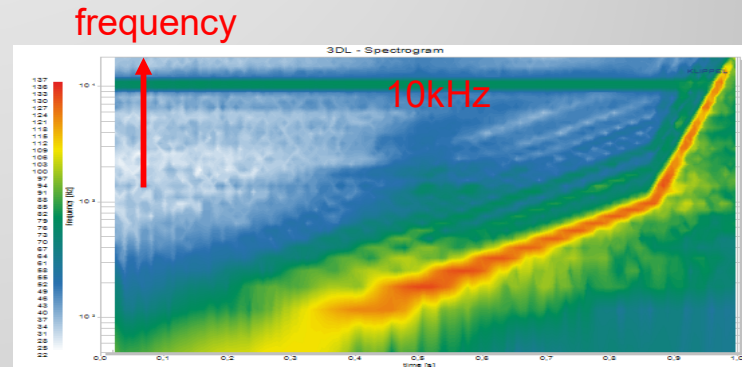
Impulsive Distortion generates high frequency components which are not masked by fundamental !

Basic Auditory Sensations



Temporal envelope variation
(e.g. amplitude modulation, transients)

Increased Roughness



High-frequency distortion
(Increasing spectral power above 3 kHz)

Increased Sharpness

Sensation: aggressive, unnatural, more noticeable

**Degradation of
Sound Quality**

Consequences for EoL-Testing

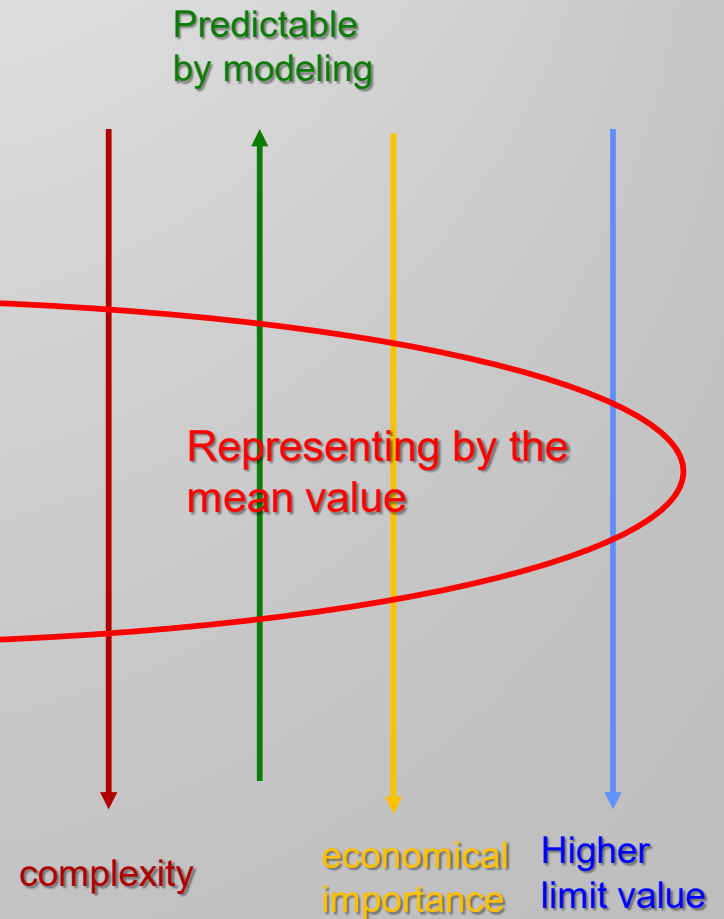
Is audibility a reliable criteria for setting PASS/FAIL limits ?

- No, some defective units produce symptoms just below the audibility threshold at EoL but the failure becomes **worse over time** and cause a field reject later !
- Thus, we have used **trained** and **experienced** operators for listening in traditional EoL testing.
- Today, we use modern test instruments that exploit available physical information and provide **more sensitivity and reliability** than the human ear for irregular defects (rub and buzz).

Questions, comments ?

Criteria for the Limits ?

- I. Audibility threshold of signal distortion (sensitive ear, critical test condition)
- II. Not acceptable degradation of audio quality as perceived by a normal end user under typical application condition
- III. A significant decrease of the value of the audio product as seen by the end-user



Audio Quality

as seen by the typical End-User

Questions:

- What is the typical end-user?
- What is the typical program material (music)?
- What is the typical acoustical environment?
- How can we simplify the assessment of the audio quality?

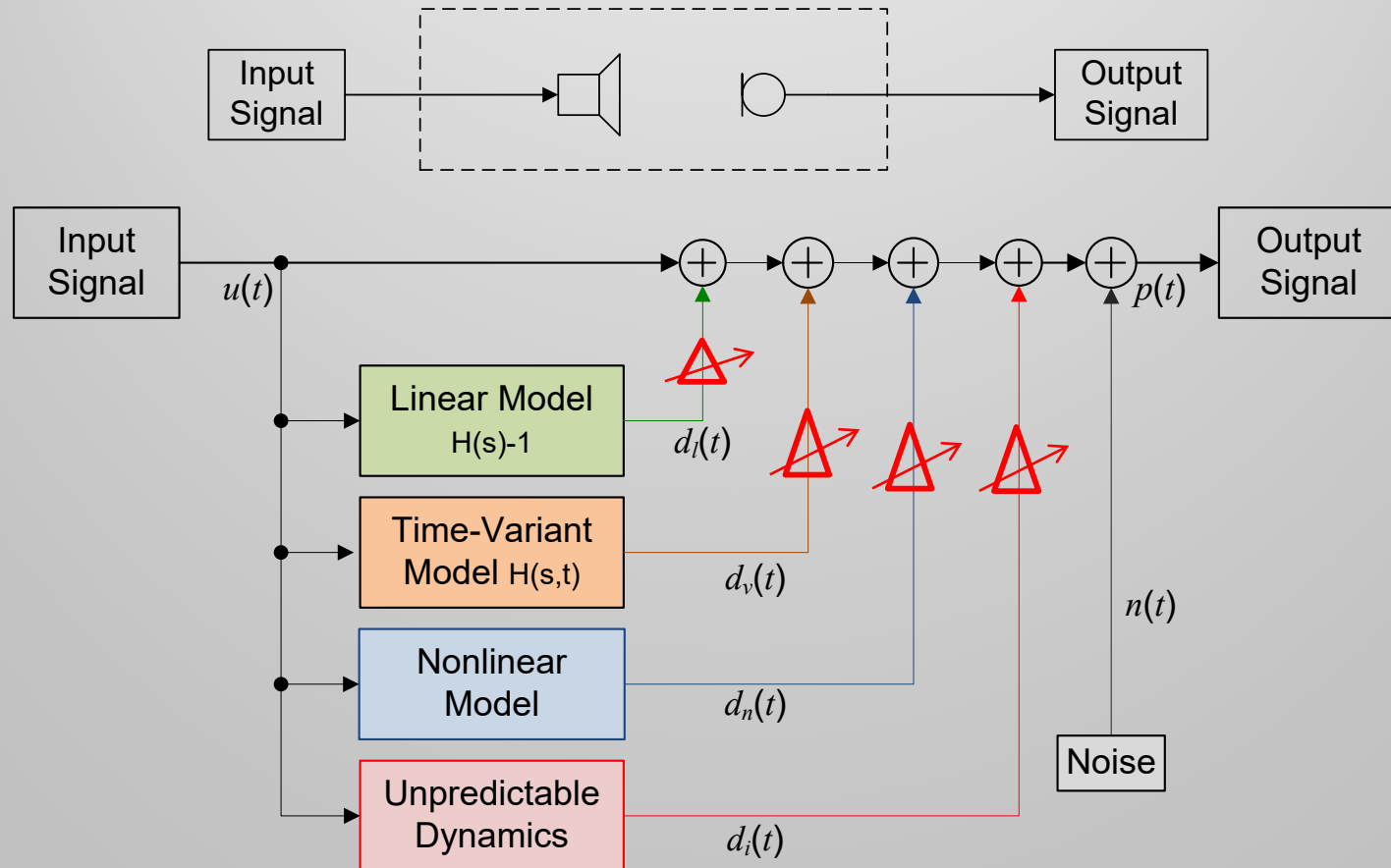
Audio Quality

as seen by the typical End-User

Methods for Assessments:

1. Modeling the perceptive and cognitive processing in ear and brain based on basic research
2. Listening to real products (selected participants, program material, listening room, double blind AB test, statistical analysis)
3. Systematic listening to a changed sound output (Auralization of signal distortion → [KLIPPEL LIVE #13](#))

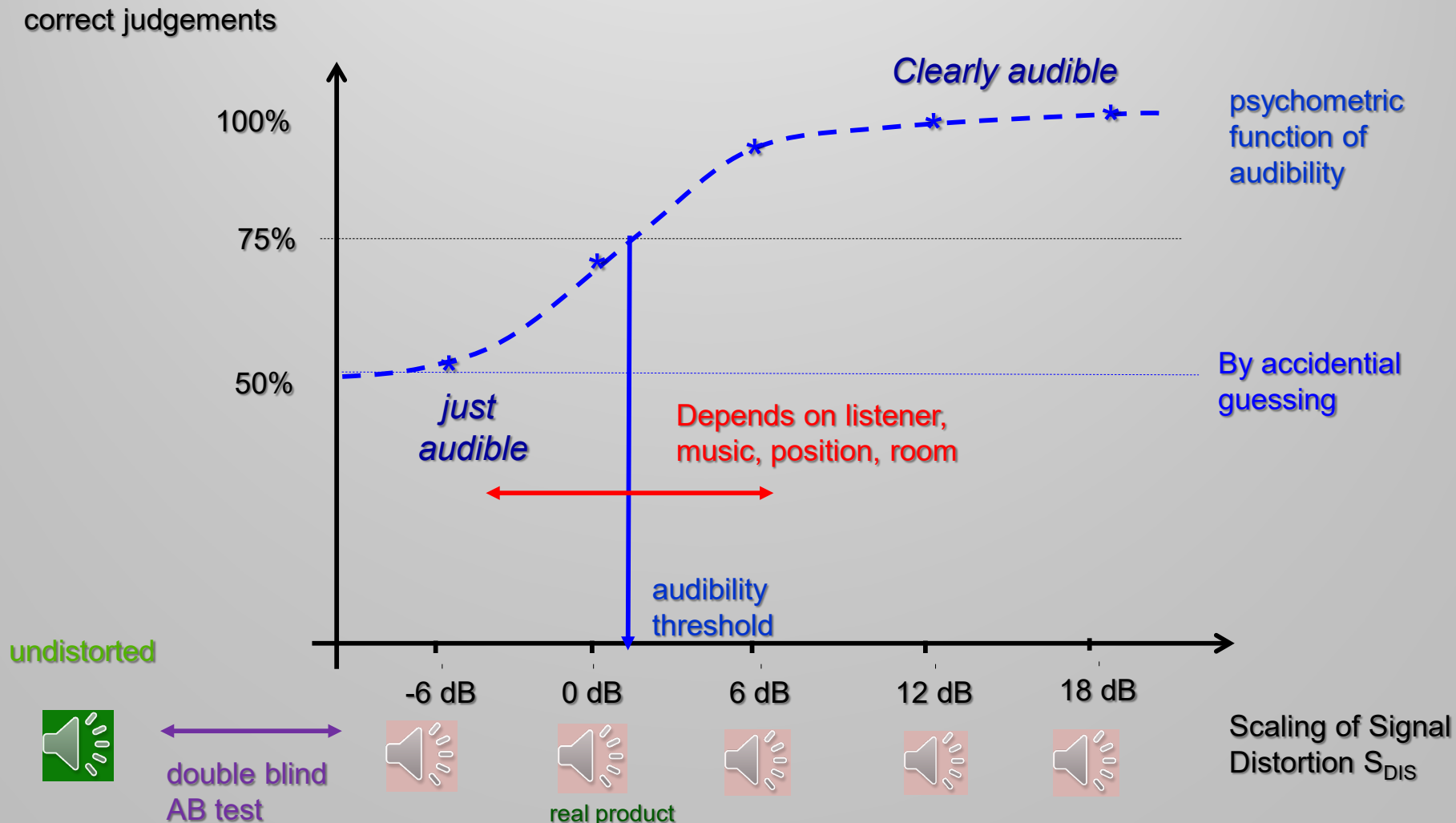
Assessing the Sensitivity of Signal Distortion



Virtual enhancement or attenuation of the distortion components (see [KLIPPEL Live #13](#))

Measurement Audibility Threshold

Distortion generated by regular nonlinearity (force factor $Bl(x)$)



Audibility and Audio Quality

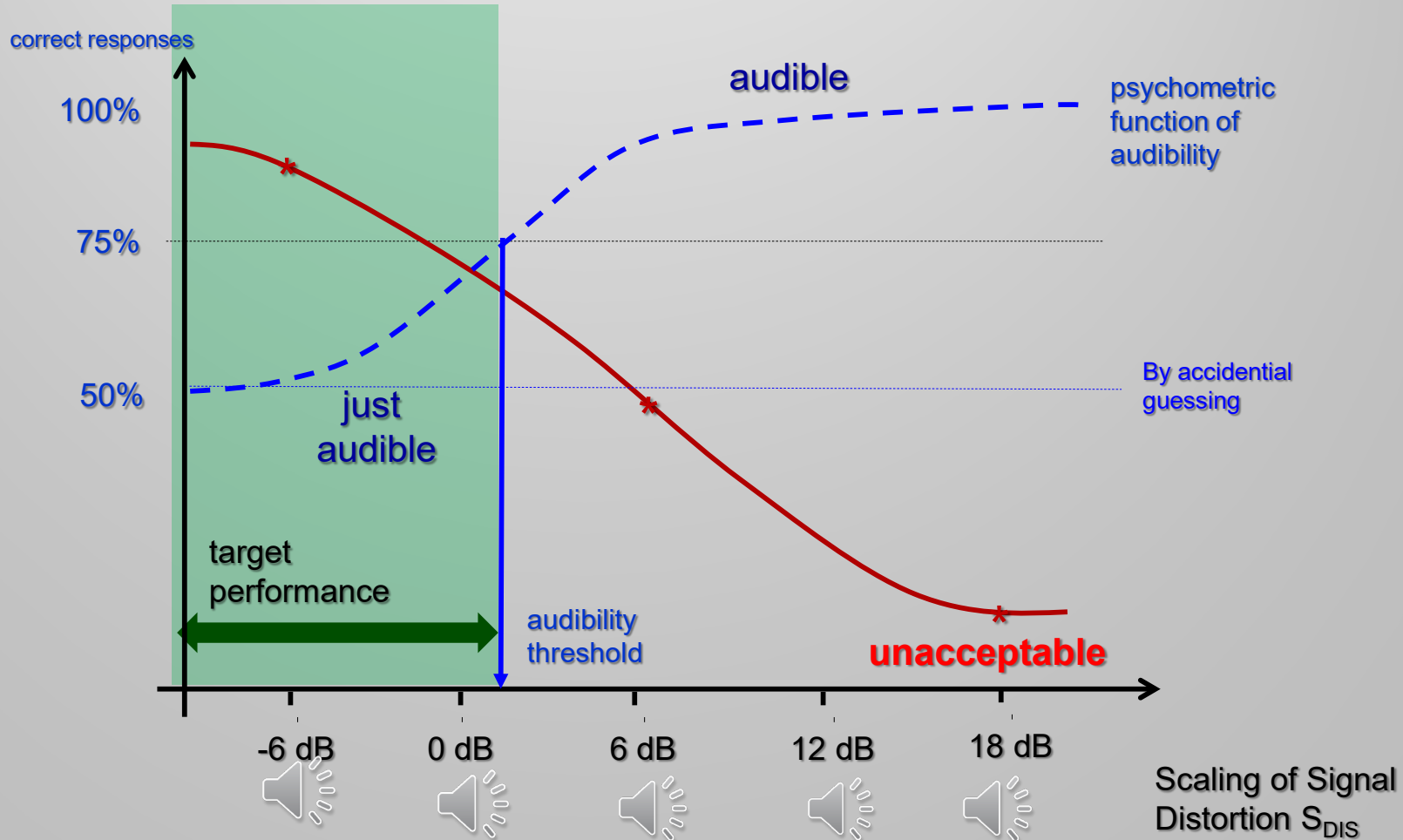
Distortion generated Regular Distortion (nonlinear force factor $Bl(x)$)

rated sound
quality

10 = „high“

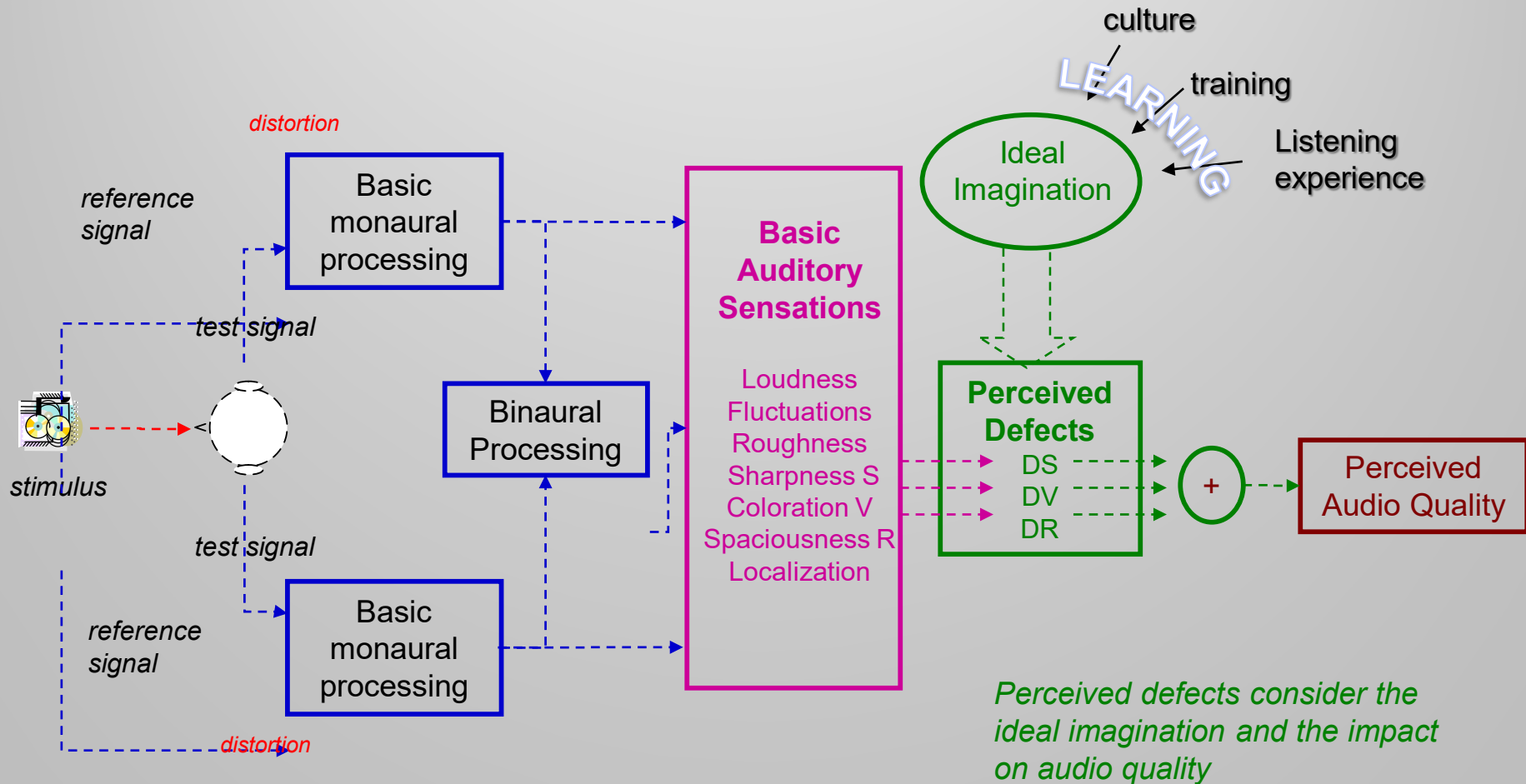
5 = „medium“

0 = „low“



Evaluation of Signal Distortion

based on Perceptual & Cognitive Modeling





Learning Linear Distortion

1 Live Test

- In each room 20 subjects evaluated 3 loudspeakers using 3 programs
- After completing tests moving into the next room

Results:

- Significant differences between loudspeakers
- No significant influence of the room

2 Binaural Reproduction Test

- Repeating test in same order as Life Test

Results:

- Significant differences between loudspeakers
- No significant influence of the room
- Similar to Live test

3 Random Order Test

Binaural reproduction but presenting room, speaker and program in random order

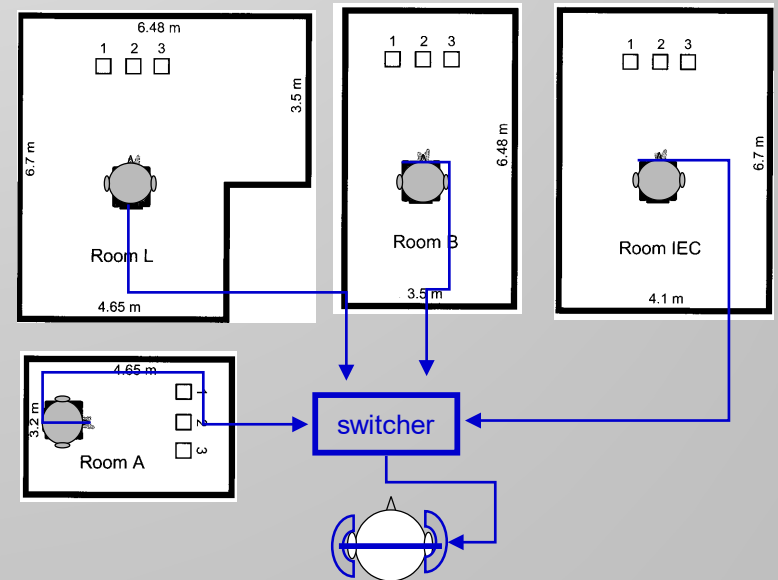
Results:

Highly significant differences between rooms

No significant differences between loudspeakers

Reference: F. Toole, Sound Reproduction, loudspeakers and rooms, focal press

F. Toole 2006, S. Olive 1996



That is Adaptation !

Generates a lot of questions, for example:
How to perform meaningful listening tests ?

Poll:

How do you (personally) assess the typical crackling sound found in vinyl records.

- A. I never heard this! 0%
- B. This crackling rather tickles the ear than obstructs the sound quality. 13%
- C. I accept this as an unavoidable artifact in records. 67%
- D. This is one of the reason why I preferred CD and other digital storage media. 7%
- E. It immediately attracts my attention and it becomes hardly bearable over time. 13%

Poll:

How would you (personally) assess the typical crackling sound found in vinyl records but generated by loose particles in your loudspeaker ?

- A. I never heard this! 15%
- B. This crackling rather tickles the ear than obstructs the sound quality. 0%
- C. I accept this as an artefact in some loudspeakers. 0%
- D. This is one of the reason why I buy better speakers. 23%
- E. It immediately attracts my attention and it becomes hardly bearable over some time. 62%

Cognitive Processing of perceived signal distortion

The **cognitive evaluation** of the perceived signal distortion is a **learning process!**

... which depends on time ...

The rating depends on the information provided by the distortion to the listeners.

Linear distortion (amplitude and phase response)

- linear distortions are coherent to the stimulus
- provides no additional relevant information to the listeners
- the listener gets accustomed to it and will ignore it (ADAPTATION, HABITUATION)

Nonlinear and impulsive distortion (rub & buzz)

- the distortion are not directly related to the stimulus (incoherent),
- over time the listener describes the signal distortion as discordant
- the rising awareness makes the distortion unbearable (SENSITIZATION)

Audibility and Audio Quality

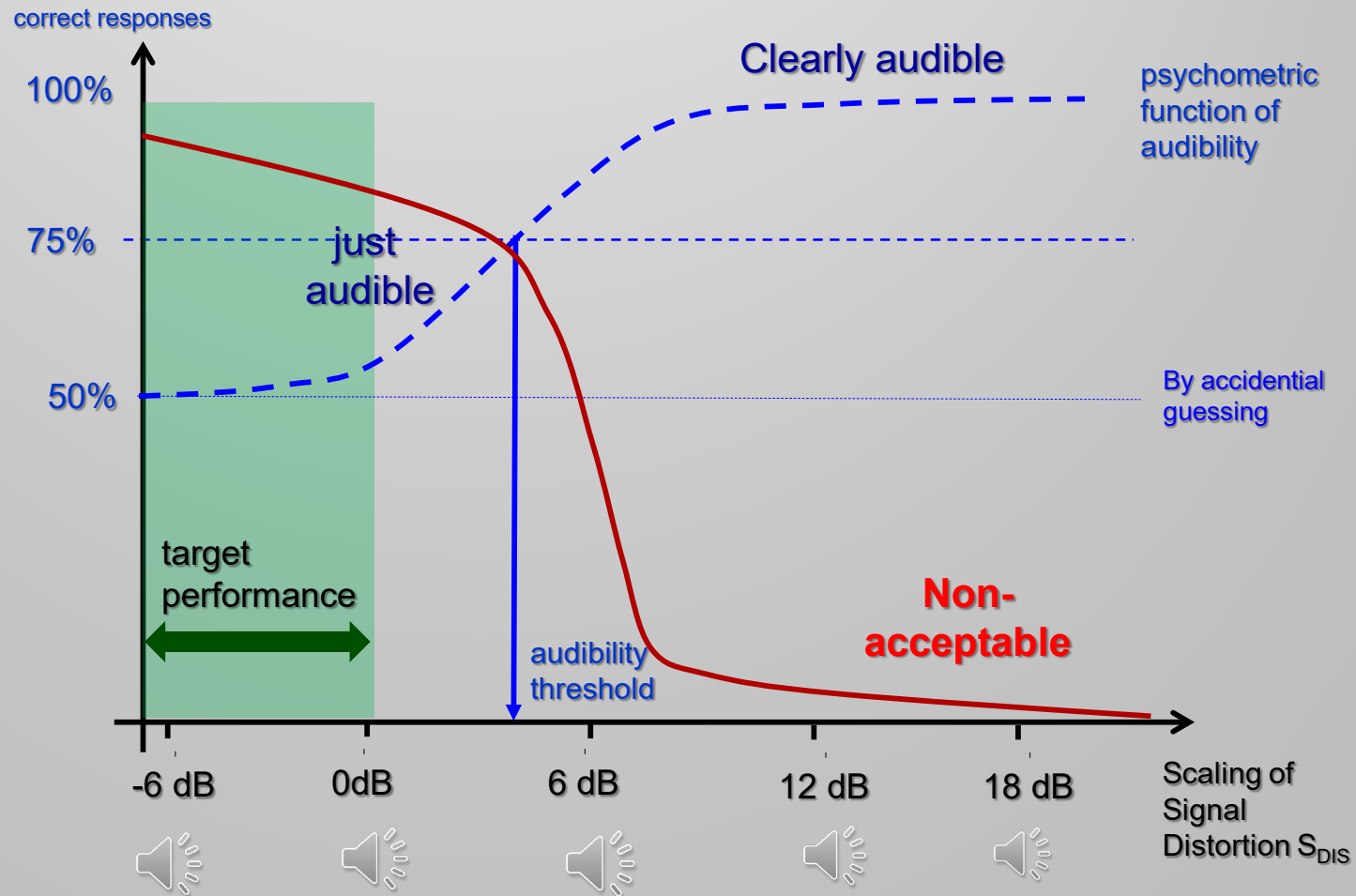
Impulsive distortion generated by rub&buzz and other loudspeaker defects

rated sound
quality

10 = „high“

5 = „medium“

0 = „low“



Working with Average Values ?



Old Wisdom:

„The pond was 50 cm deep on average, but nevertheless the cow drowned.“

Remaining Question

Can we neglect the variance in hearing, music and room influence ?

No: The sensitization goes on under critical condition !

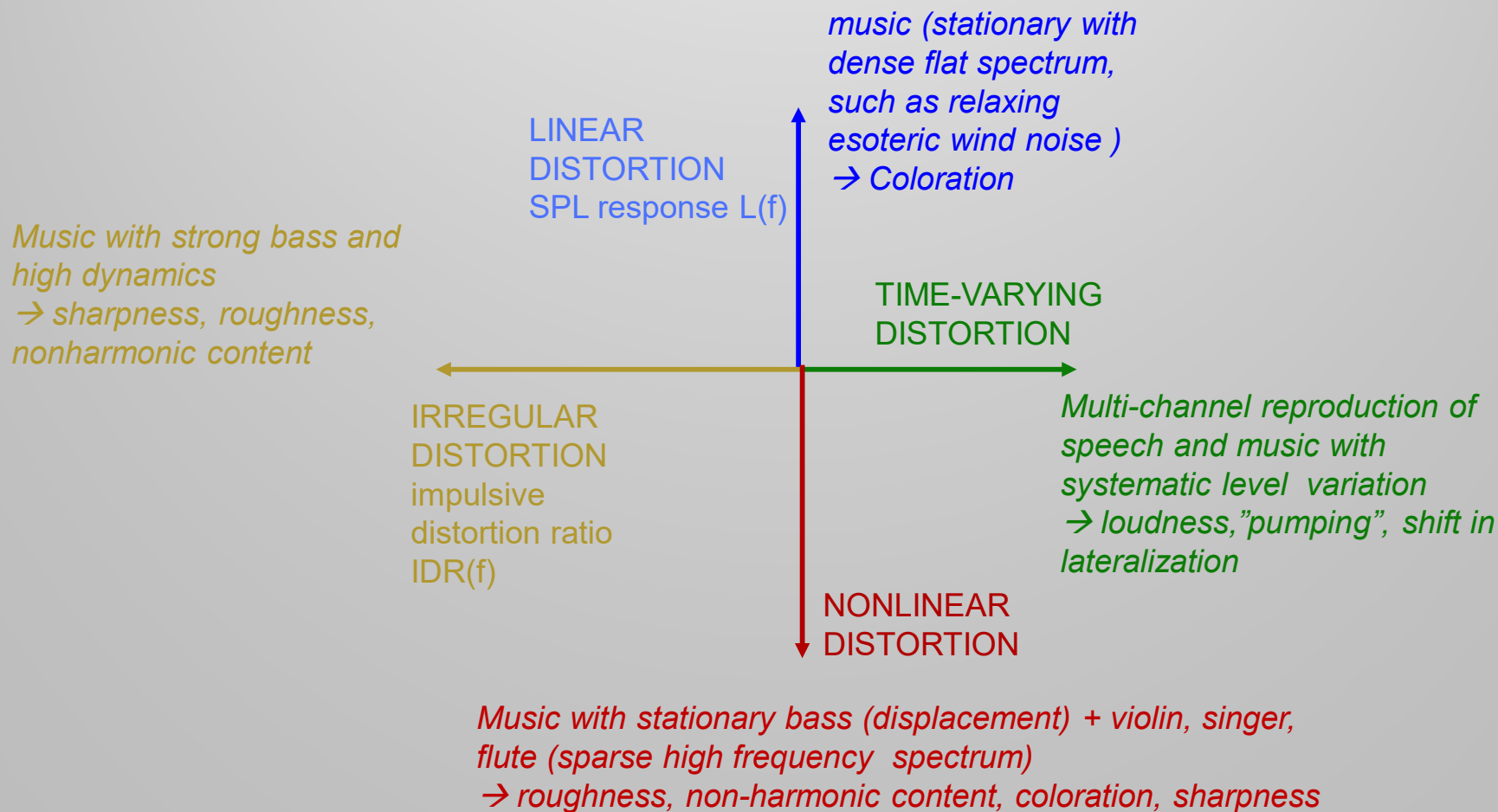
Solutions:

1. Generating virtual test objects generated by physical modeling and auralization techniques
2. Assessing the influence listening conditions on audio quality by perceptual and physical modeling
3. Automated listening tests on the web to get more insight into the cognitive processing of the end user

Example: Piano music is a critical stimulus for distortion generated by smartphones with side-fire ports!

One Typical Music for all Signal Distortion ?

No, the stimulus has a high impact (physical generation, perceptual masking, disturbance to musical idea) on perceived audio quality !

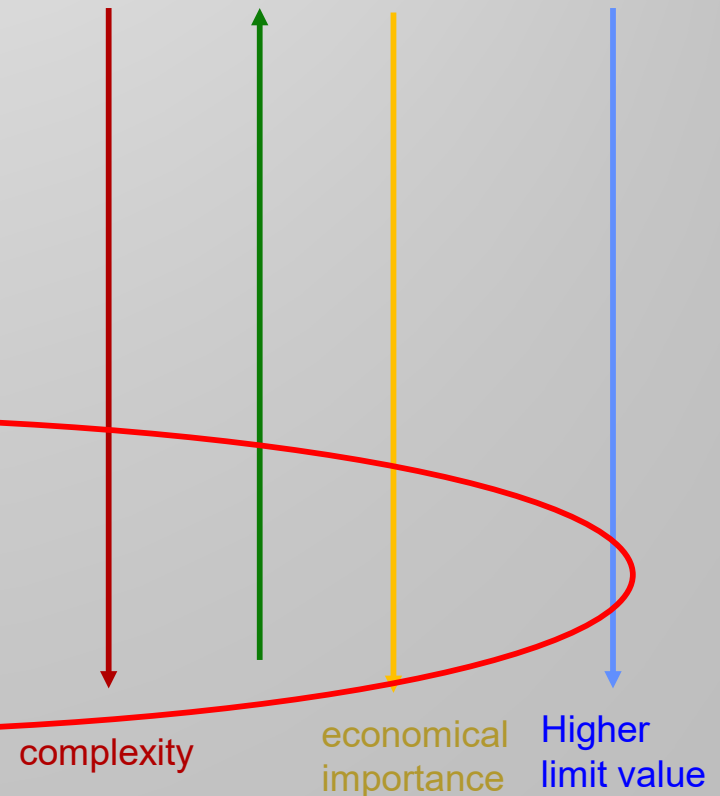


Questions, comments ?

Criteria for the Limits ?

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- II. Not acceptable degradation of audio quality as perceived by a normal end user under typical application condition
- III. A significant decrease of the value of the audio product as seen by the end-user

Predictable
by modeling



Poll:

Would you make a compromise and trade audio quality for other benefits ?

- A. Never ! 0%
- B. Yes, if the audio device is significantly smaller, lighter and more convenient. 56%
- C. Yes, if the operation time of a battery powered device is significantly extended. 22%
- D. Yes, if the output SPL is significantly increased. 0%
- E. Yes, other reasons. 22%

Benefits of the Audio Device

Dimensions of the performance space:

- size, volume, shape, weight
- maximum output ($\text{SPL}_{\max}$, power $P_{a,\max}$)
- efficiency (power consumption P_E , heating, mobile operation time in battery powered devices)

Well defined in standards

- perceptual audio quality (spectral and spatial properties, distortion)
- reliability (probability of failure)
- endurance of external stress (overload, environment)

A central topic in audio engineering

- artistic product design and ergonomics
- technical story
- reputation of the brand, personal identification with the product
- enjoyment or hedonistic preference

More research required by other experts

Value = Benefit Cost Ratio

Performance Sensitivity

$$\mathbf{W} = \{w_1, \dots, w_k, \dots\}$$

Benefit
(weighted
performance)

performance features in
 $\mathbf{P} = \{p_1, \dots, p_k, \dots\}$
(SPL_{max}, THD, ...)

End User Value V
(acceptance, sales
volume)

$$V(\mathbf{D}) = \frac{\sum_{\forall k} w_k p_k(\mathbf{D})}{\sum_{\forall j} C_j(\mathbf{D})}$$

Design variables
 $\mathbf{D} = \{d_1, \dots, d_k, \dots\}$

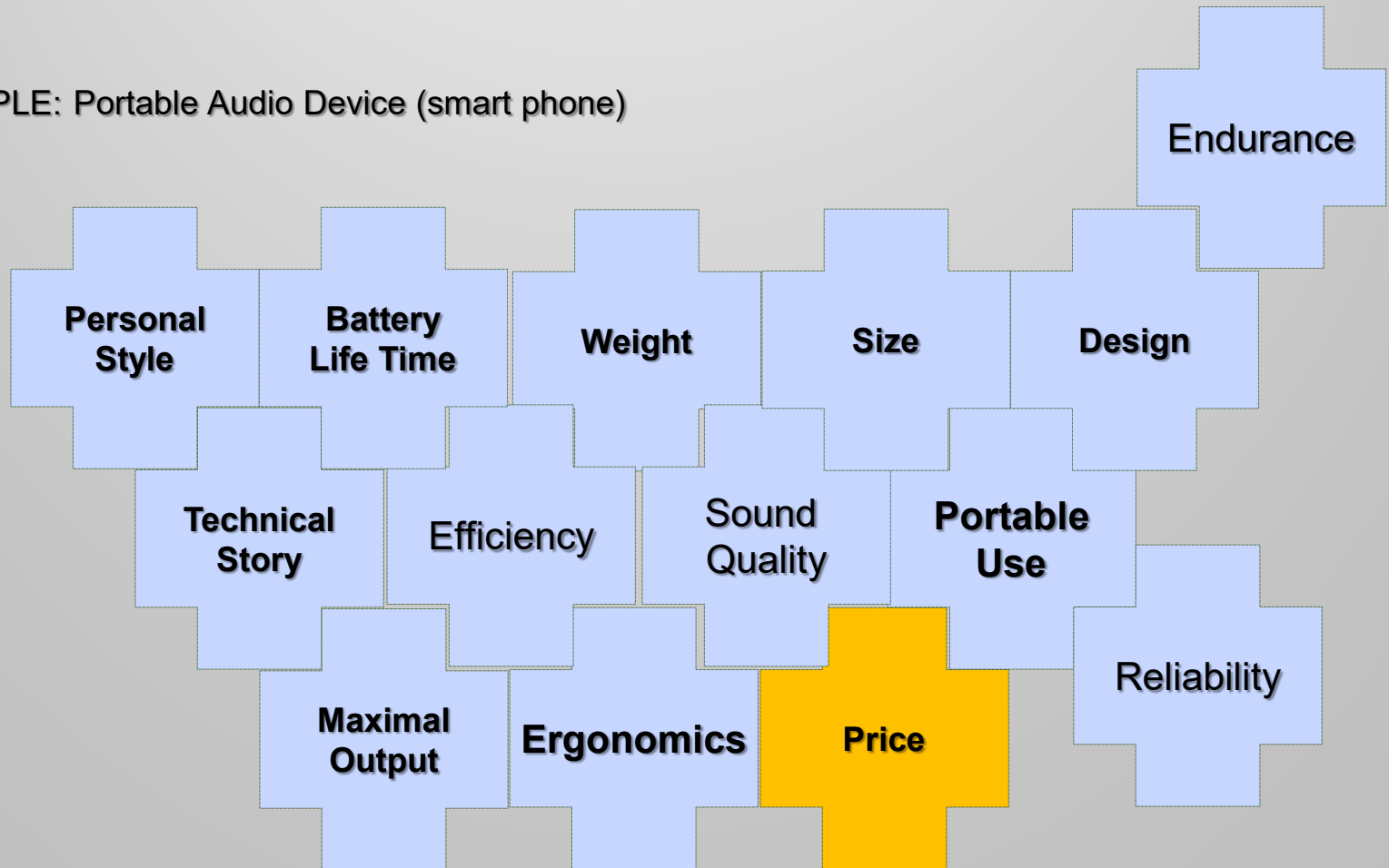
Cost structure

Objective:

Maximizing the end user value V with the optimum performance **P** and minimum costs C_j

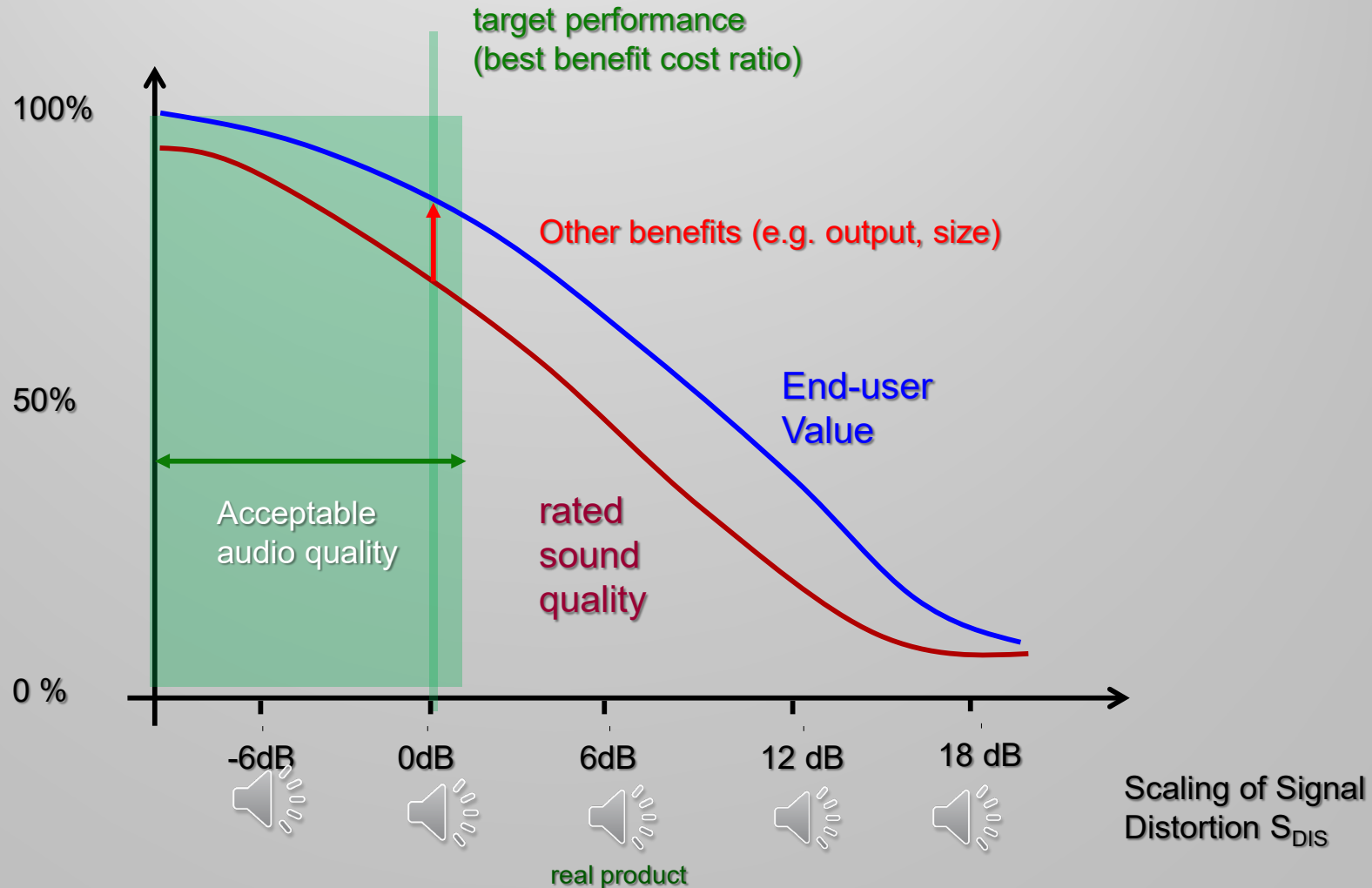
Performance Sensitivity w_k weights the Performance characteristics p_k

EXAMPLE: Portable Audio Device (smart phone)



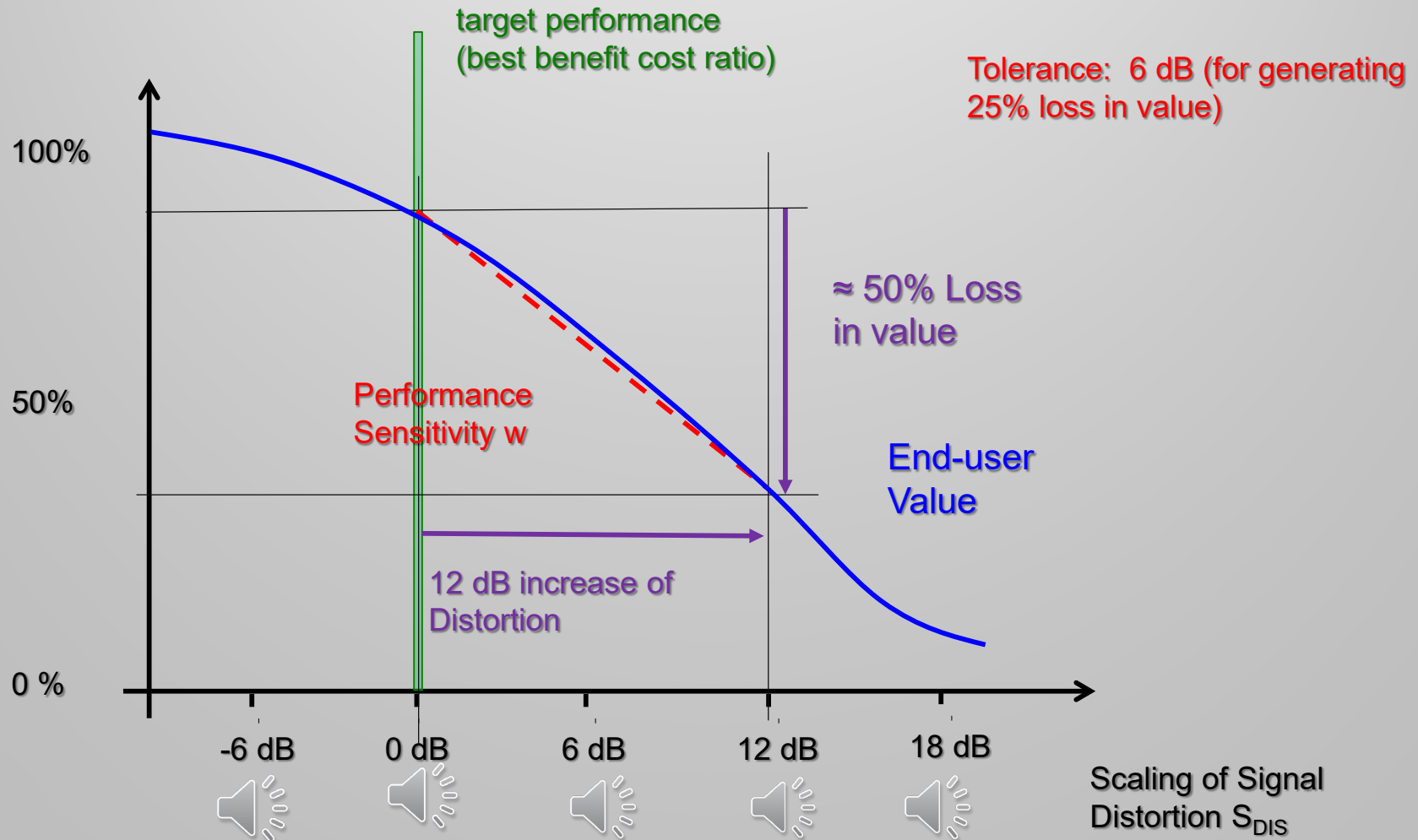
Audio Quality and End-User Value

Distortion generated by regular nonlinearity (force factor $Bl(x)$)



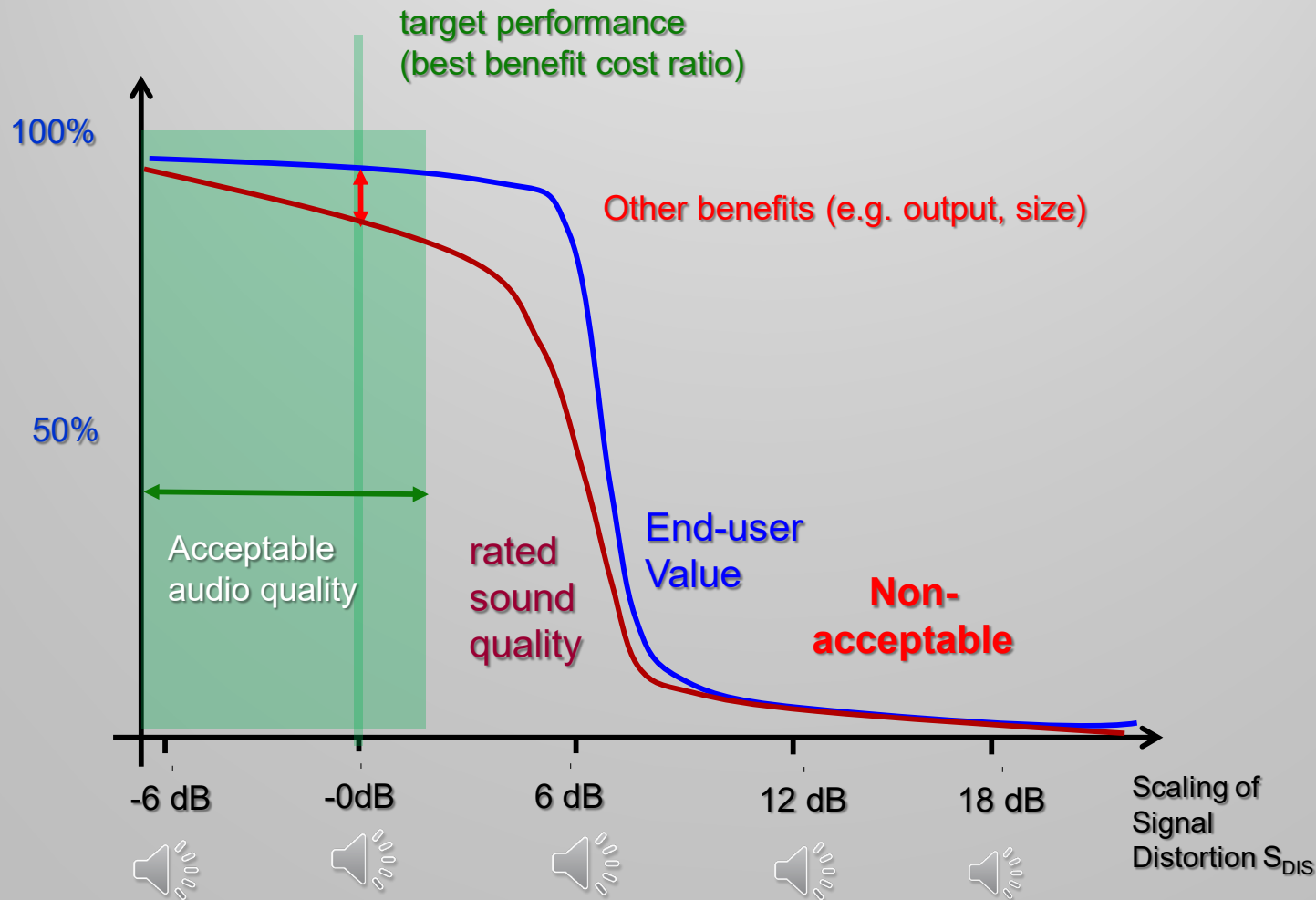
Performance Sensitivity

Distortion generated regular nonlinearities (force factor $BI(x)$)



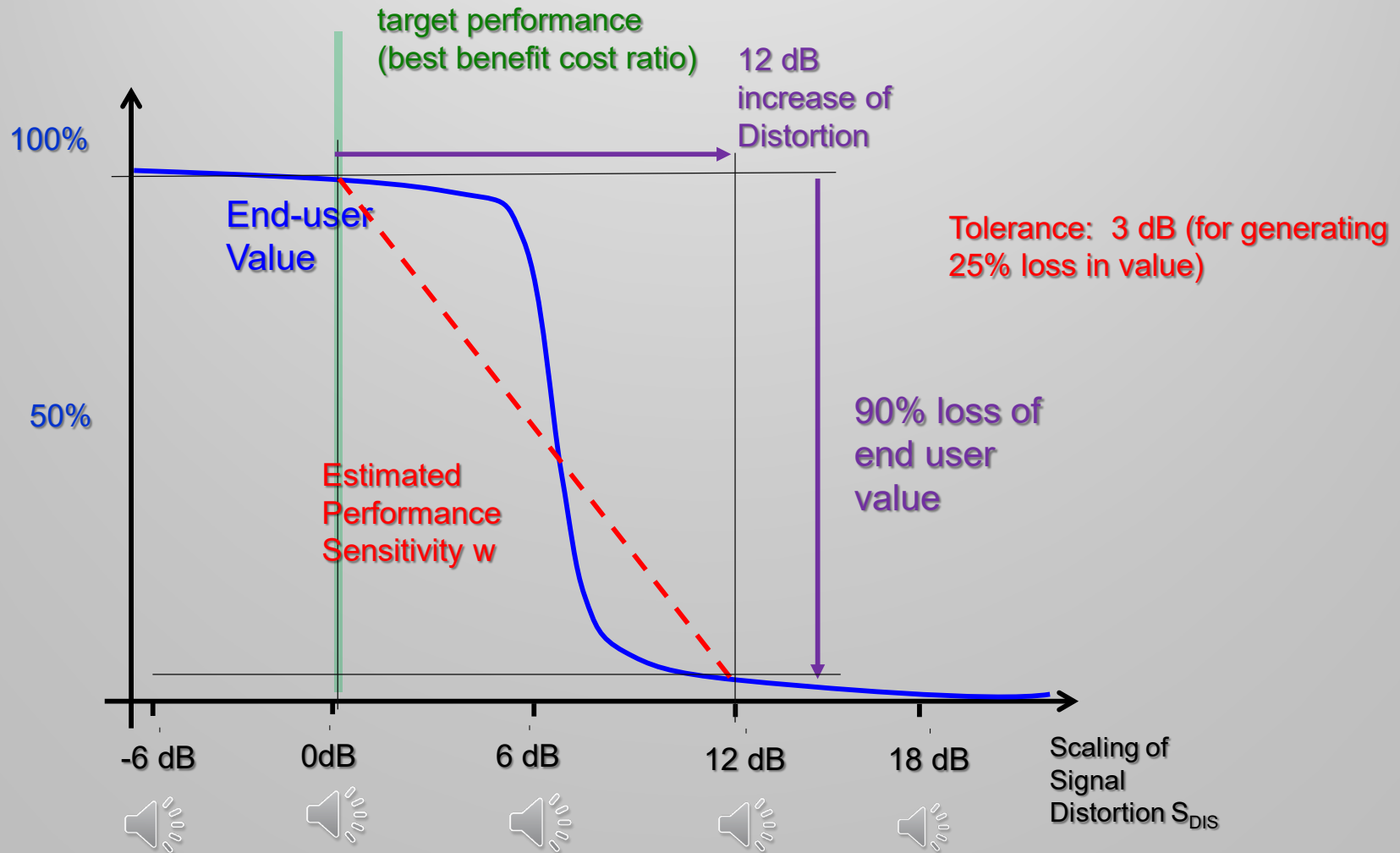
Audibility and Audio Quality

Impulsive distortion generated by rub&buzz and other loudspeaker defects

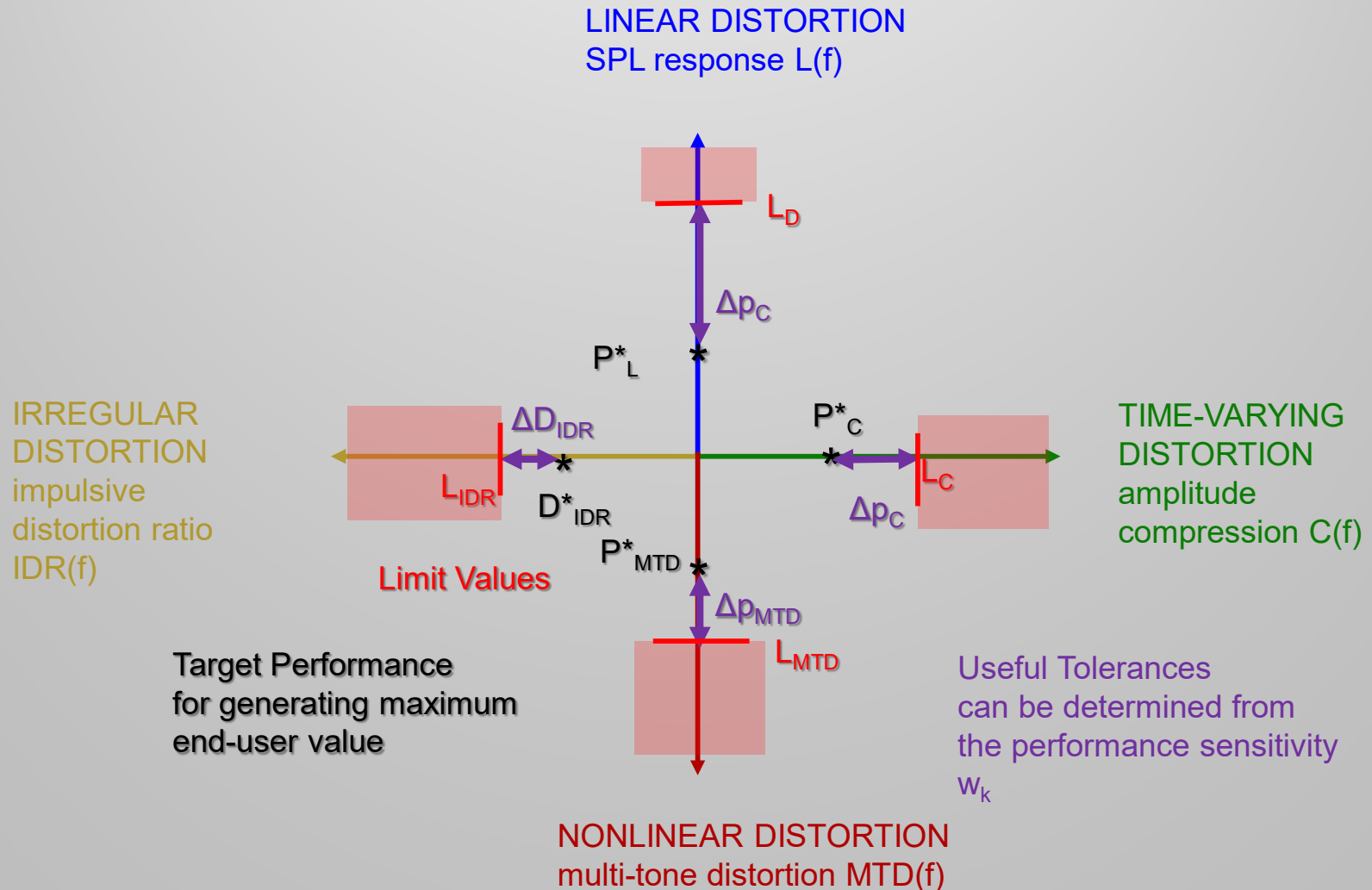


Performance Sensitivity

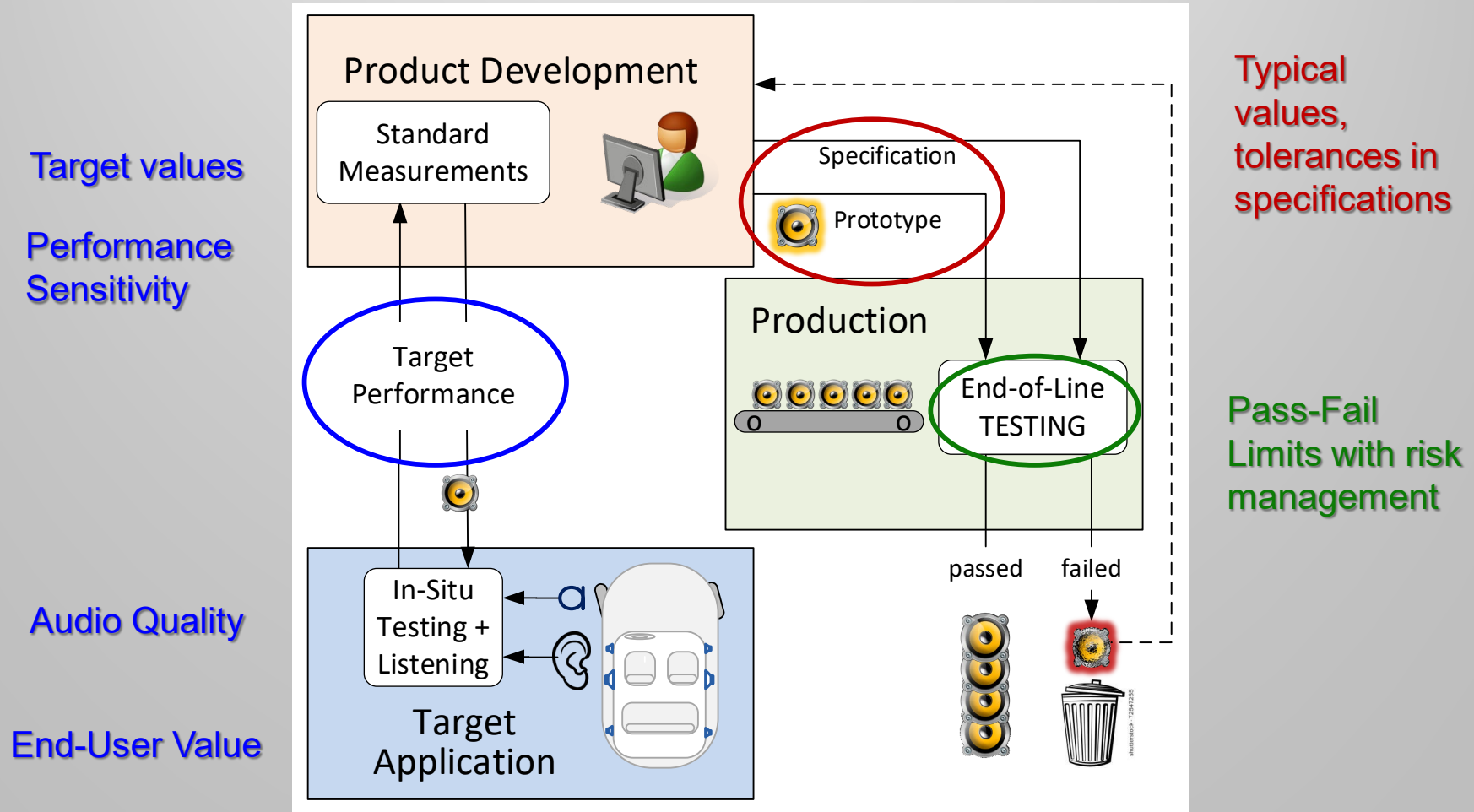
Impulsive distortion generated by rub&buzz and other loudspeaker defects



Target Values and Tolerances of Signal Distortion



Life Cycle of an Audio Device



More about this topic

Webinar presented at the Virtual ALTI-EXPO 2020

Klippel, “Linking Cost, Performance, End-User Satisfaction by Physical and Perceptual Assessment”,



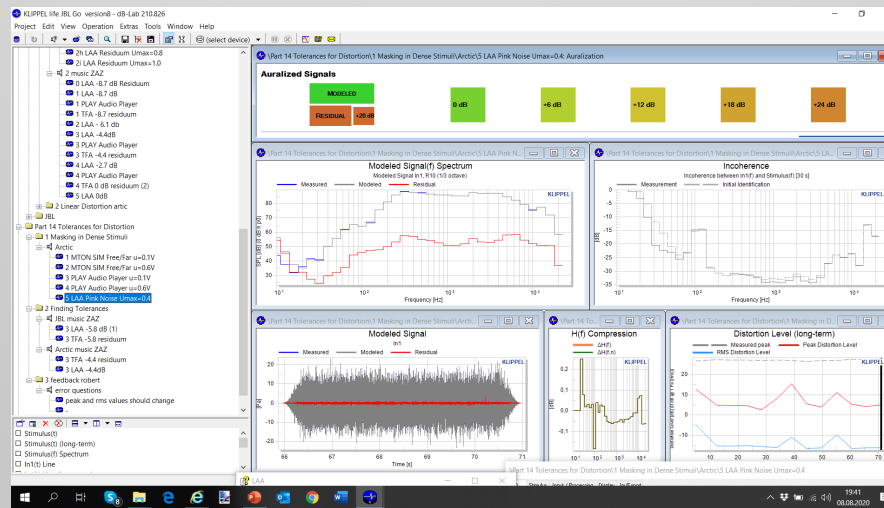
AES Paper:

W.Klippel, Creating Audio Products With Maximum End-User Value, J. Audio Eng. Soc.
Vol. 68, No. 7, 2020 July (open access, freely available online)

Demo: Finding Tolerances

Tools: Using dedicated software modules of the KLIPPEL Analyzer

- Live Audio Analyzer (LAA)



JBL
Bluetooth
Speaker
(one
channel)



Arctic Competitive
Bluetooth
Speaker
(stereo, only left
channel is used)



Discussion

Summary

- The human ear is very sensitive for signal distortion under critical conditions
- Audio quality is more than audibility of signal distortion
- Maximizing the end-user value requires a compromise between all performance criteria and cost
- Target values depend on the particular application (end user, environment, stimulus)
- Performance sensitivity is a powerful basis for defining meaningful tolerances
- Pass/Fail limits consider not only the properties of the approved prototype but also the risk of delivering a defective product to the customer

Open Questions

We have now discussed the complexity of the setting limits for assessing audio quality. How can we apply this information for assessing the maximum output?

The last 15th KLIPPEL Live webinar titled
15th Rating the maximum SPL value for product
will address the points:

- Best practice for rating maxSPL
- Exploiting background information from design and target application
- Automatic search methods with predefined limits
- Linking IEC 60268-21 with other standards and methods
- Final conclusion of the webinar series

Next Section

1. Modern audio equipment needs output based testing
2. Standard acoustical tests performed in normal rooms
3. Drawing meaningful conclusions from 3D output measurement
4. Simulated standard condition at a single evaluation point
5. Maximum SPL – giving this value meaning
6. Selecting measurements with high diagnostic value
7. Amplitude Compression – less output at higher amplitudes
8. Harmonic Distortion Measurements – best practice
9. Intermodulation Distortion – music is more than a single tone
10. Impulsive distortion - rumble & buzz, abnormal behavior, defects
11. Pitfalls in Testing Wireless Audio Devices
12. Benchmarking of audio products under standard conditions
13. Auralization of signal distortion – perceptual evaluation
14. Setting meaningful tolerances for signal distortion
15. Rating the maximum SPL value for product