EFFICIENT AND PERCEPTUALLY PLAUSIBLE 3-D SOUND FOR VIRTUAL REALITY

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Audio and Acoustics Group (Ivan Tashev)
Microsoft Research, Redmond Lab

INTRODUCTION

METHOD

RESULTS

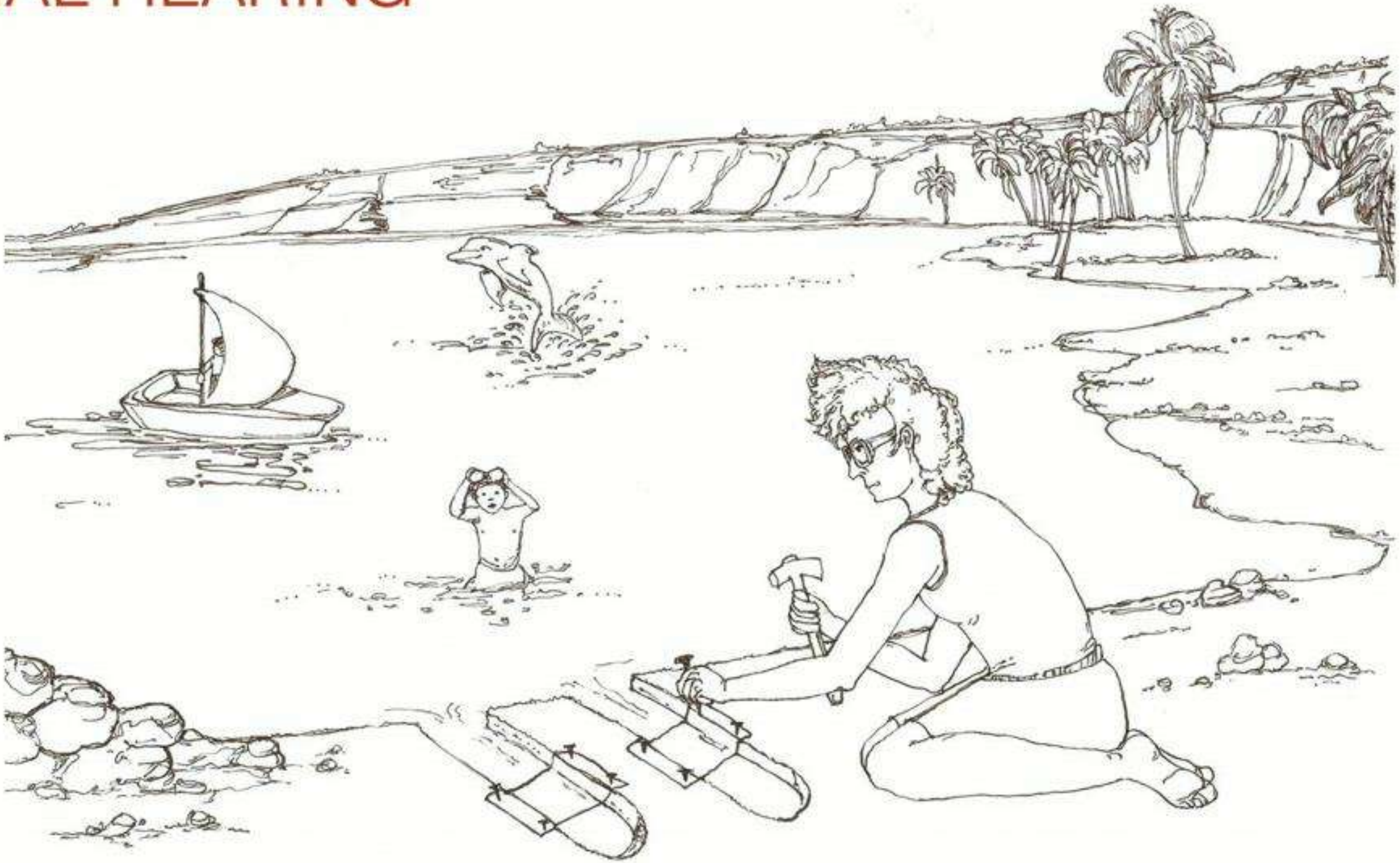
DISCUSSION

MOTIVATION

"HoloLens Demo at Penn Museum" by pennlibtrl (CC BY-SA 2.0)

- 3-D Audio improves presence and immersion
- Graphics rendering consumes most of the compute
- Room acoustical simulation is expensive

SPATIAL HEARING



after A. S. Bregman (1994): Auditory scene analysis, MIT Press, Cambridge, USA, pp. 5.
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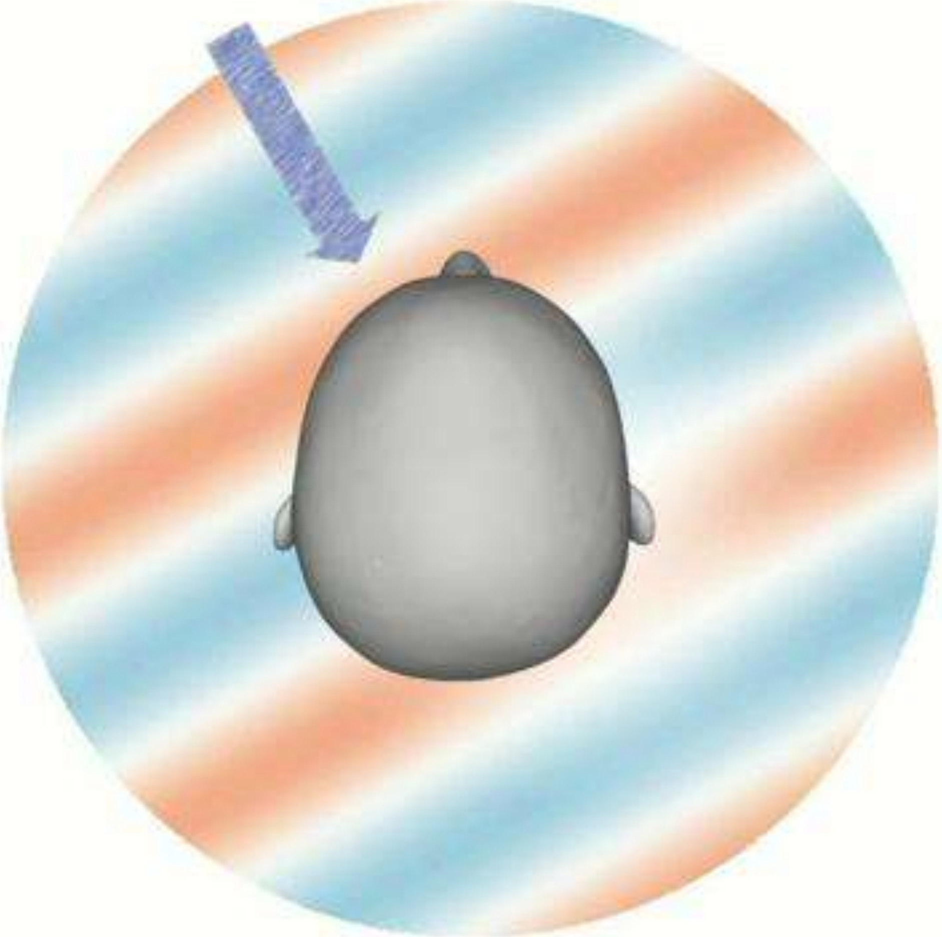
SPATIAL HEARING



Blauert (**1997**). *Spatial hearing. The psychophysics of human sound localization*, (MIT Press, Cambridge, Massachusetts)
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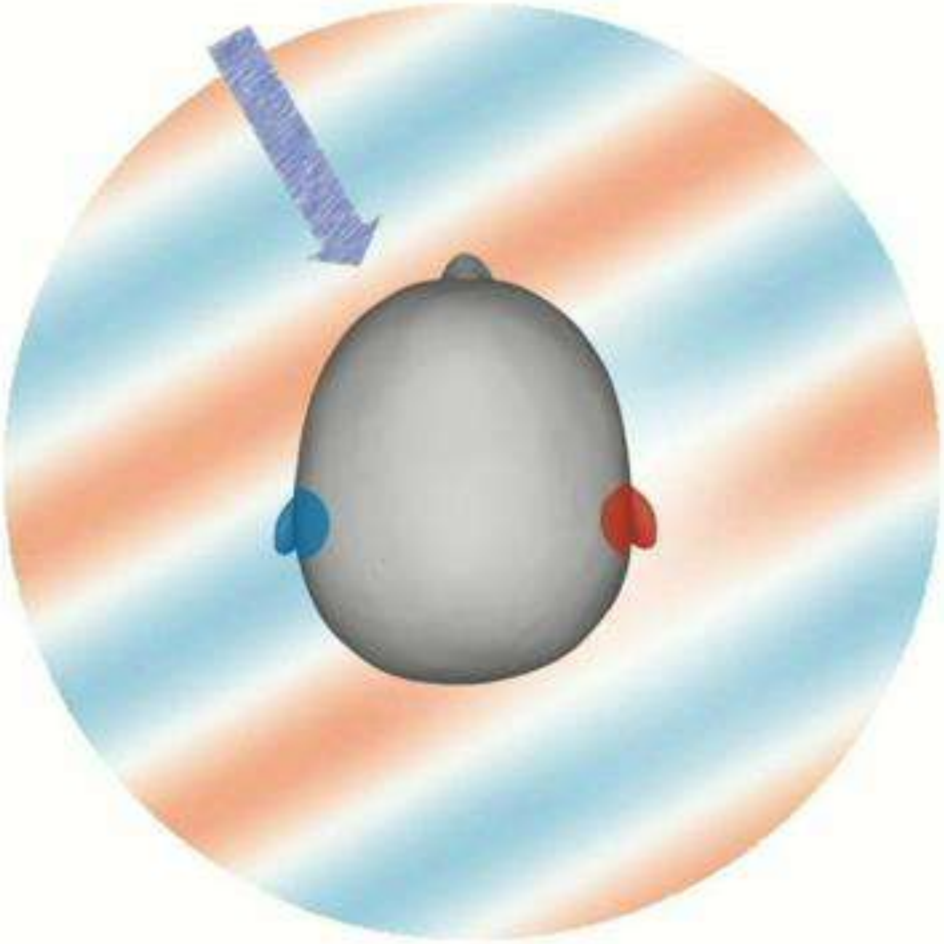

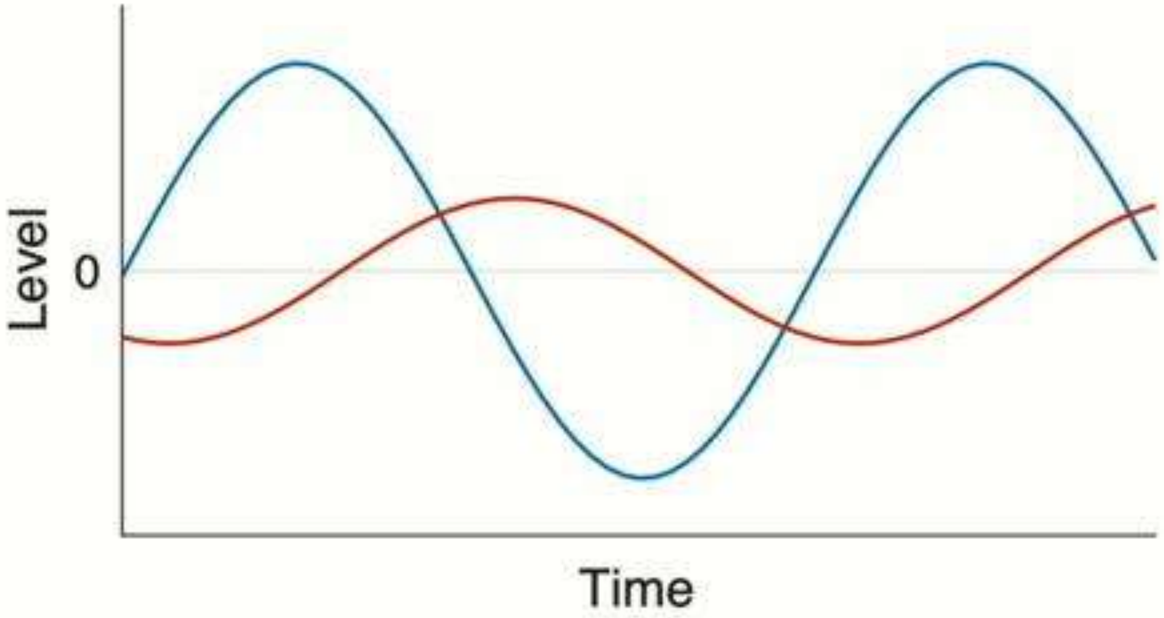

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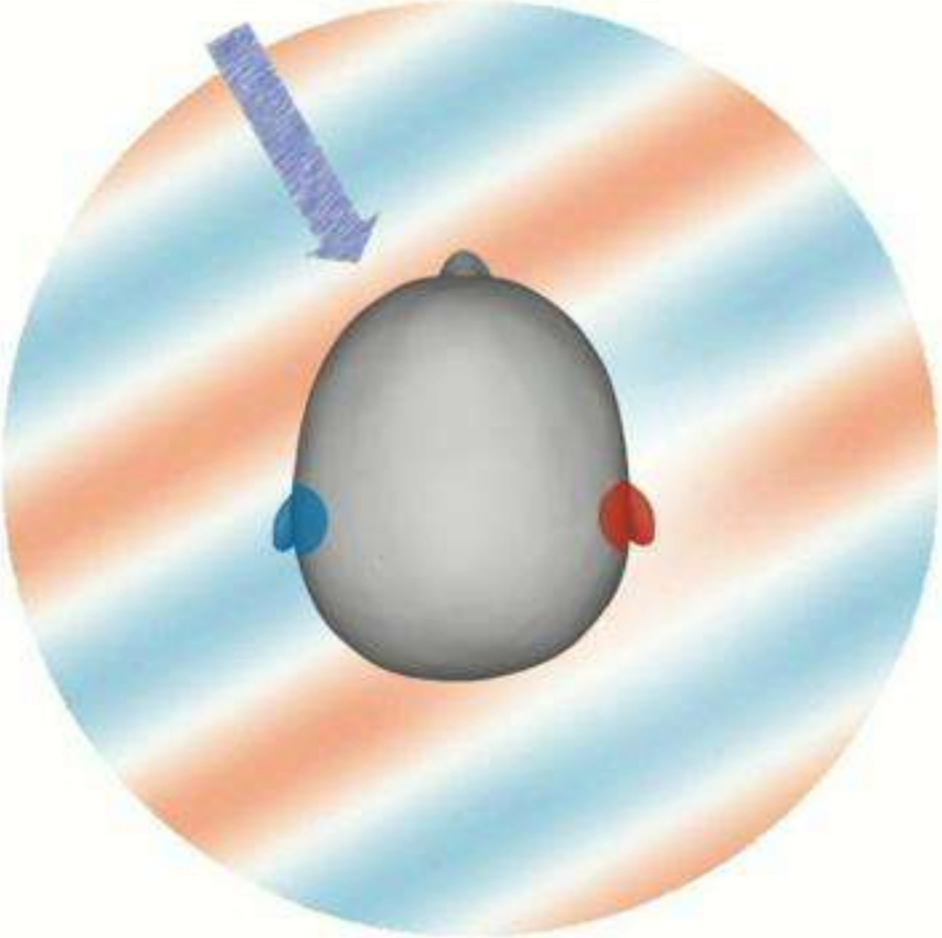
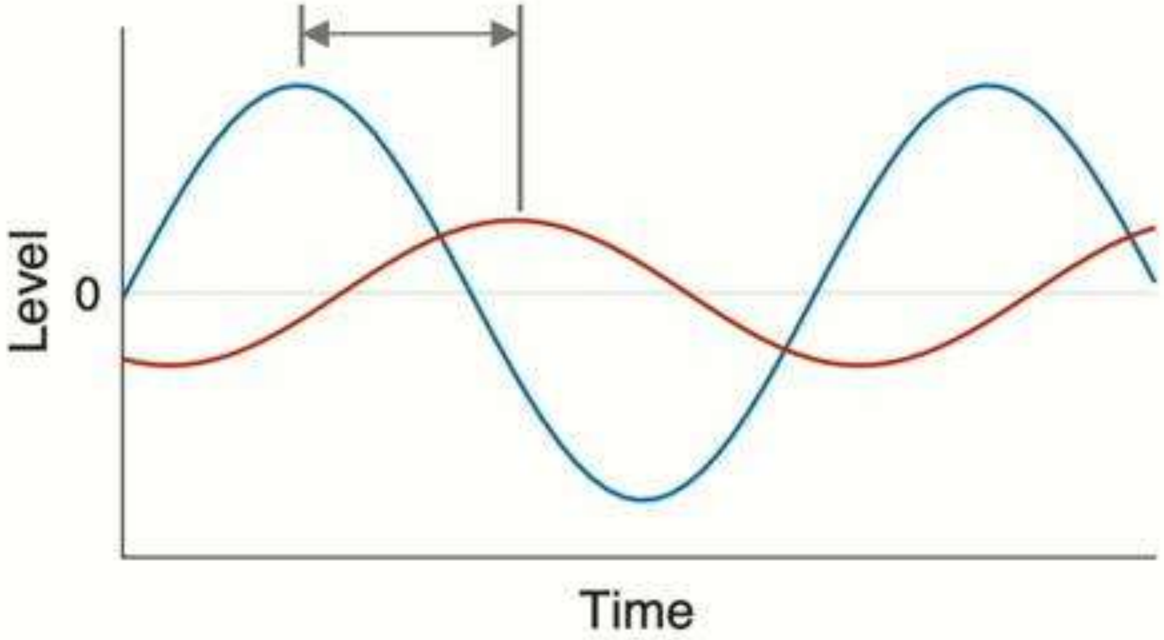


Interaural time difference



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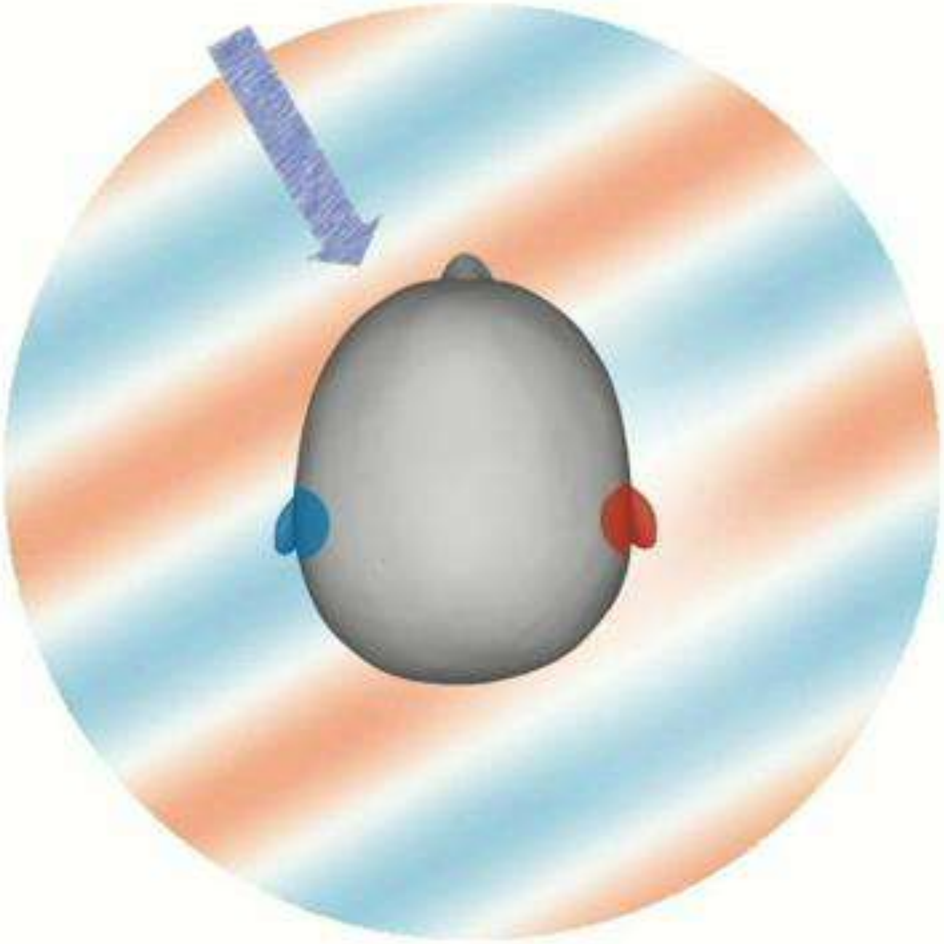

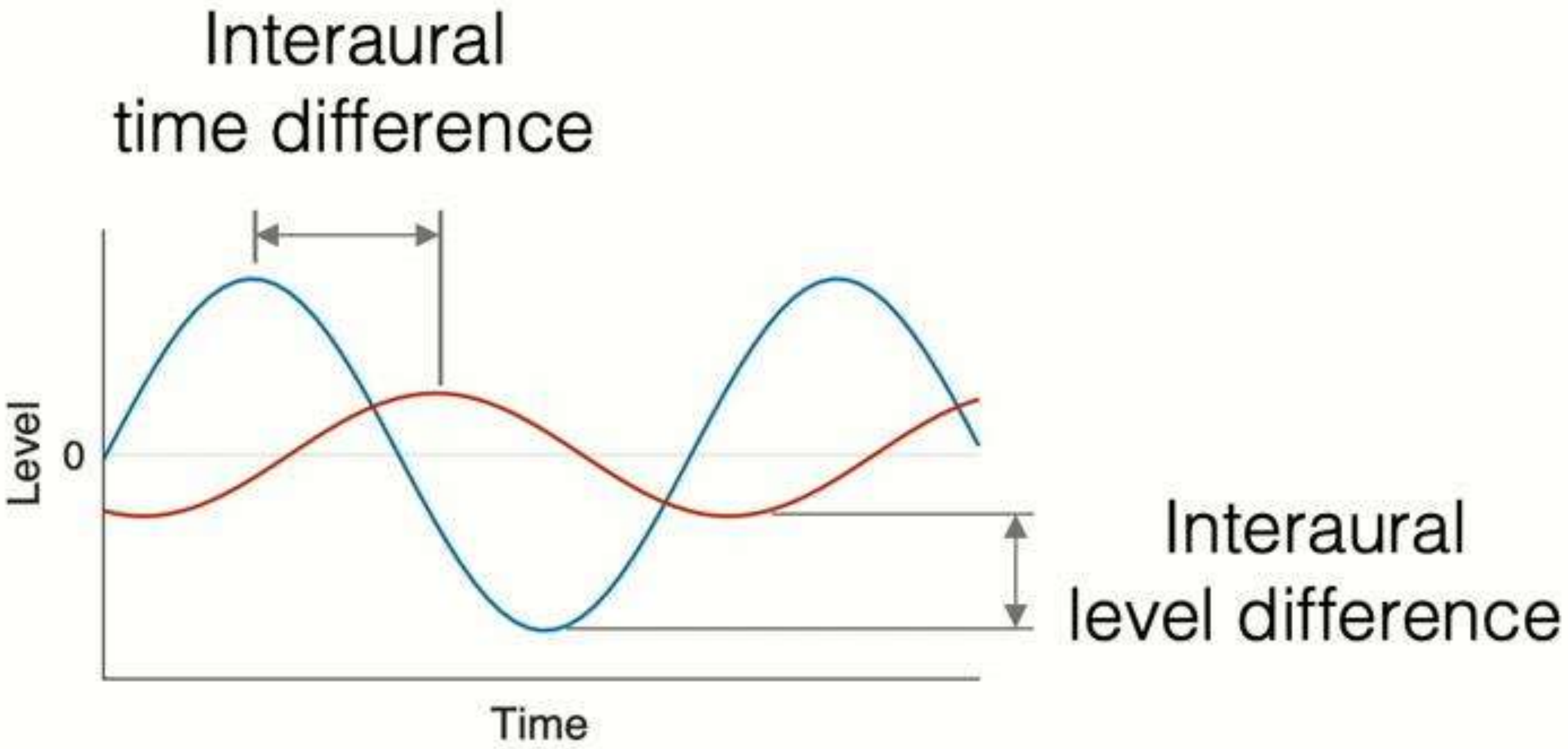

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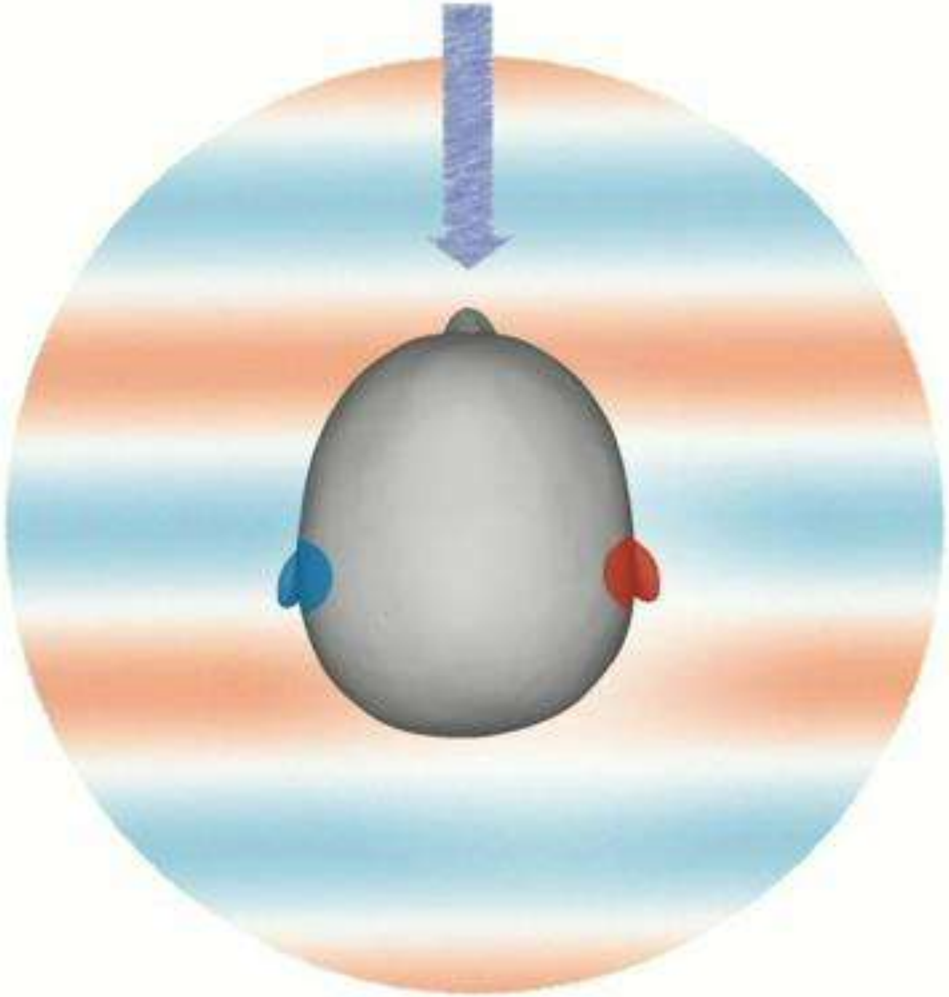

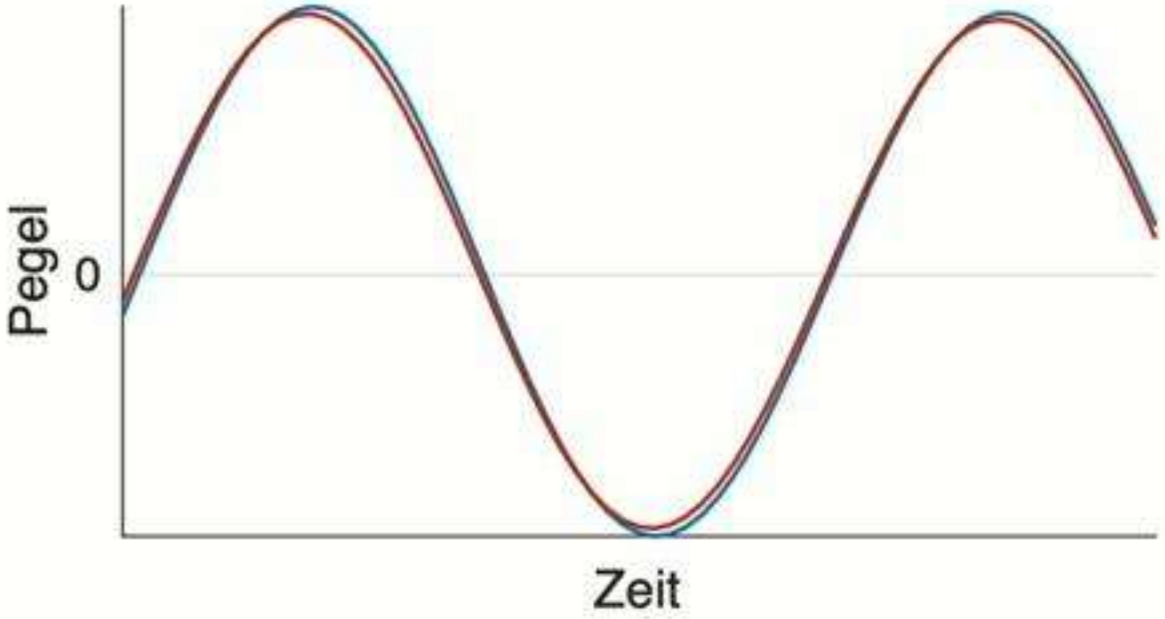

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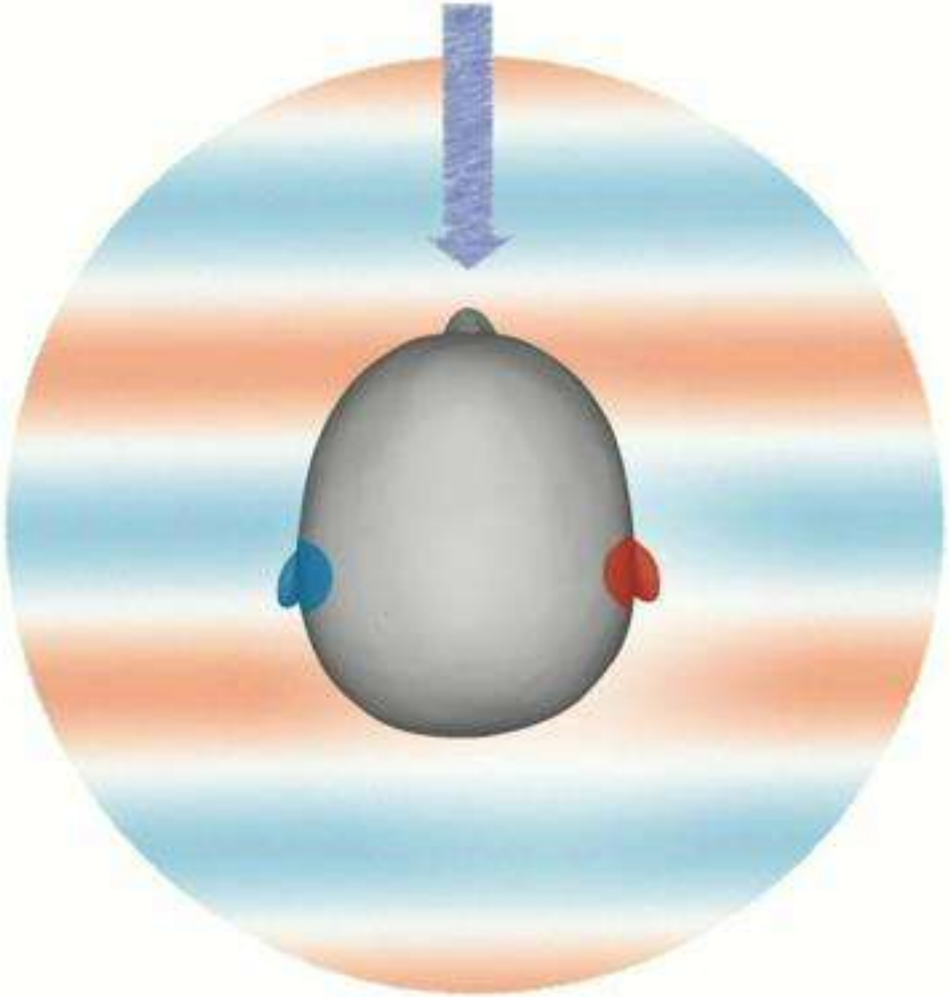

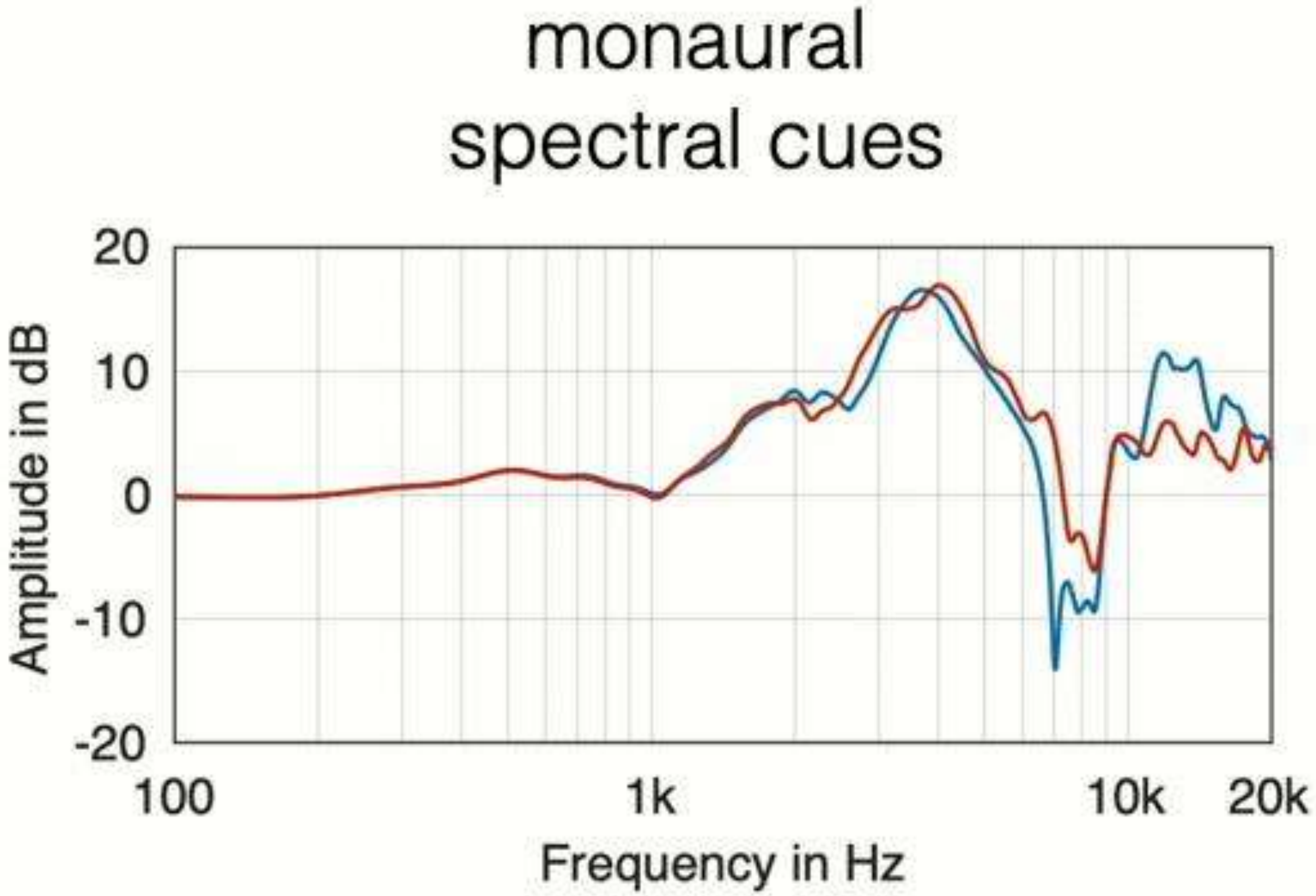

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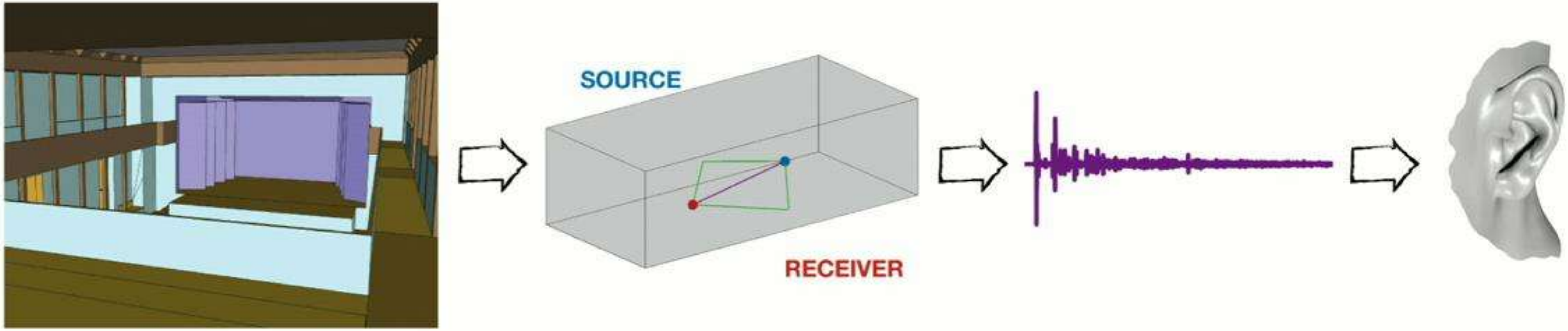
ACOUSTICAL SIMULATION



ROOM MODEL

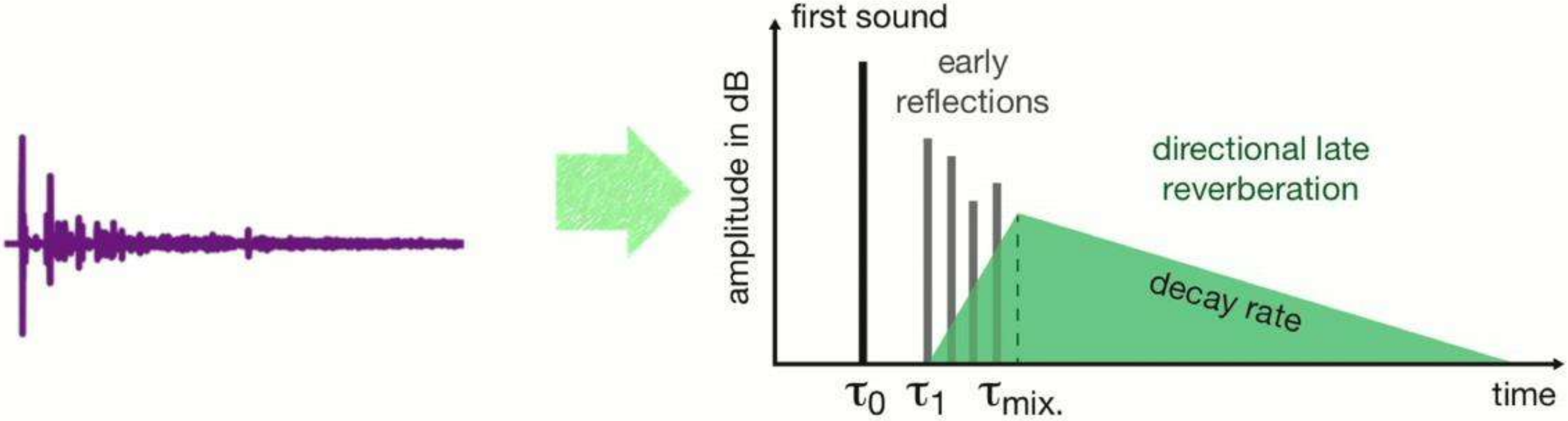
SIMULATION

IMPULSE RESPONSE

AURALIZATION

Images: Fabian Brinkmann (CC-BY 4.0)

PARAMETRIC SPATIAL AUDIO


first sound
early reflections
directional late reverberation
decay rate
amplitude in dB
τ_0 τ_1 $\tau_{mix.}$
time

Lindau *et al*. (2012) Perceptual evaluation of model- and signal-based predictors of the mixing time… JAES **60**(11): 887 – 898.
Godin *et al*. (2019) Aesthetic modification of room impulse responses... *AES Conf. Immersion and Interactive Audio*, York, UK.
Images: Fabian Brinkmann (CC-BY 4.0)

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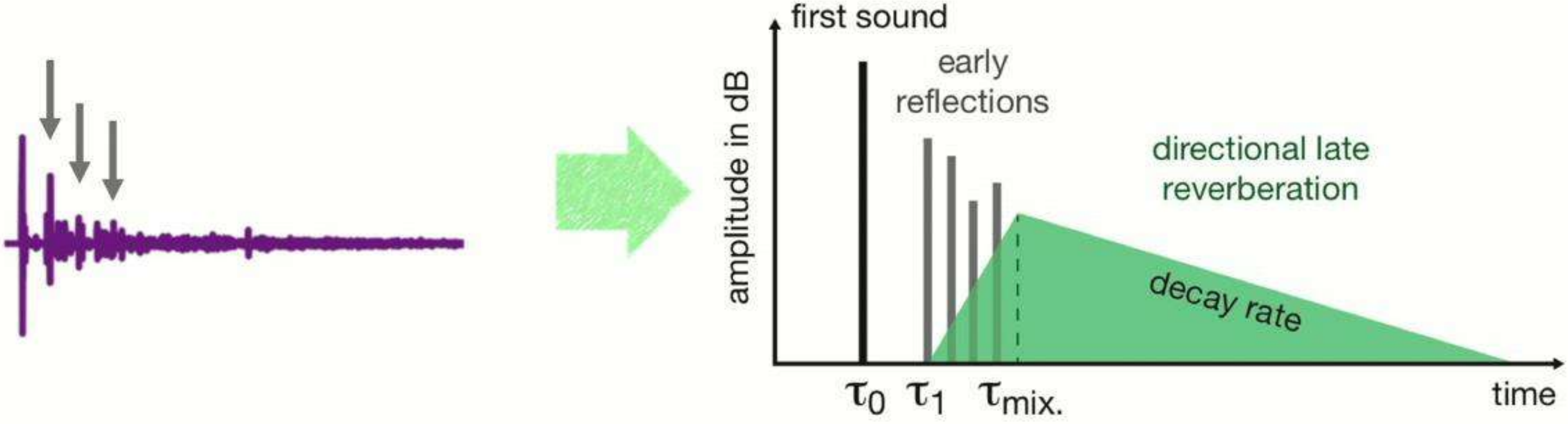

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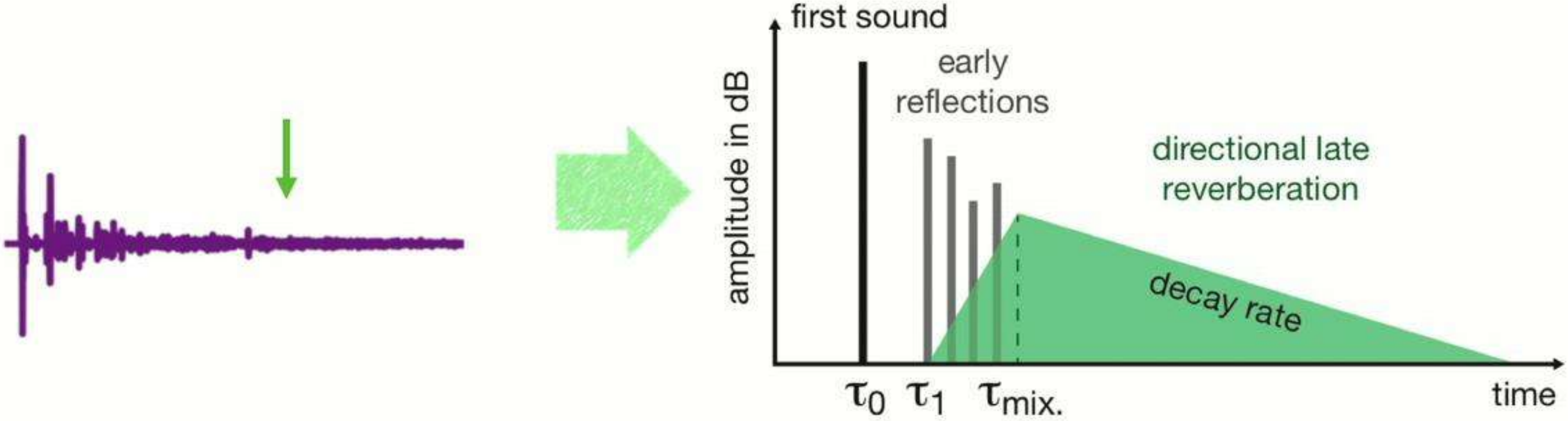

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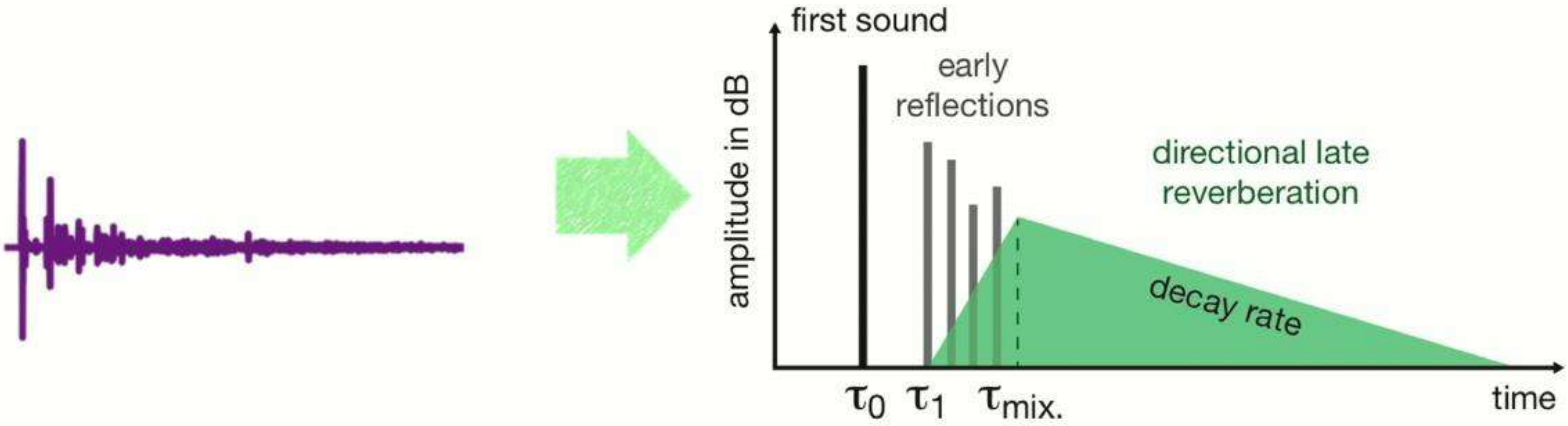

- Cheap rendering
- Low memory
- Aesthetic modification

Lindau *et al.* (2012) Perceptual evaluation of model- and signal-based predictors of the mixing time… JAES **60**(11): 887 – 898.
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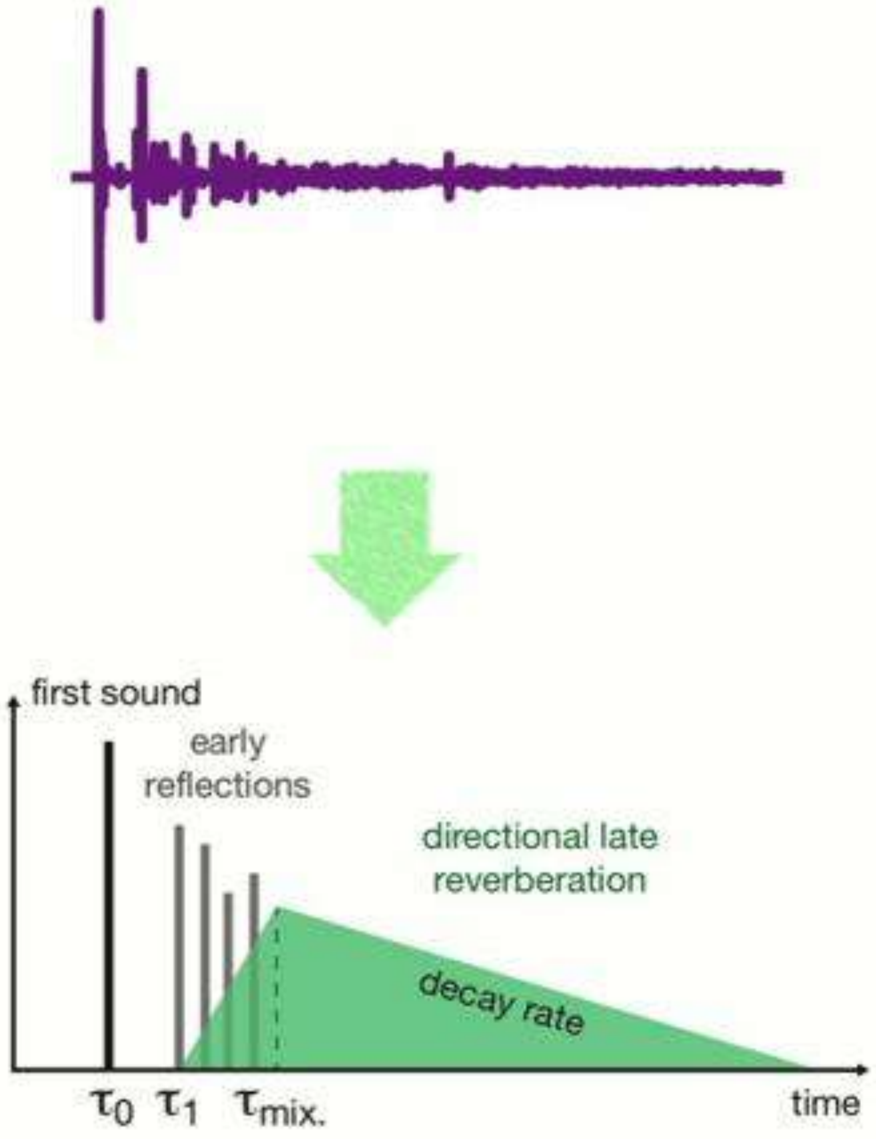
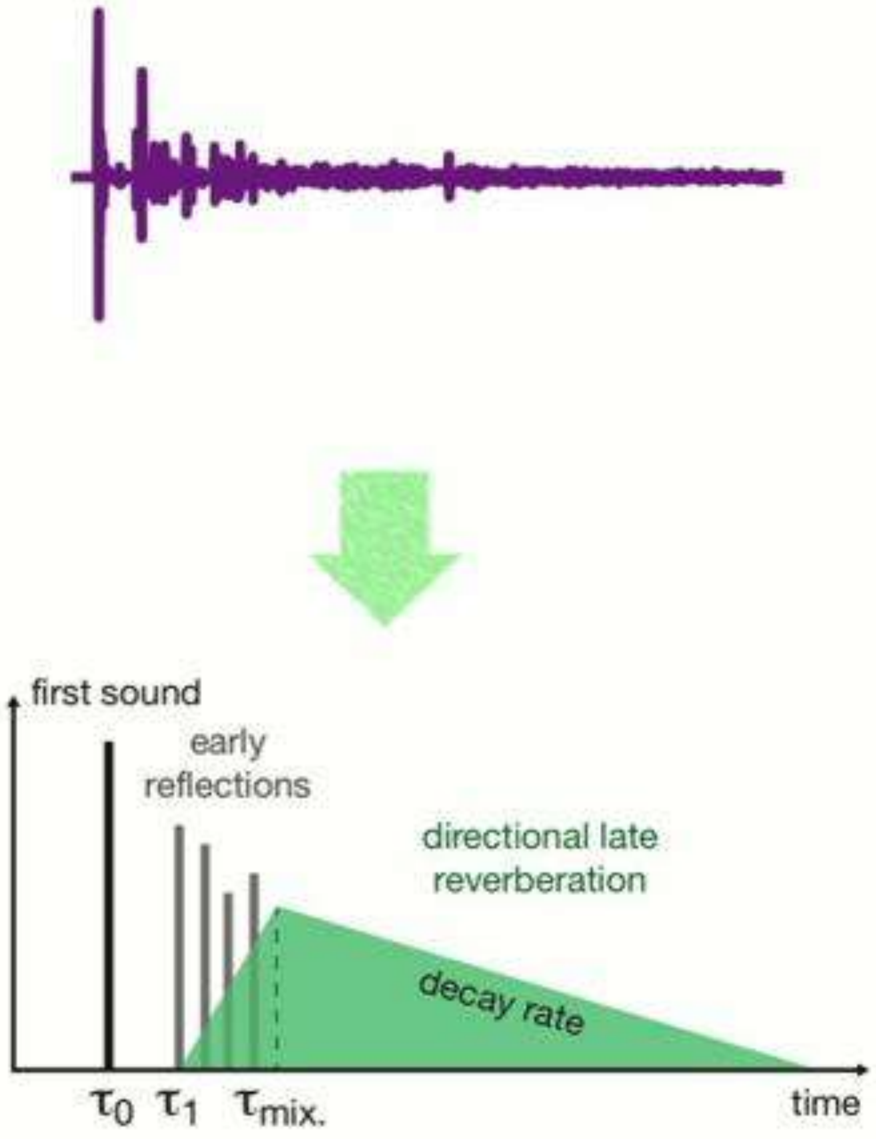
PARAMETRIC DE- AND ENCODING IN CONSIDERATTION OF EARLY REFELCTIONS



- Encoding (offline)
  - Dependency on environment
  - Dependency on audio content
  - Scalable to match computational resources
  - Smooth spatial distribution
  - Low-cost and short memory

Images: Fabian Brinkmann (CC-BY 4.0)

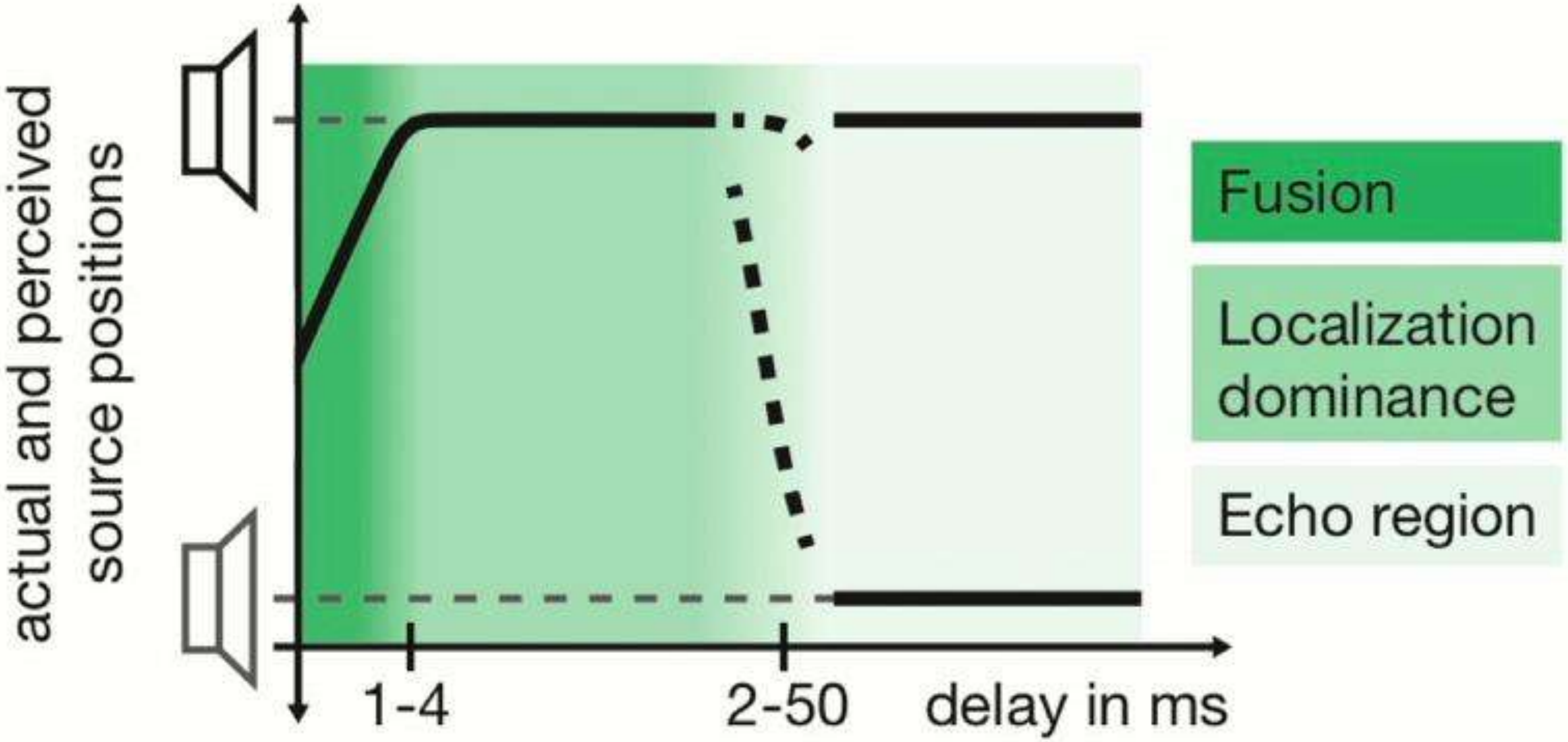
PARAMETRIC DE- AND ENCODING IN CONSIDERATTION OF EARLY REFELCTIONS



- Encoding (offline)
  - Dependency on environment
  - Dependency on audio content
  - Scalable to match computational resources
  - Smooth spatial distribution
  - Low-cost and short memory
- Decoding (real-time)
  - Efficient
  - Perceptually plausible

Images: Fabian Brinkmann (CC-BY 4.0)

PRECEDENCE IN ROOM ACOUSTICS – TEMPORAL ASPECTS



Litovsky *et al.* (1999): The precedence effect. *J. Acoust. Soc. Am.* **104**(4): 1633 – 1654.

Brown *et al.* (2015): The precedence effect in sound localization. *J. Assoc. Res. Otolaryng.* **1**(16):1 – 28.

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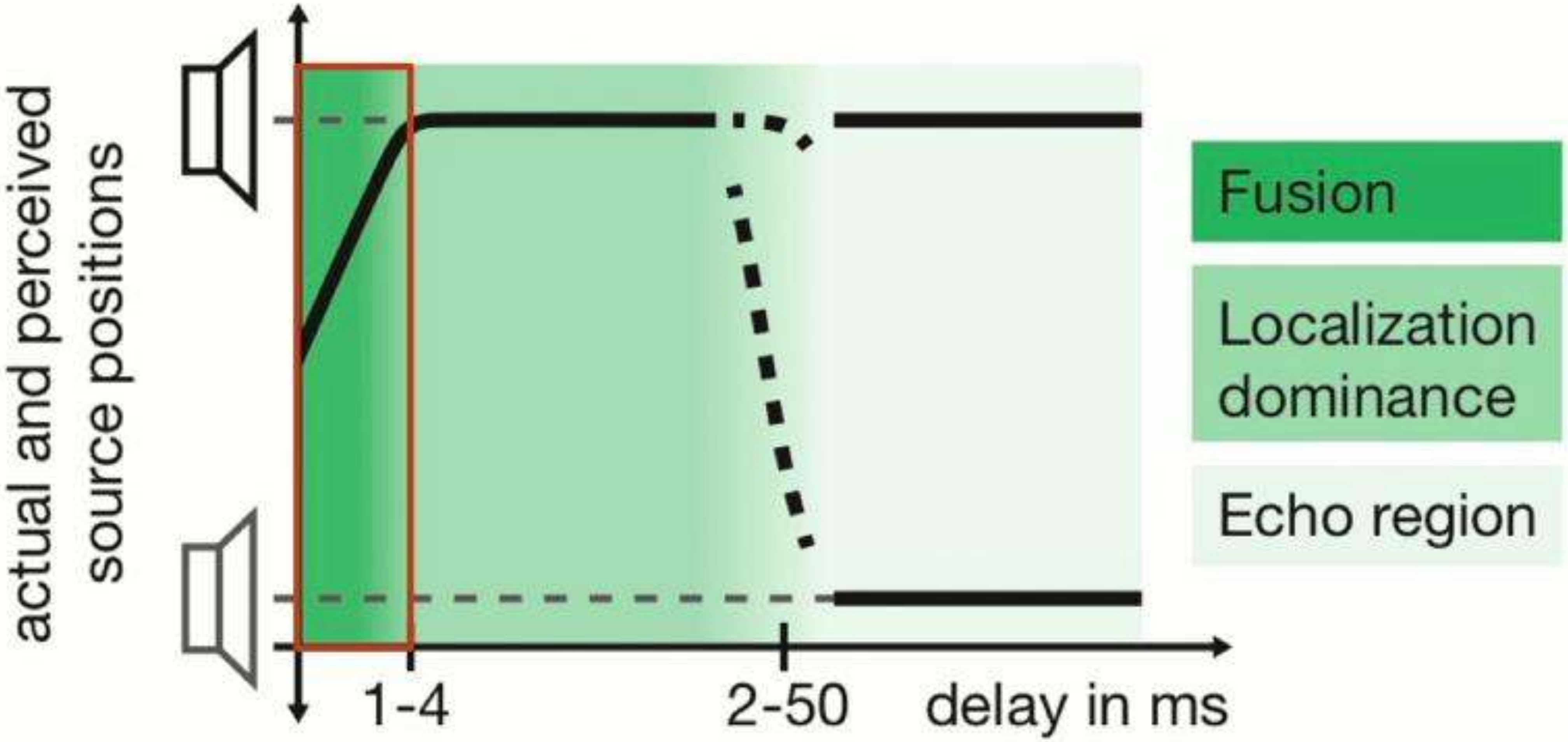

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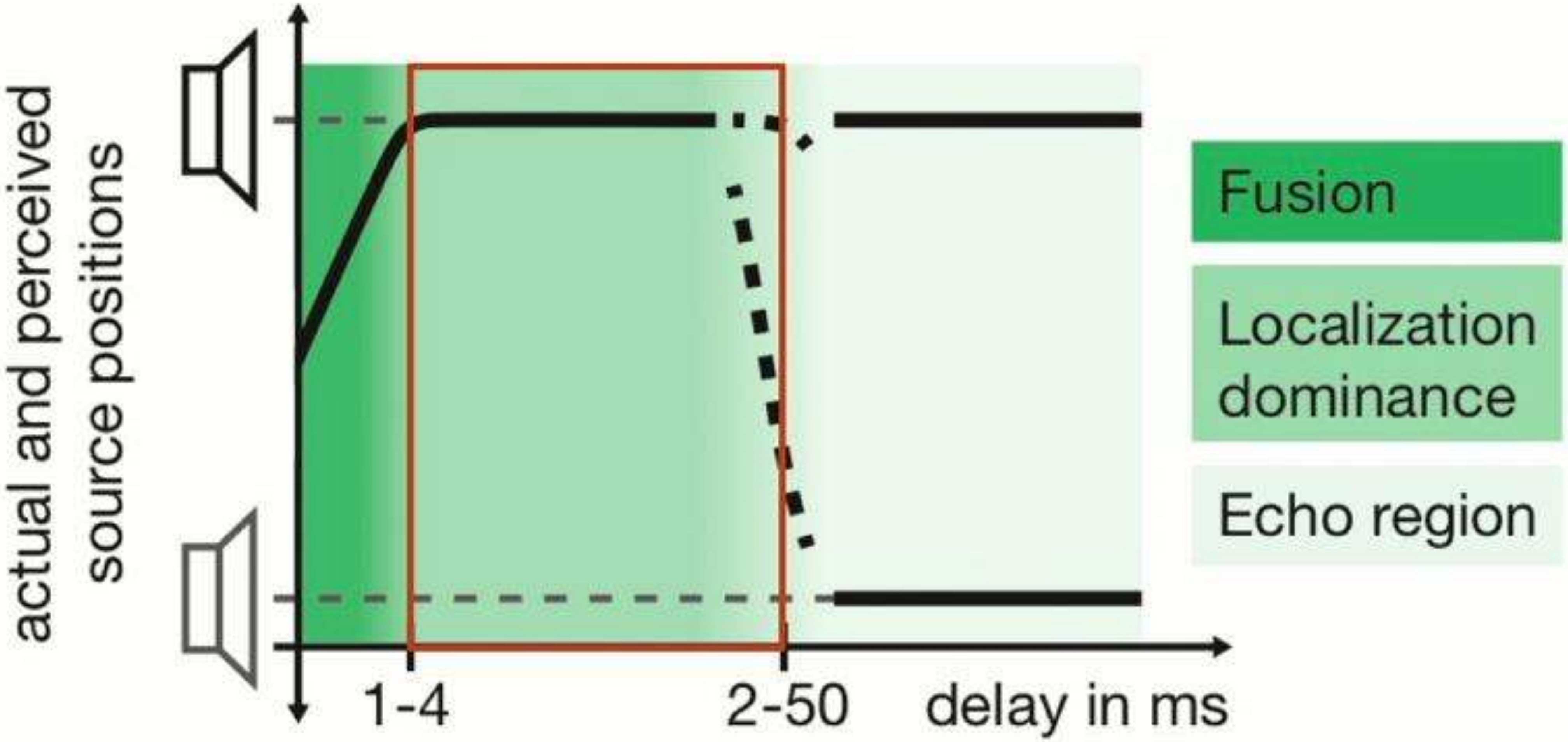

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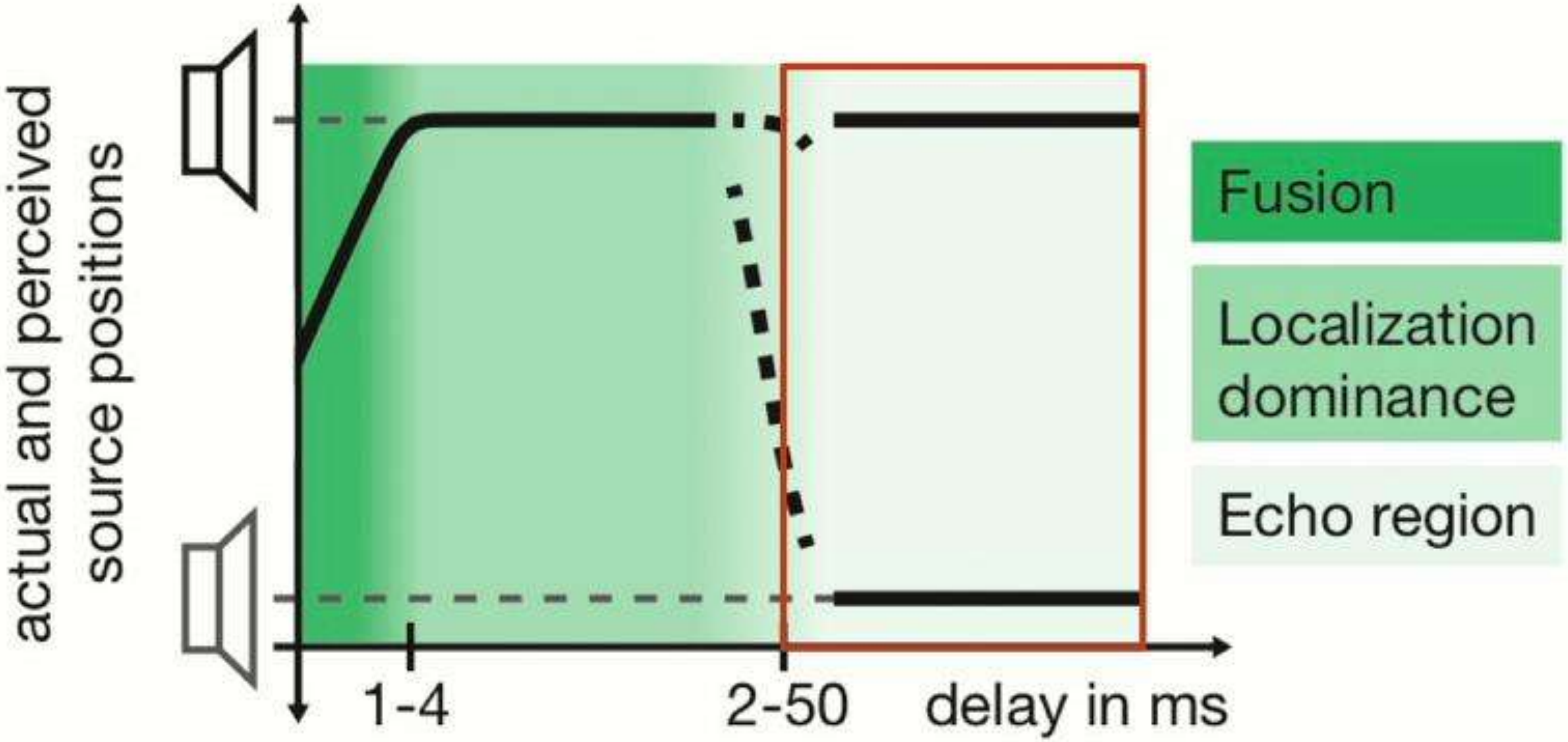

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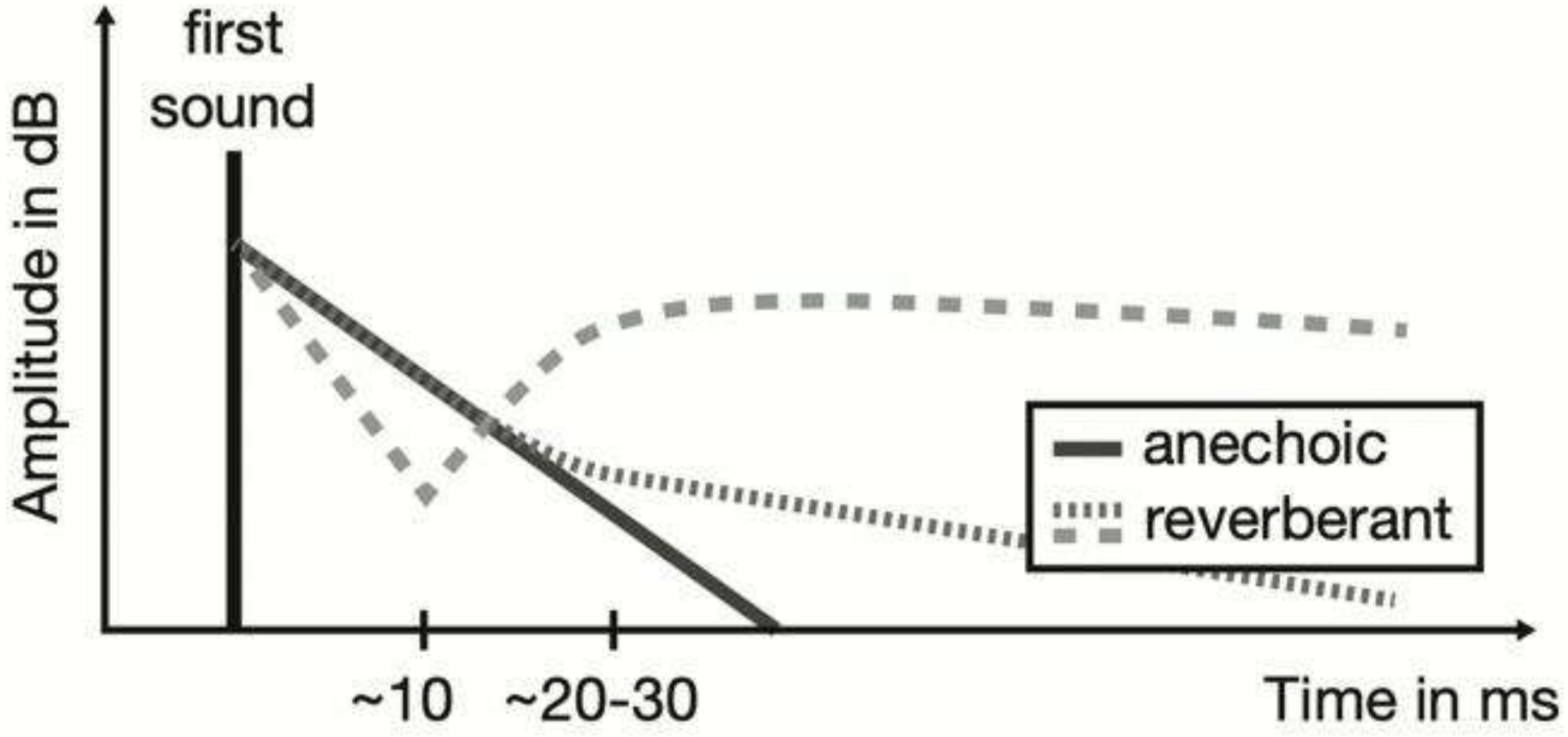
PRECEDENCE IN ROOM ACOUSTICS – ENERGETIC ASPECTS



Olive and Toole (1989): The detection of reflections in typical rooms. *J. Audio Eng. Soc.* **37**(7/8): 539–553.

Rakerd *et al.* (2000): Echo suppression in the horizontal and median sagittal plane. *J. Acoust. Soc. Am.* **107**(2):1061–1064.

Jensen and Welti (2003): The importance of reflections in a binaural room impulse response. *114th AES Convention.*

PRECEDENCE IN ROOM ACOUSTICS – SPATIAL ASPECTS

- Decreased threshold with increasing spatial separation
- Differences of 10 - 15 dB

Bech (1995/1996): Timbral aspects of reproduced sound in small rooms. Part I/II. *J. Acoust. Soc. Am.* **97**(3) and **99**(6).

Litovsky and Cunningham (2001): Investigation of the relationship among three common measures of precedence. *J. Acoust. Soc. Am.*

Best *et al.* (2004): Separation of concurrent broadband sound sources… *J. Acoust. Soc. Am.* **115**(1):324–336.

INTRODUCTION

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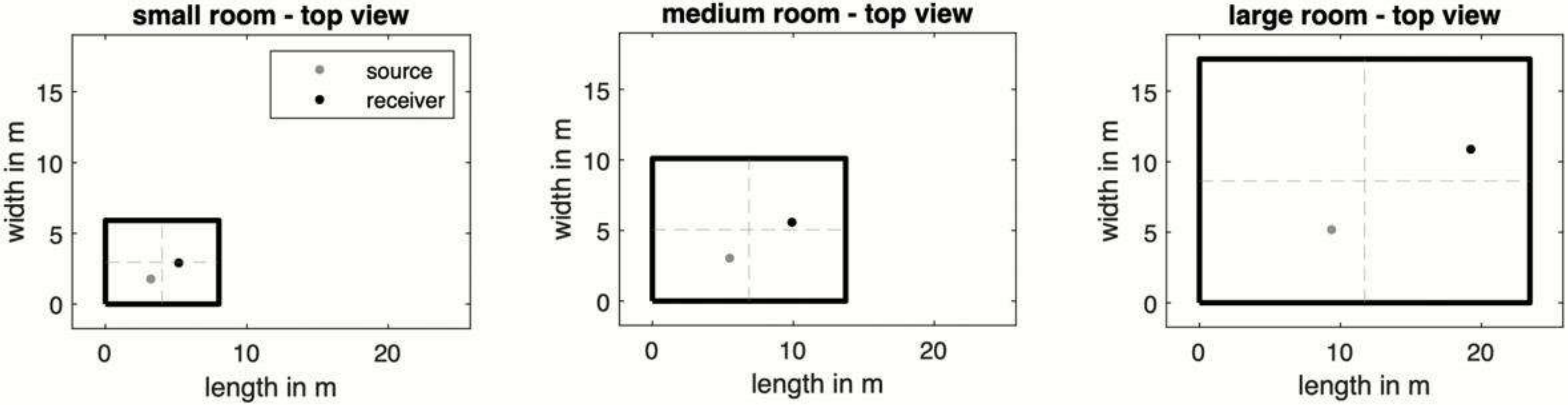
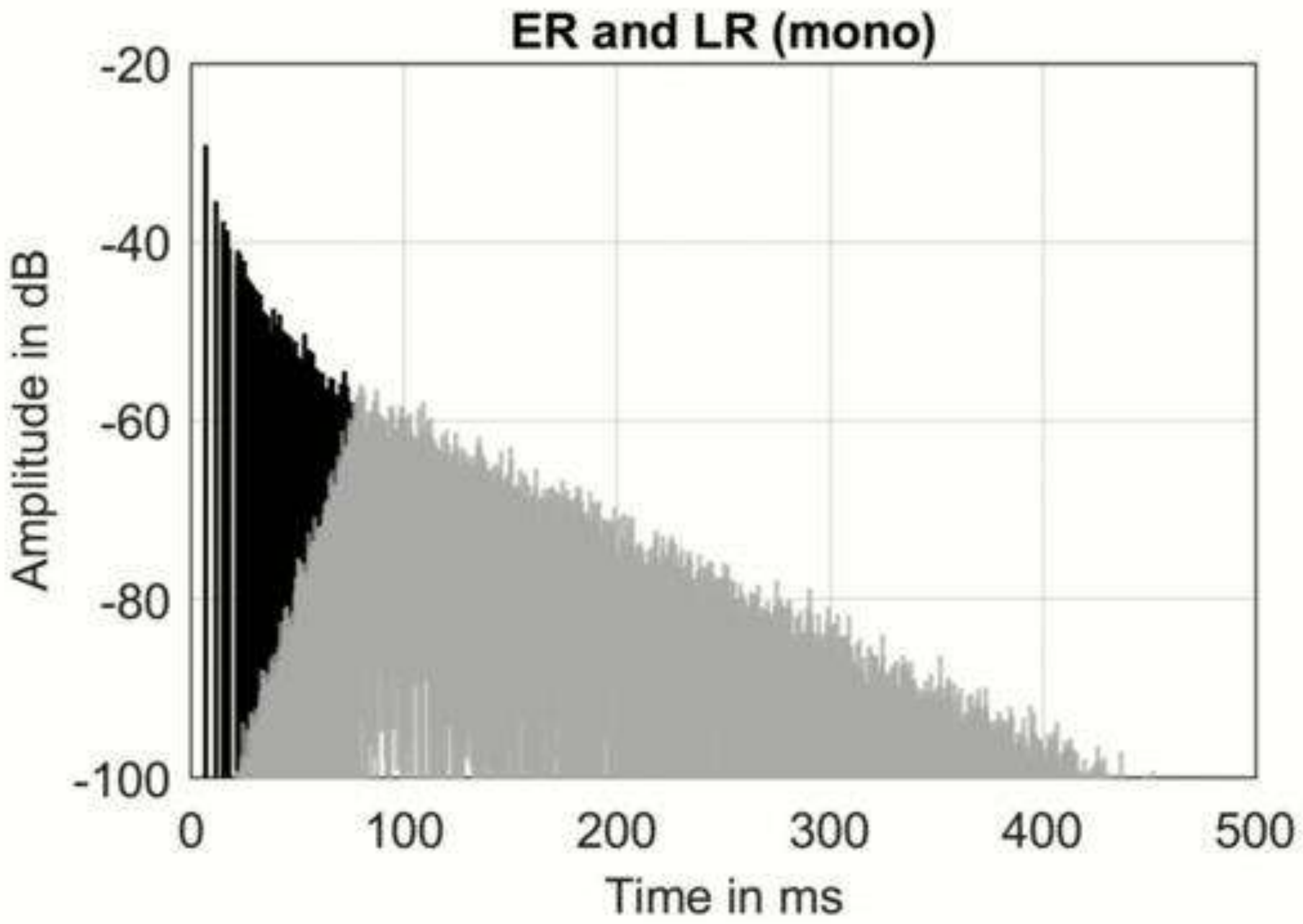
DATABASE

- 9 empty shoe box rooms
  - 3 Reverberation times: 0.5 s, 1 s, 2 s
  - 3 Volumes: 200 m^3, 1000 m^3, 5000 m^3



DATABASE – IMAGE SOURCE MODEL



Brinkmann and Weinzierl (2017): AKtools. 142nd AES Convention, Berlin, Germany

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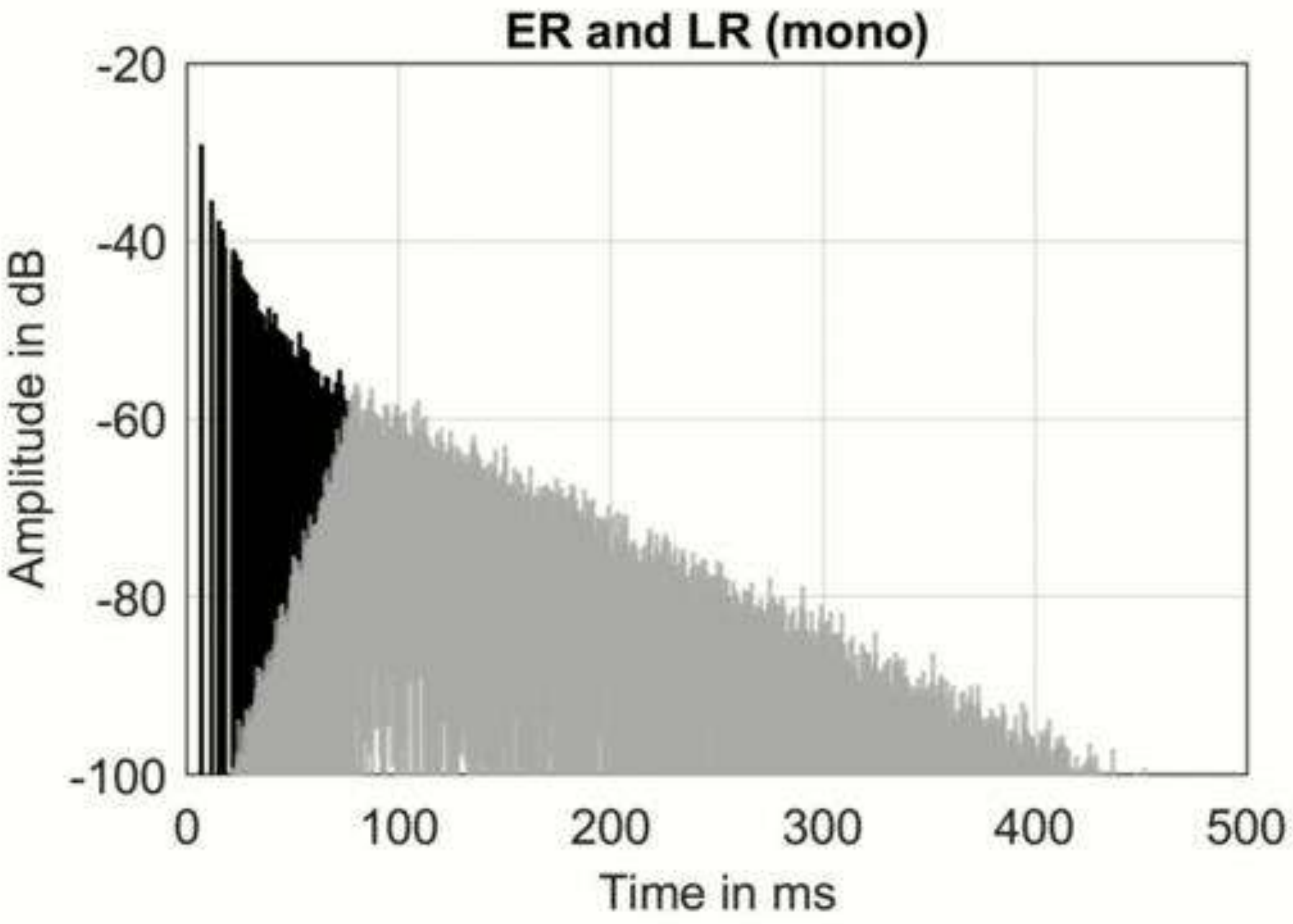
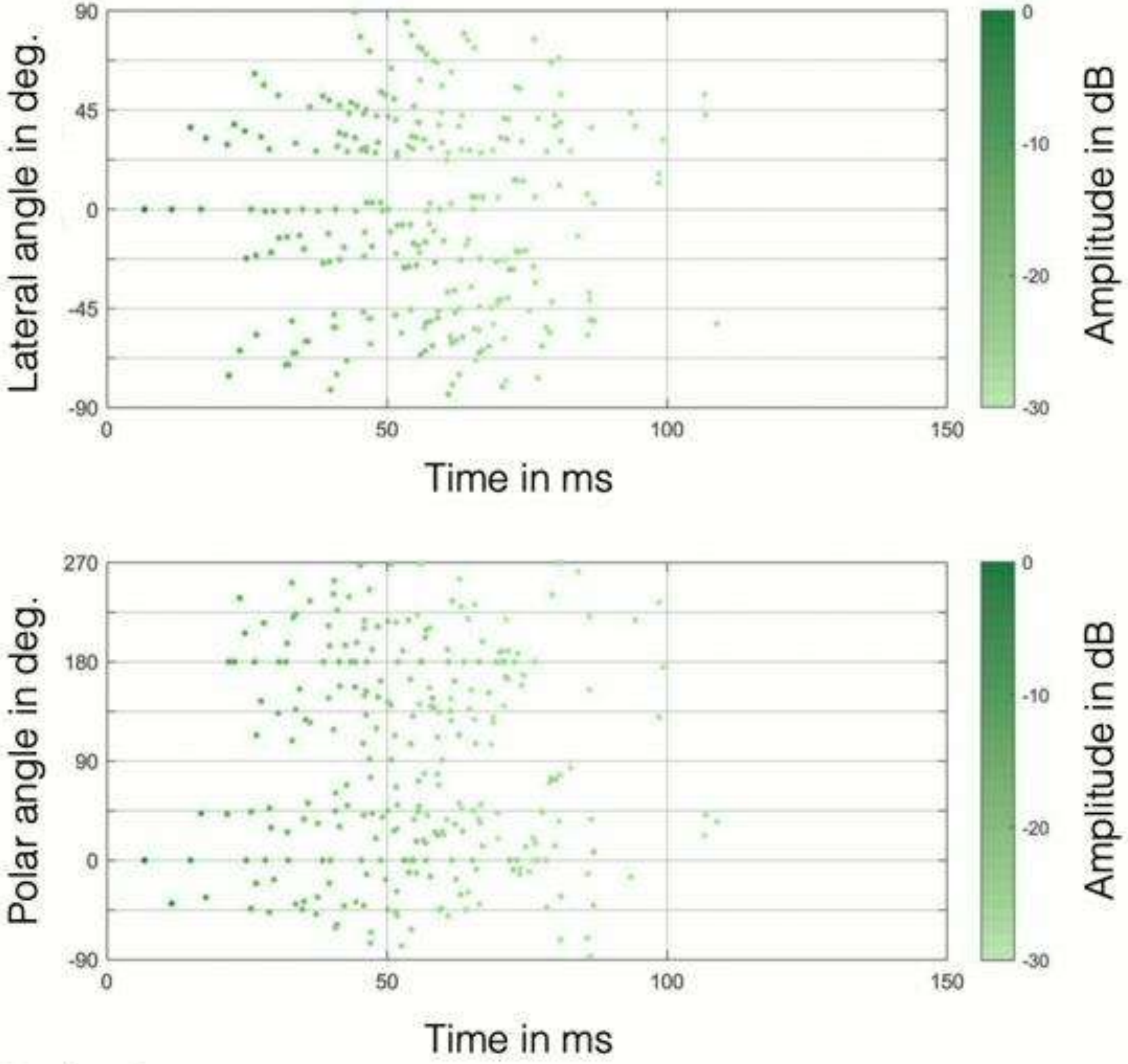




Brinkmann and Weinzierl (2017): AKtools. 142nd AES Convention, Berlin, Germany

DATABASE - TRITON

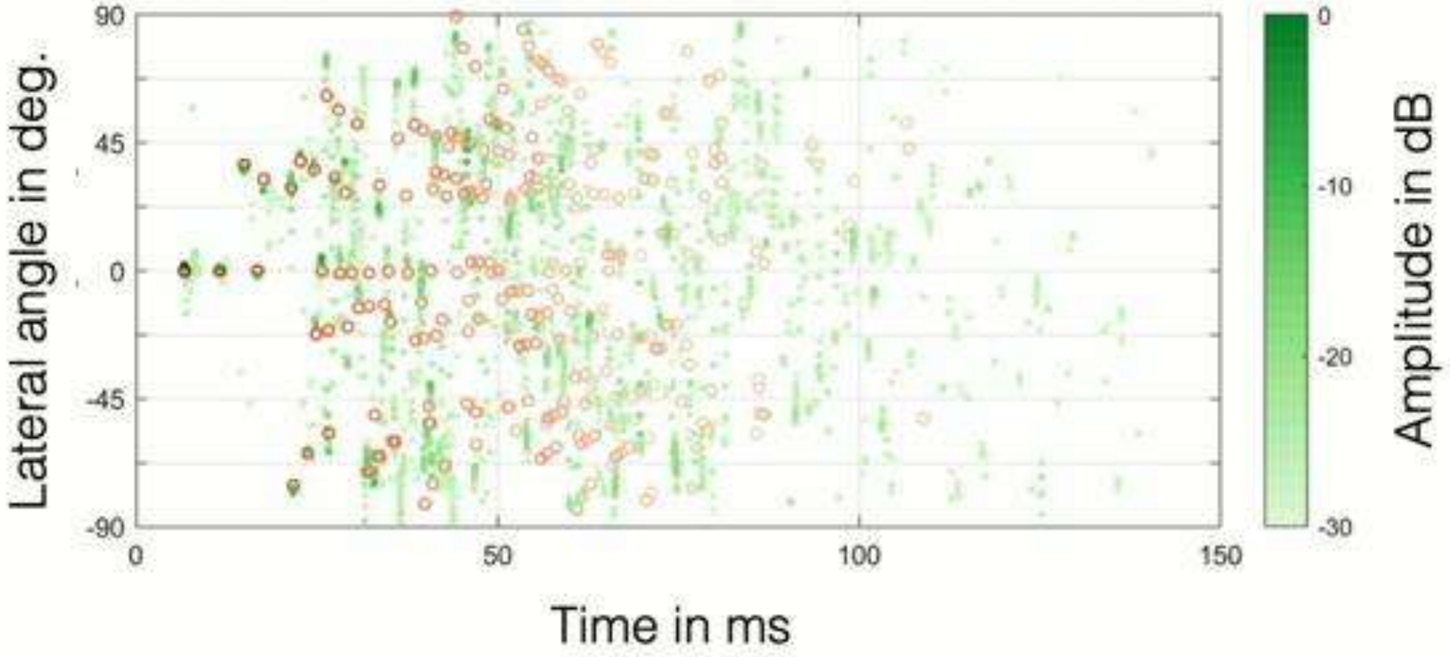
- Wave based simulation up to 8 kHz
- Direction from sound intensity $\boldsymbol{I}$

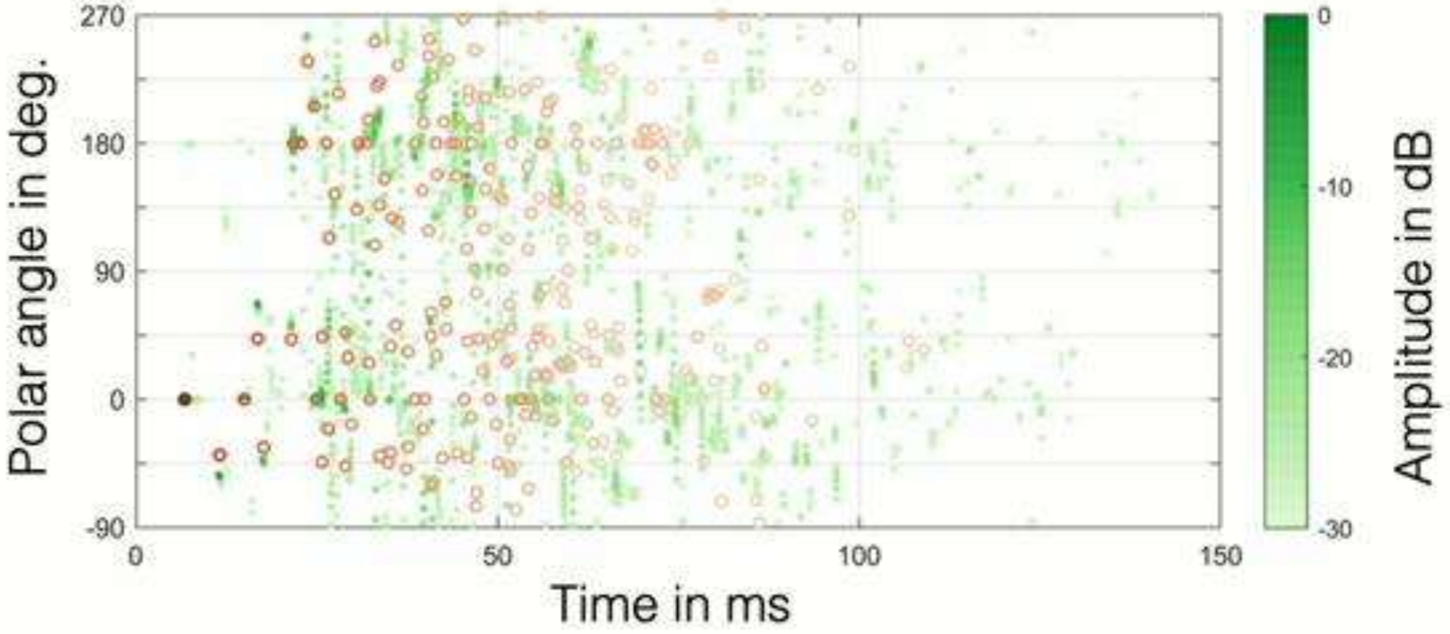
$$\boldsymbol{I} = p\boldsymbol{v}, \qquad \boldsymbol{v} = -\frac{1}{\rho_0}\int \nabla p \,\mathrm{d}t$$

- Pressure gradient $\boldsymbol{\nabla p}$ from neighboring points in x/y/z-direction
- 10th order, zero phase low-pass @ 2 kHz

Raghuvanshi and Snyder (2018): Parametric directional coding for precomputed sound propagation. *ACM Trans. Graph.*

DATABASE - TRITON





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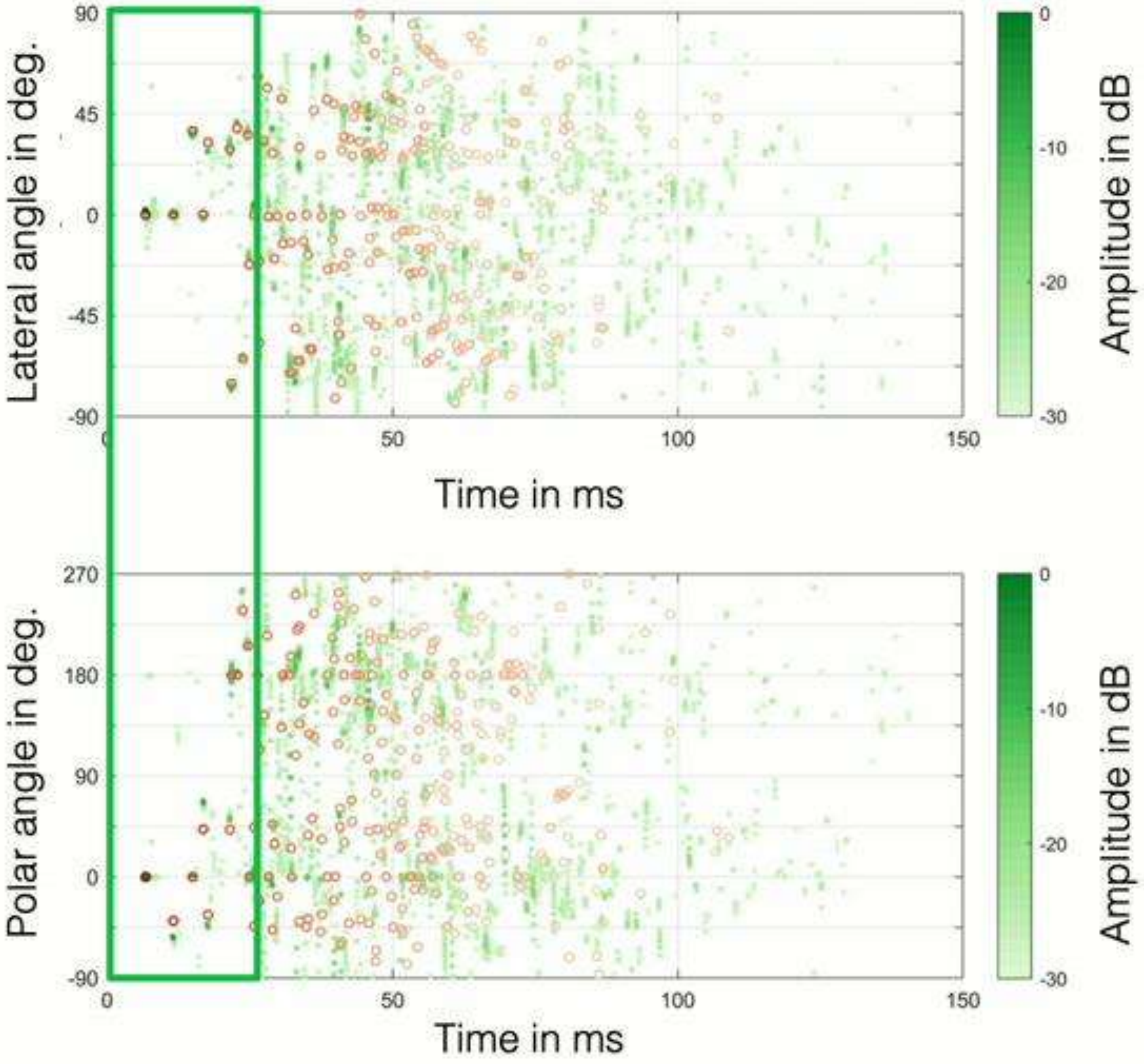

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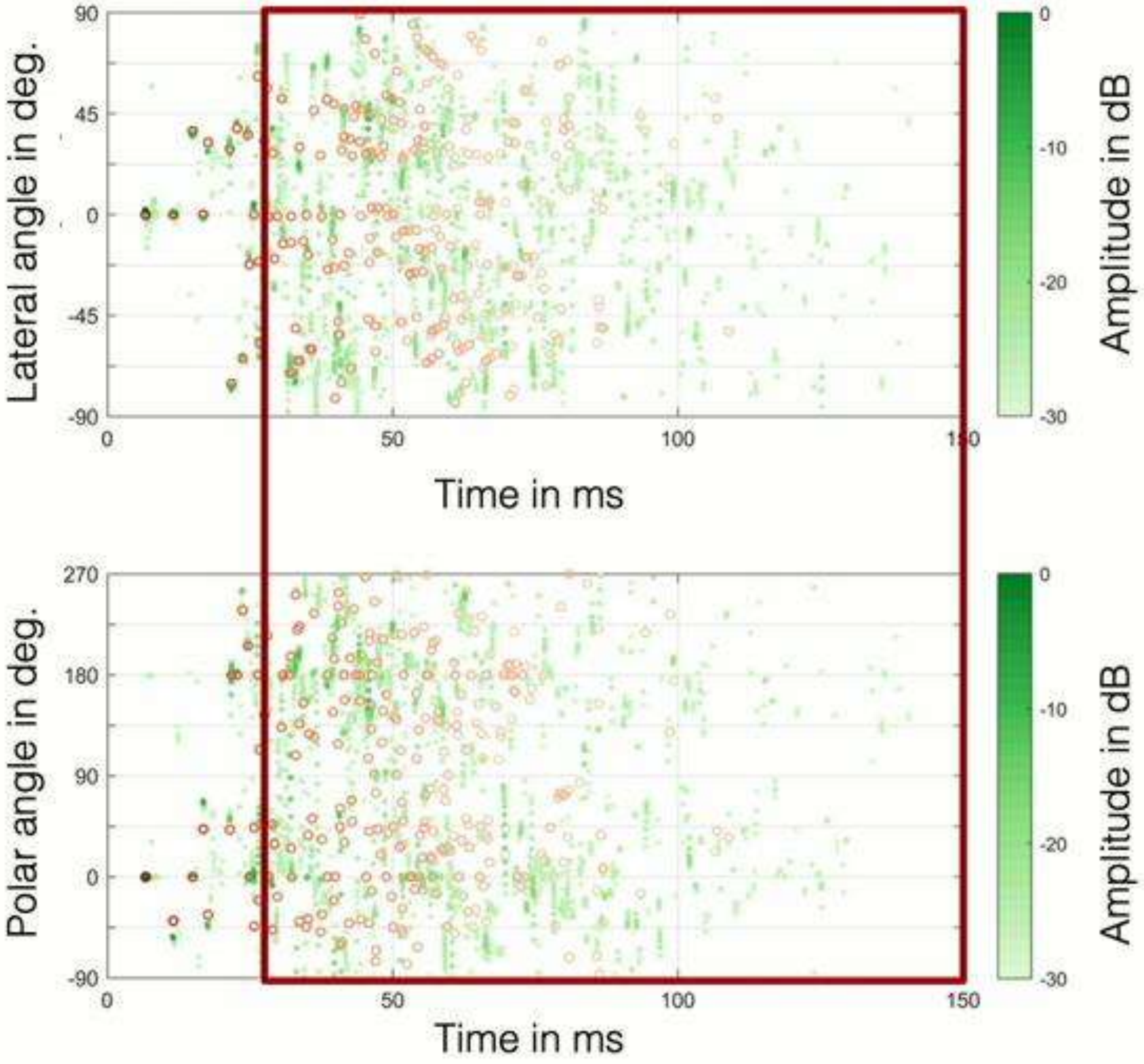

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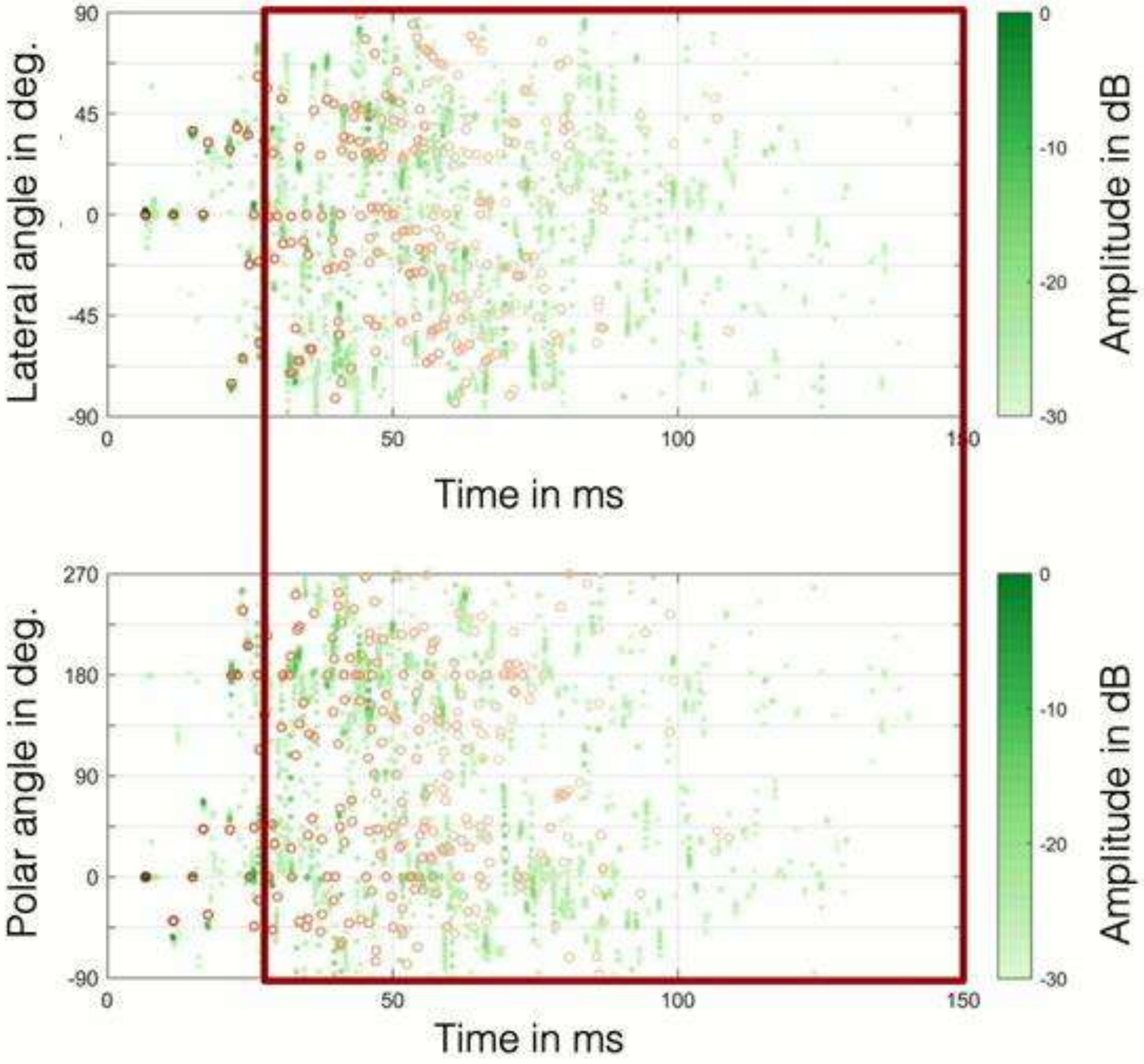

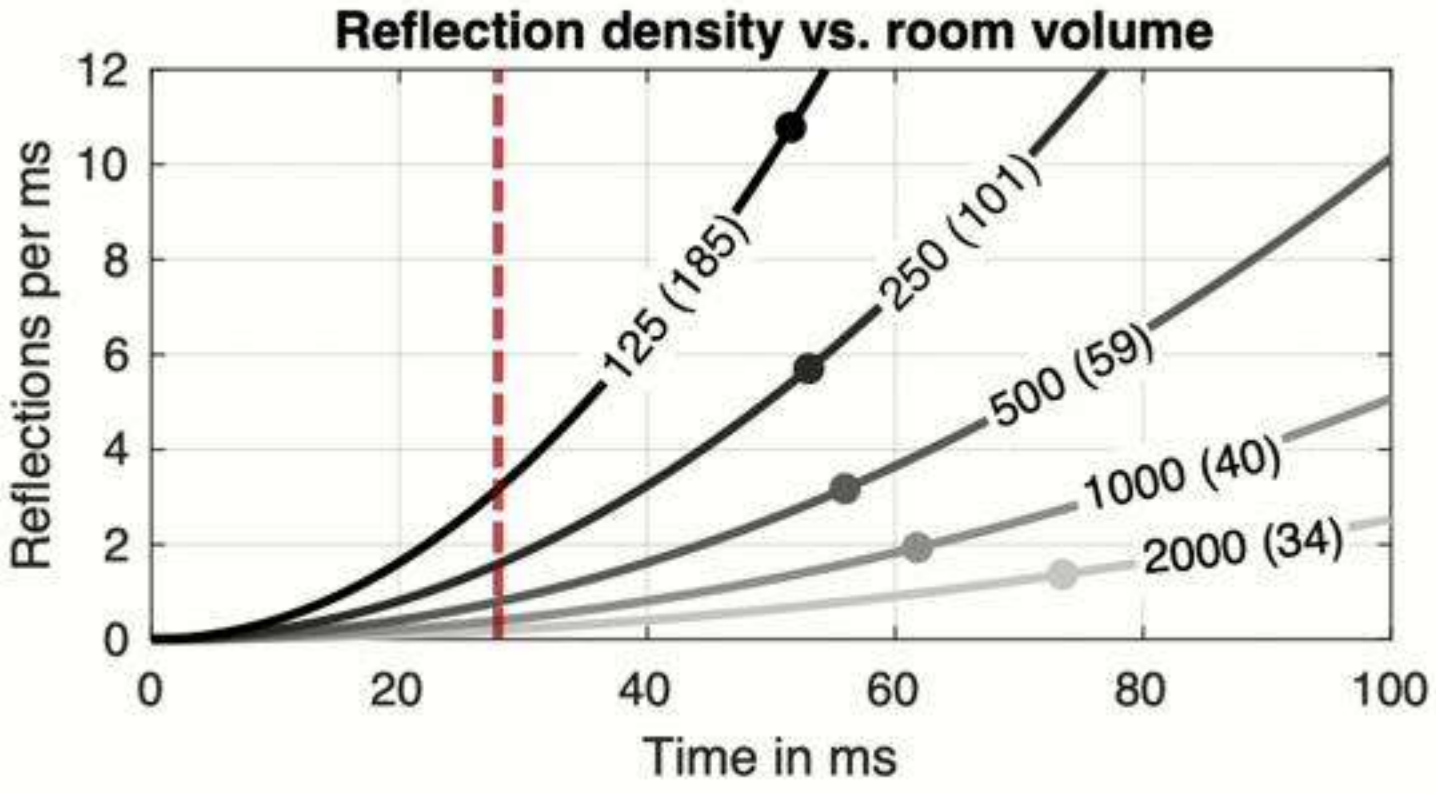

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PROPOSED ENCODING

a) estimate τ_0, a_0, and $\sphericalangle_0 = \{\phi_0, \theta_0\}$

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b) estimate τ_i, a_i, and $\sphericalangle_i$ based on masking threshold

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c) select N reflections

PROPOSED ENCODING

a) estimate τ_0, a_0, and $\sphericalangle_0 = \{\phi_0, \theta_0\}$

b) estimate τ_i, a_i, and $\sphericalangle_i$ based on masking threshold

c) select N reflections

d) estimate late reverberation based on residual energy

PROPOSED ENCODING: τ_0, a_0

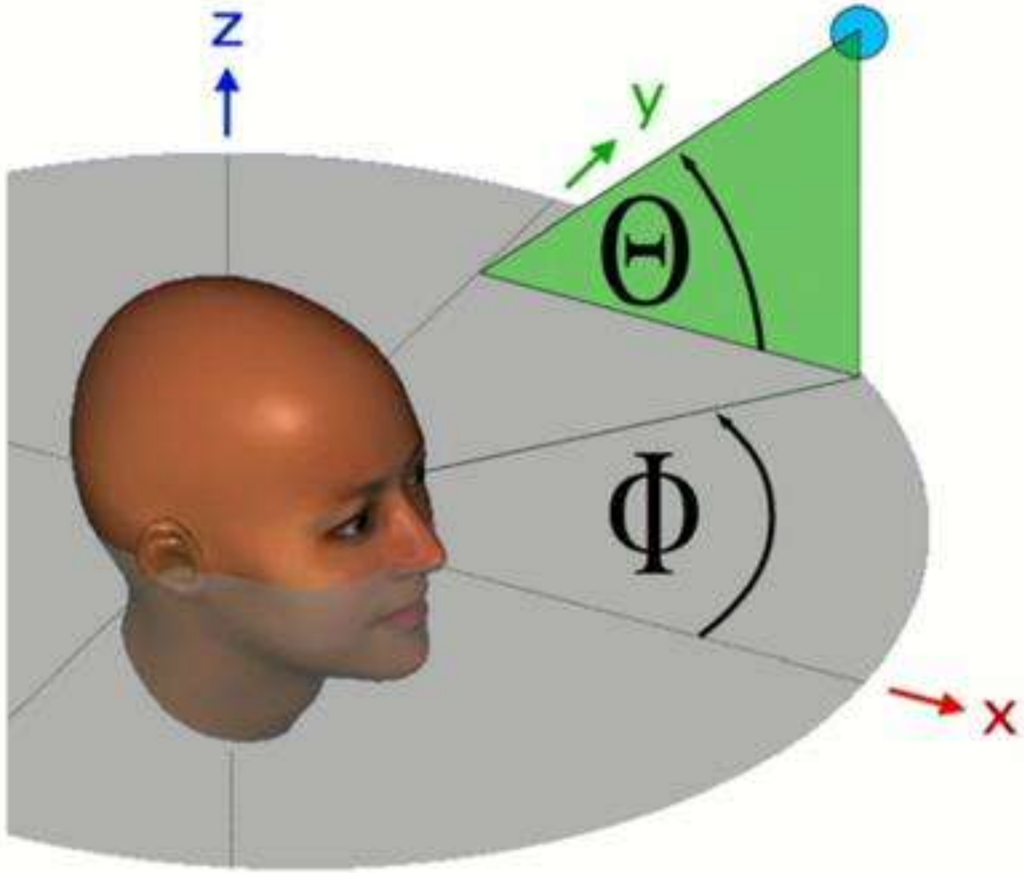
τ_0: Onset estimator according to [1]

$$a_0 = \left[\frac{1}{1.5\ \mathrm{ms}} \int_{\tau_0 - 0.5\ \mathrm{ms}}^{\tau_0 + 1\ \mathrm{ms}} p(t)^2 \mathrm{d}t\right]^{1/2}$$

[1] Raghuvanshi and Snyder (2018): Parametric directional coding for precomputed sound propagation. *ACM Trans. Graph.*

PROPOSED ENCODING: $\sphericalangle_0$

$$\phi_0 = \frac{1}{\int_{\tau_0-0.5\text{ ms}}^{\tau_0+1\text{ ms}} p^2 \mathrm{d}t} \int\limits_{\tau_0-0.5\text{ ms}}^{\tau_0+1\text{ ms}} p(t)^2 \phi(t) \mathrm{d}t$$



Ziegelwanger and Majdak (2014): Modeling the direction continuous time-of-arival. *J. Acust. Soc. Am.* **135**(3): 1278 – 1293.

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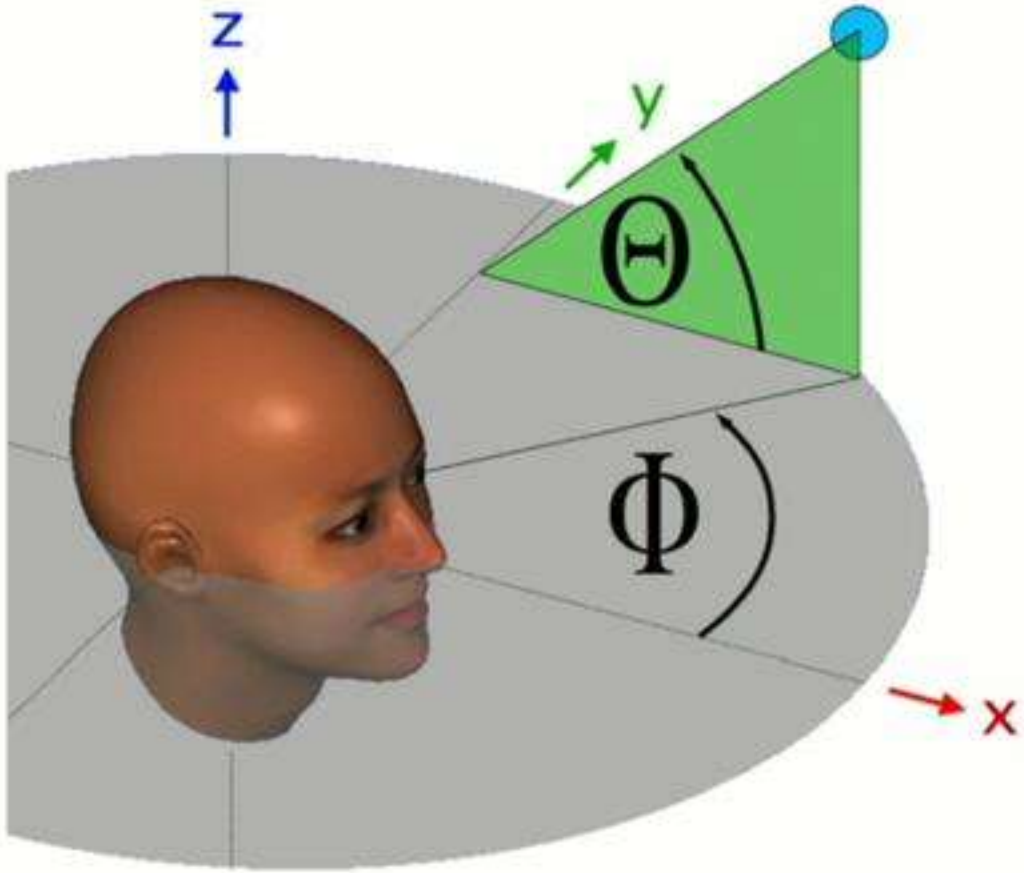
$$\phi_0 = \frac{1}{\int_{\tau_0-0.5\text{ ms}}^{\tau_0+1\text{ ms}} p^2 \mathrm{d}t} \int_{\tau_0-0.5\text{ ms}}^{\tau_0+1\text{ ms}} p(t)^2 \phi(t) \mathrm{d}t$$

$$\theta_0 = \angle\left(\int_{\tau_0-0.5\text{ ms}}^{\tau_0+1\text{ ms}} p(t)^2 e^{-i\theta(t)}\,\mathrm{d}t \right)$$



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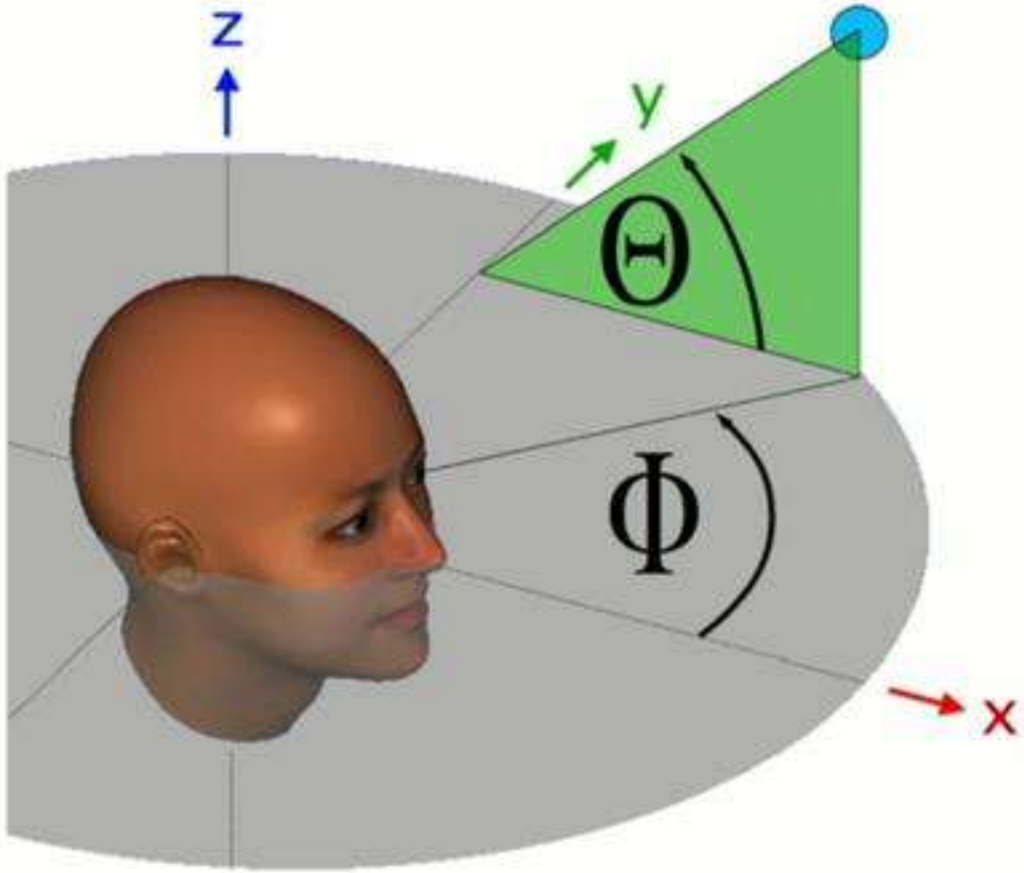

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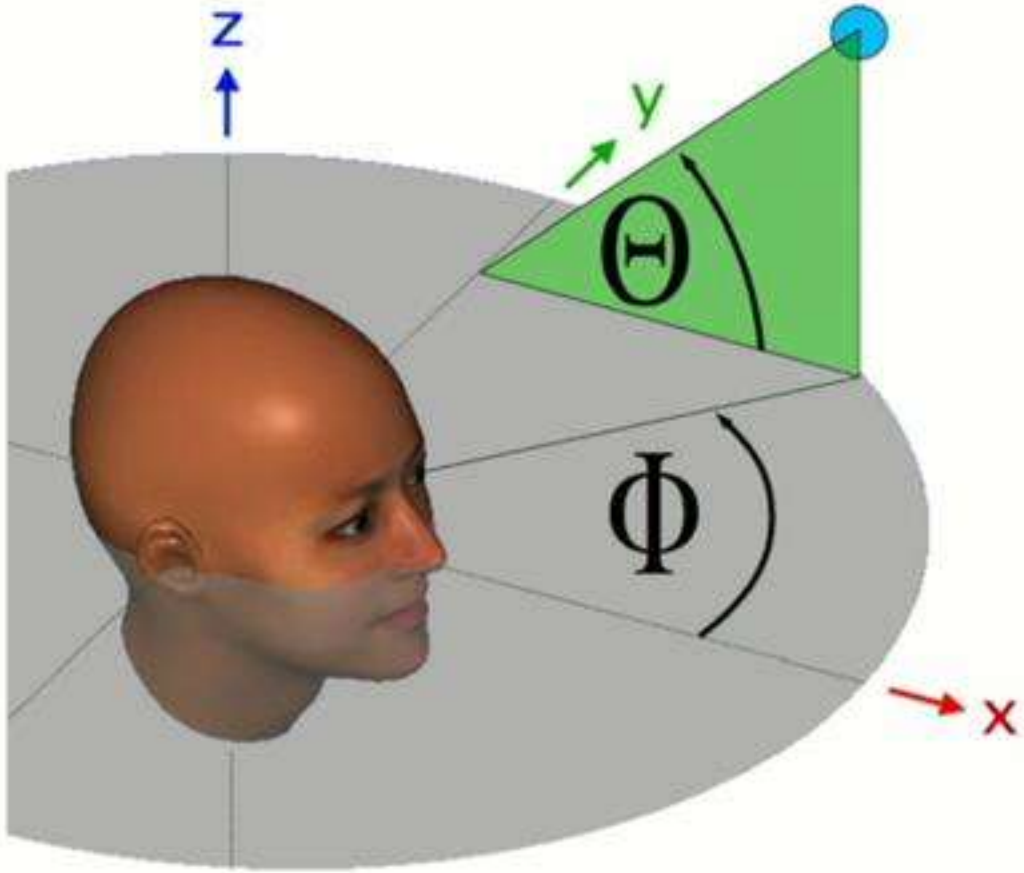
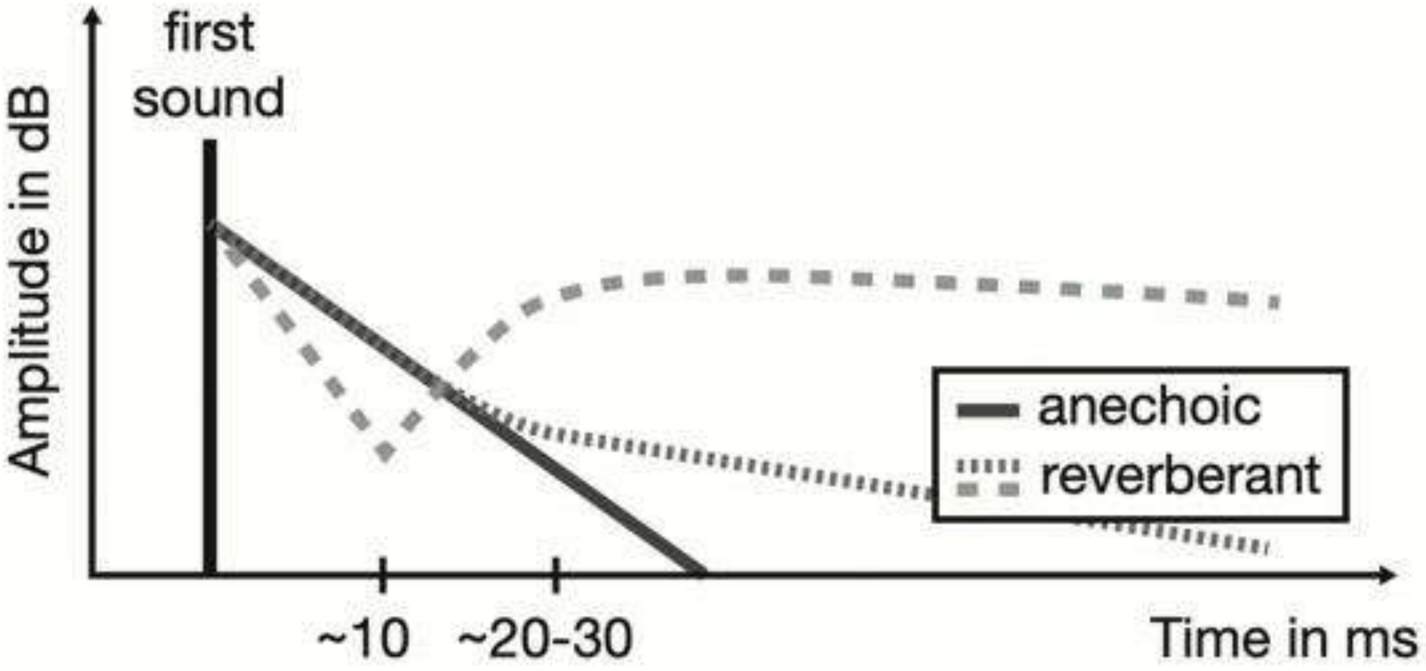
$$\theta_0 = \angle\left(\int\limits_{\tau_0-0.5\text{ ms}}^{\tau_0+1\text{ ms}} p(t)^2 e^{-i\theta(t)}\, \mathrm{d}t \right)$$



Ziegelwanger and Majdak (2014): Modeling the direction continuous time-of-arival. *J. Acust. Soc. Am.* **135**(3): 1278 – 1293.

PROPOSED ENCODING: MASKING THRESHOLD



slope: -1 dB/ms

offset: -10 dB

v-shape: add 35% reflection energy to threshold

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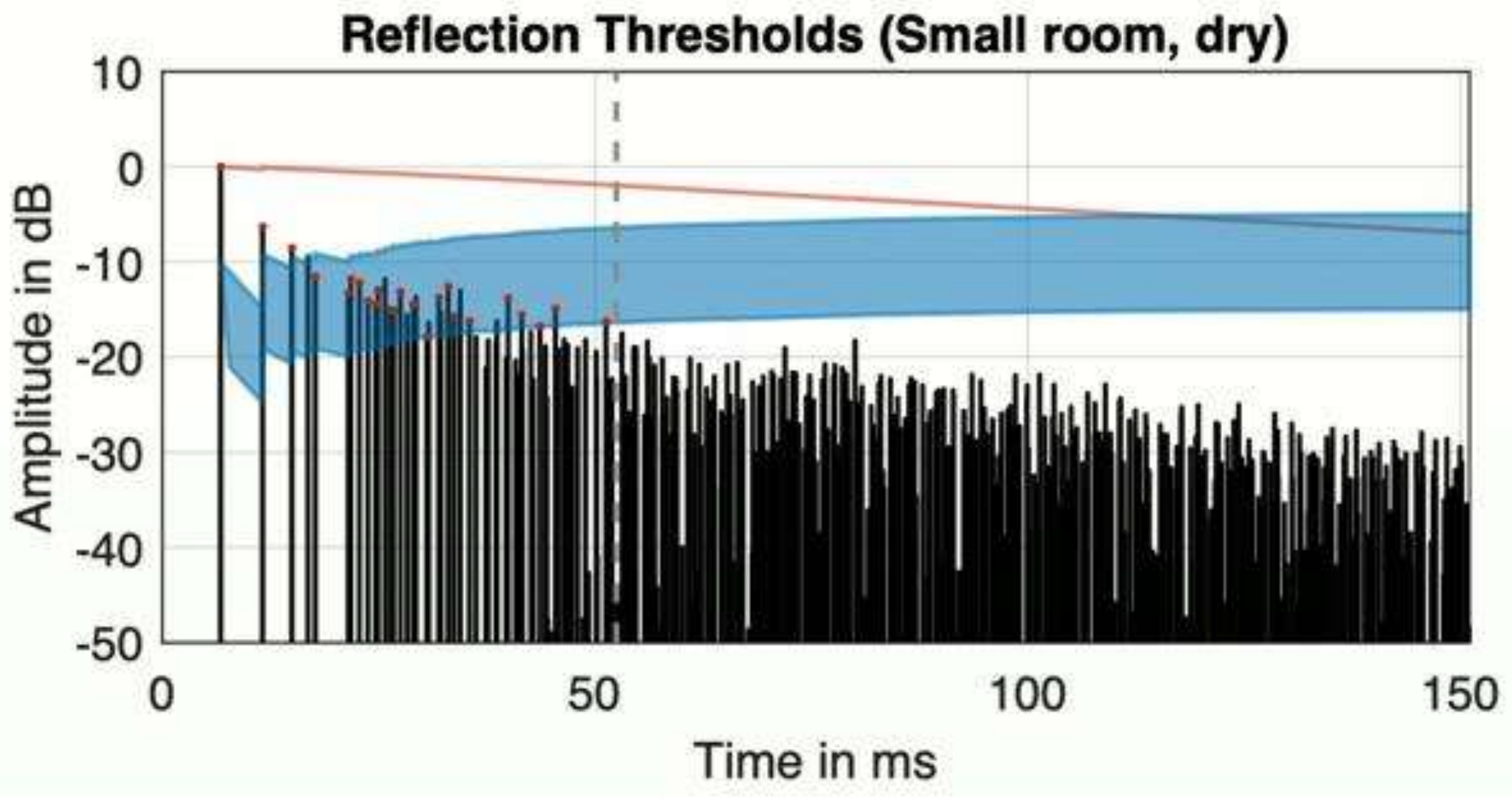

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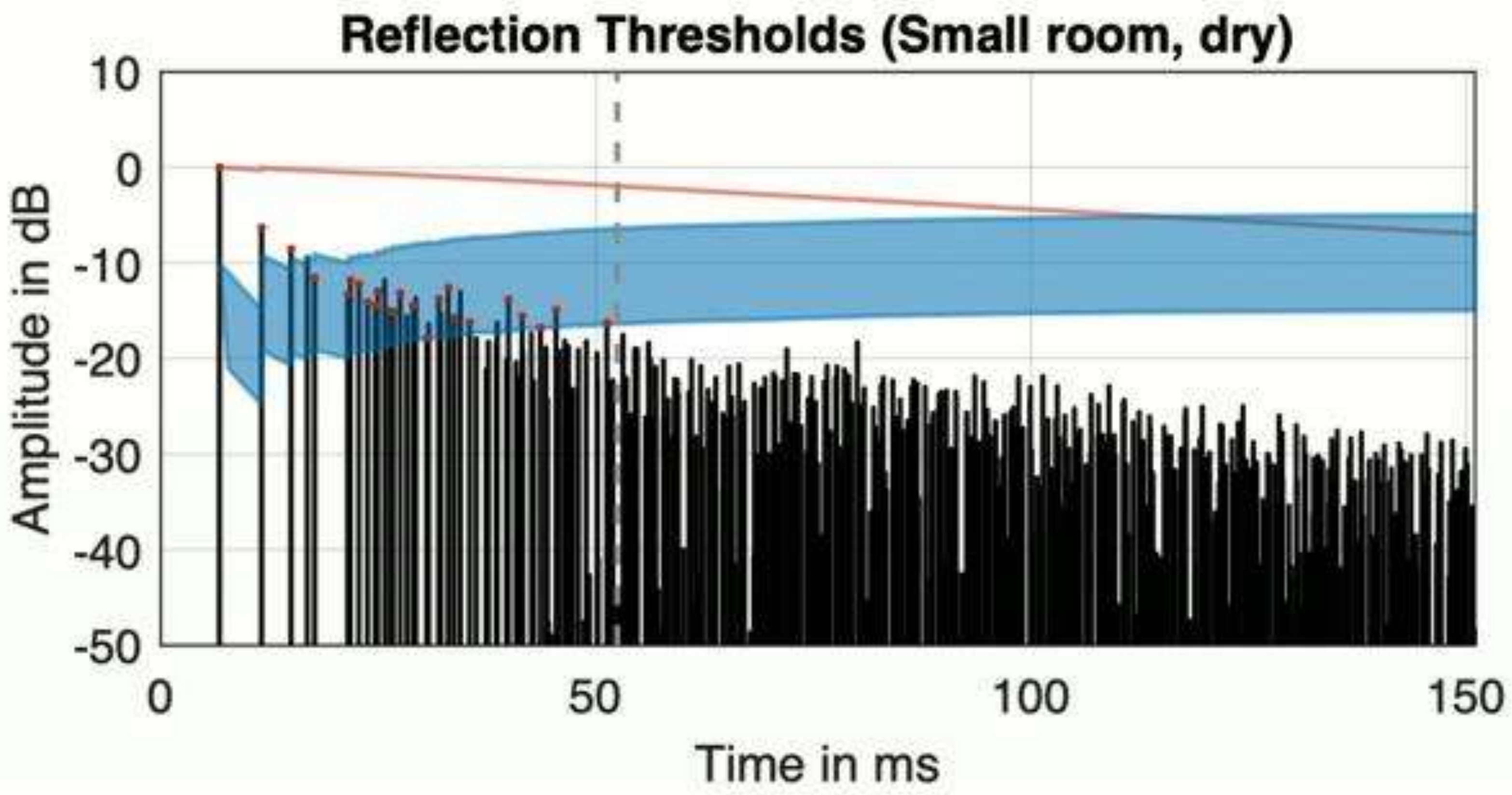
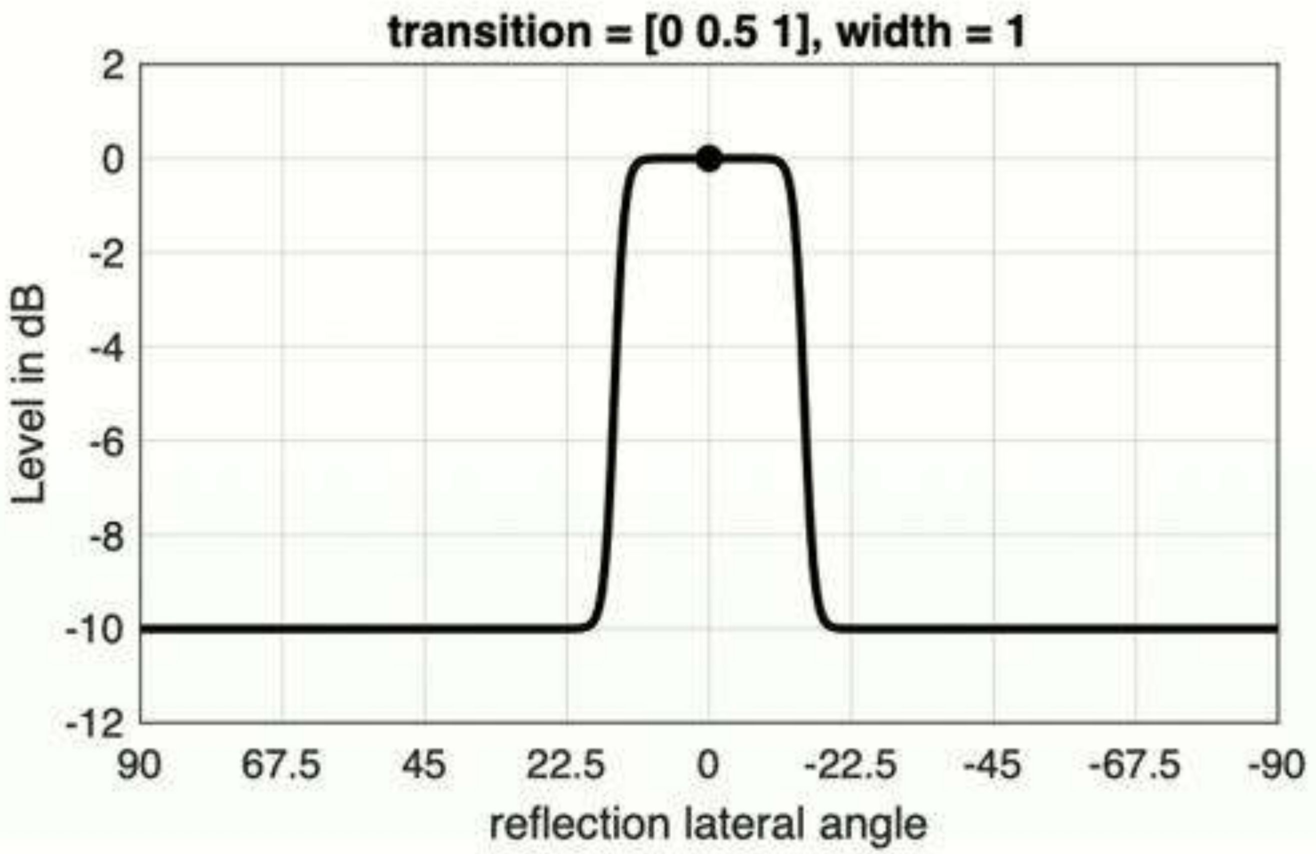




slope: -1 dB/ms

offset: -10 dB

v-shape: add 35% reflection energy to threshold

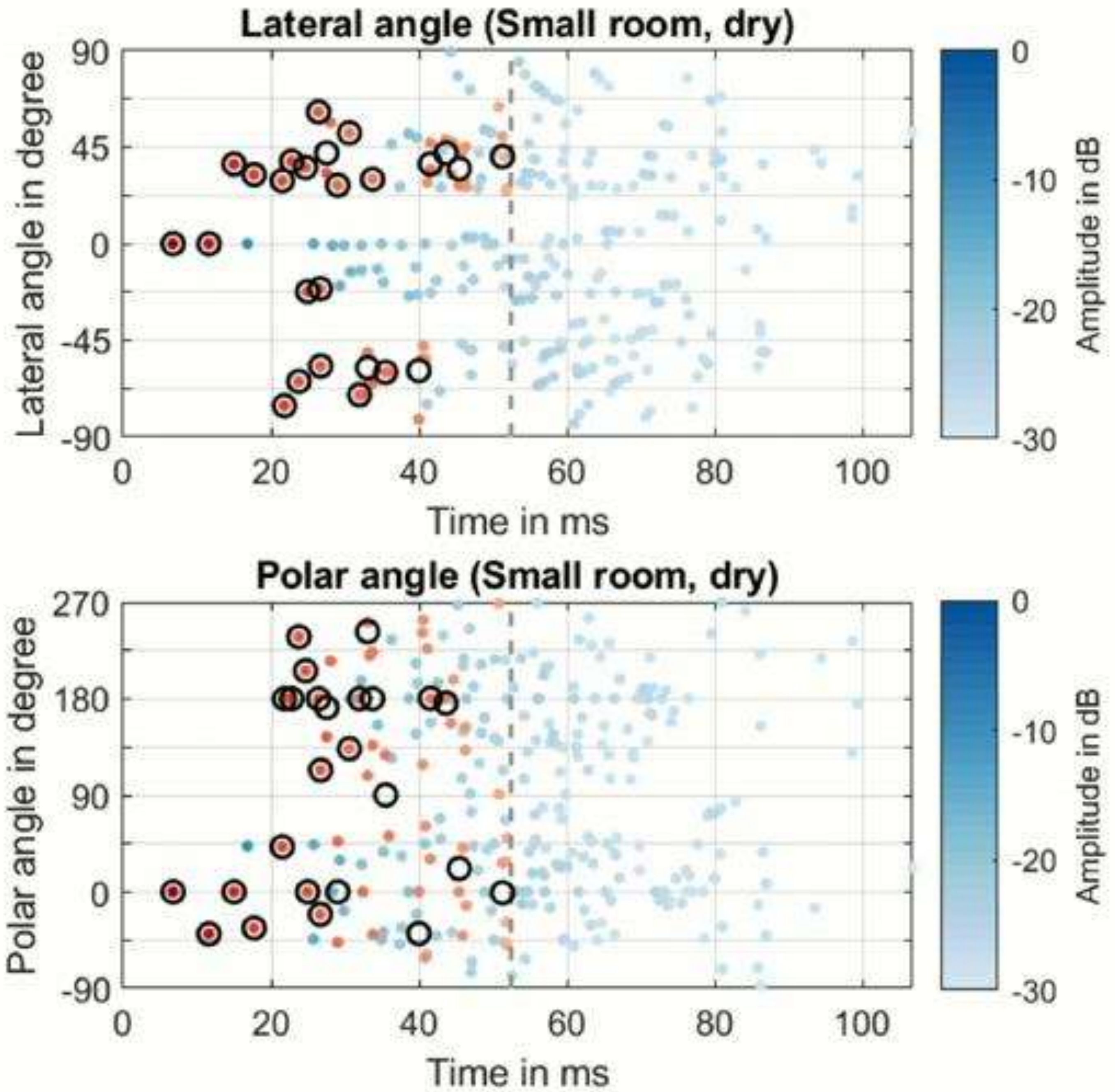
width according to [1]

depth: -10 dB

[1] Best *et al.* (2004): Separation of concurrent broadband sound sources… *J. Acoust. Soc. Am.* **115**(1):324–336.

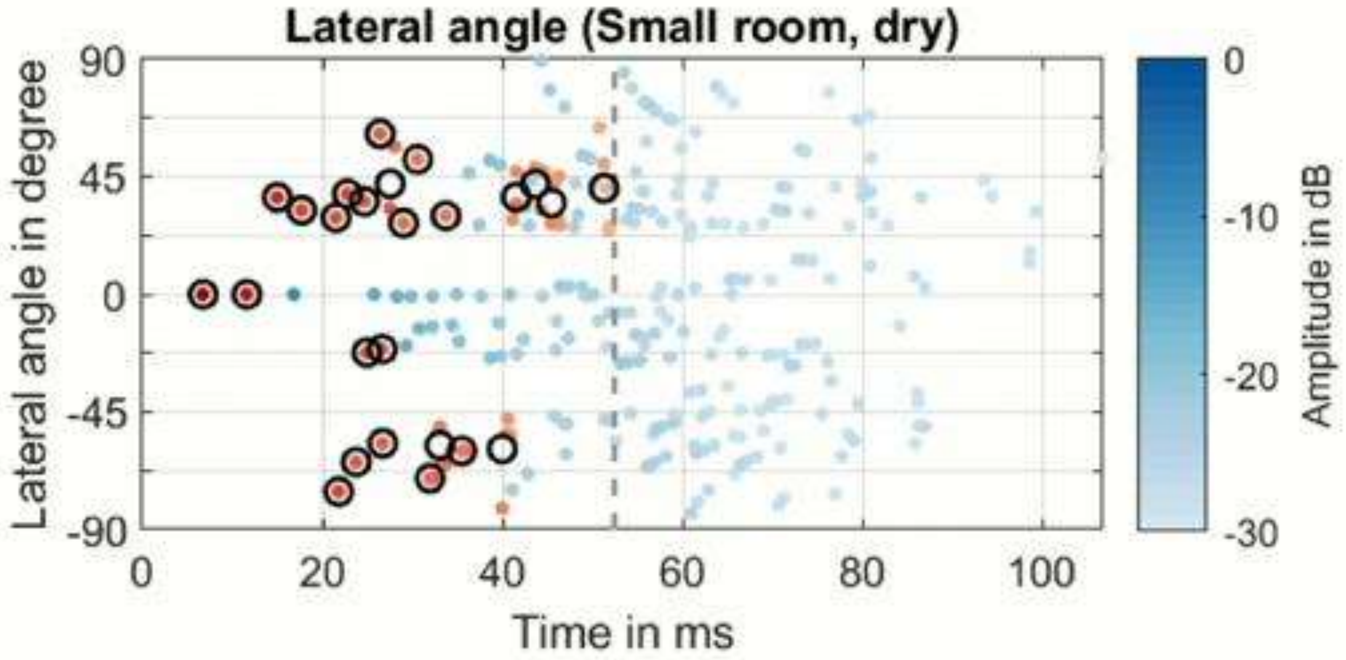
PROPOSED ENCODING: DETECTED REFLECTIONS

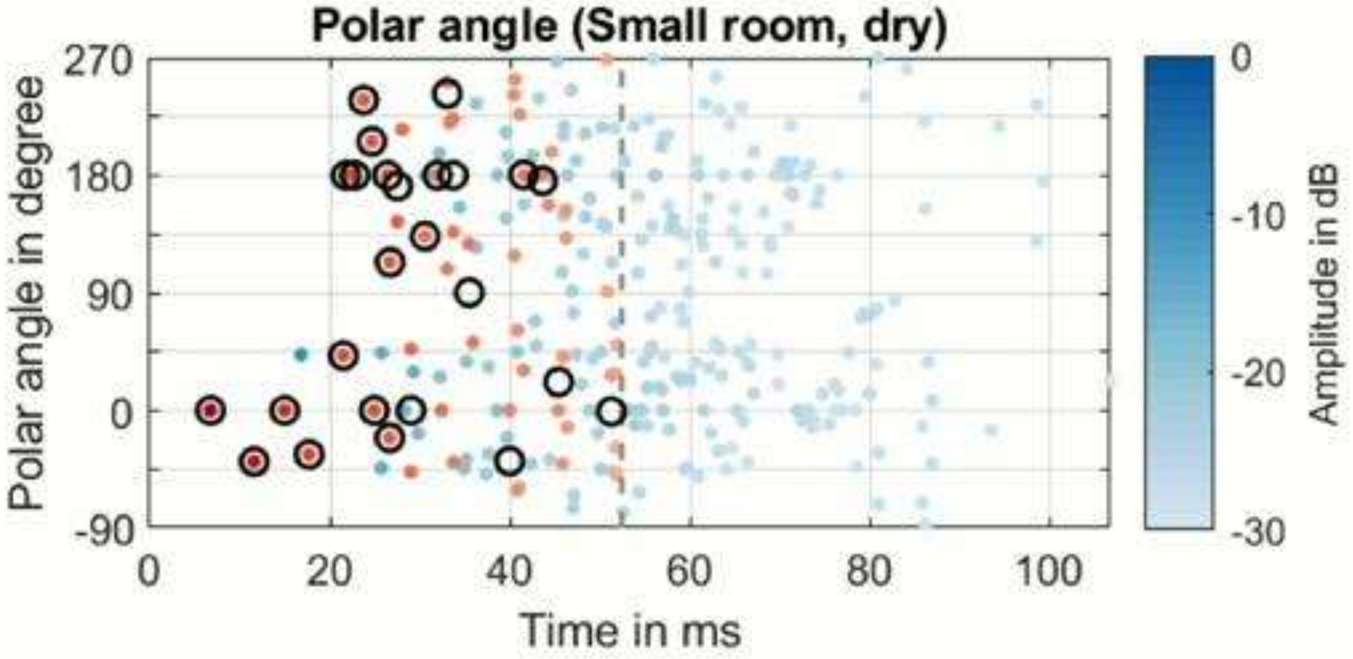
Image source model



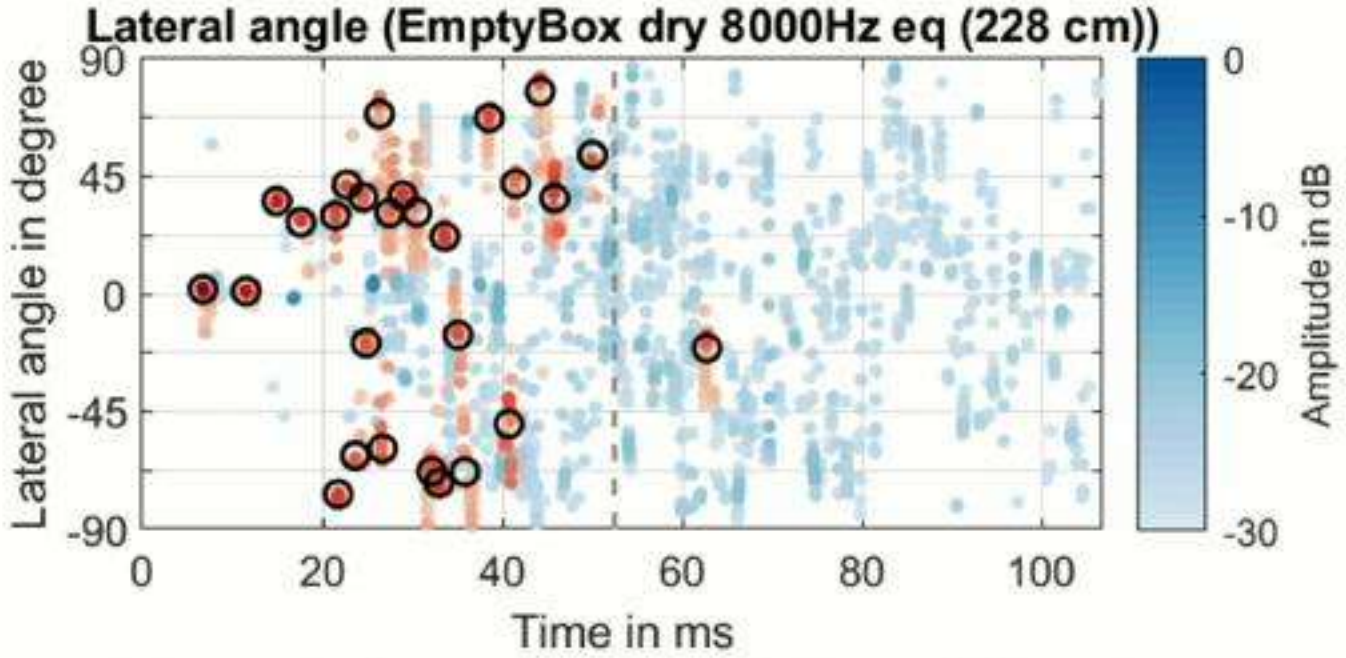
PROPOSED ENCODING: DETECTED REFLECTIONS

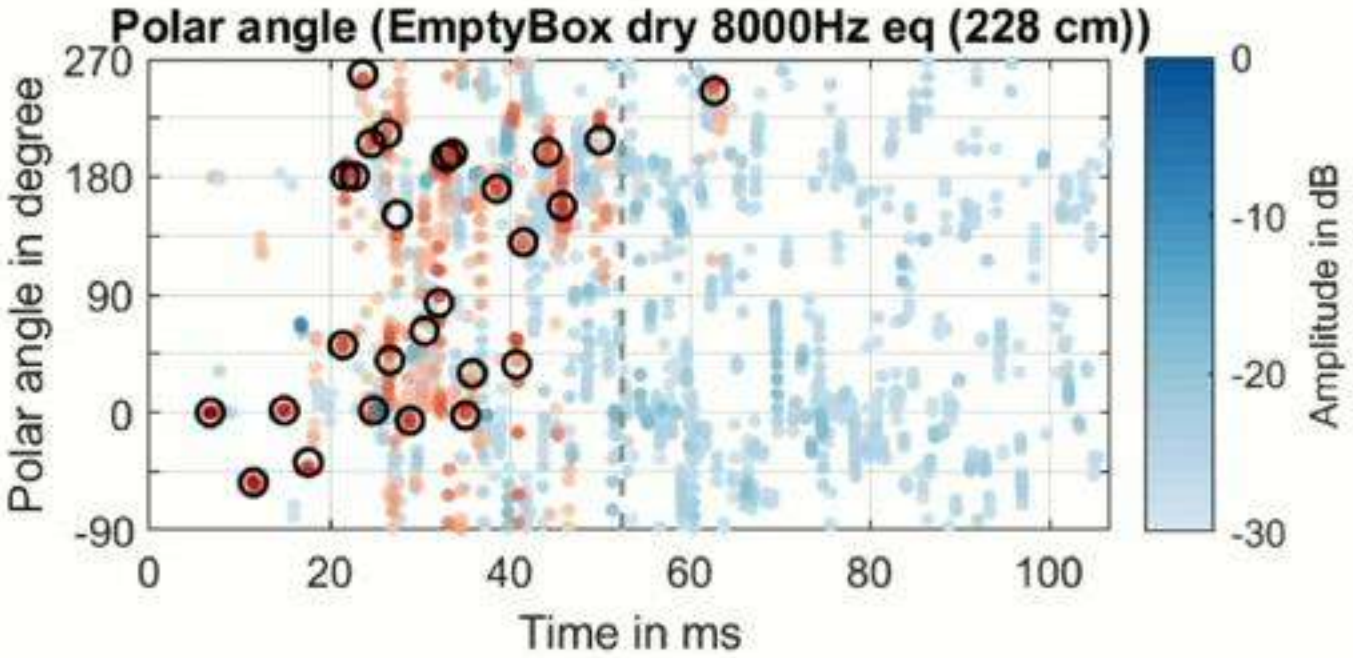
Image source model


Lateral angle (Small room, dry)

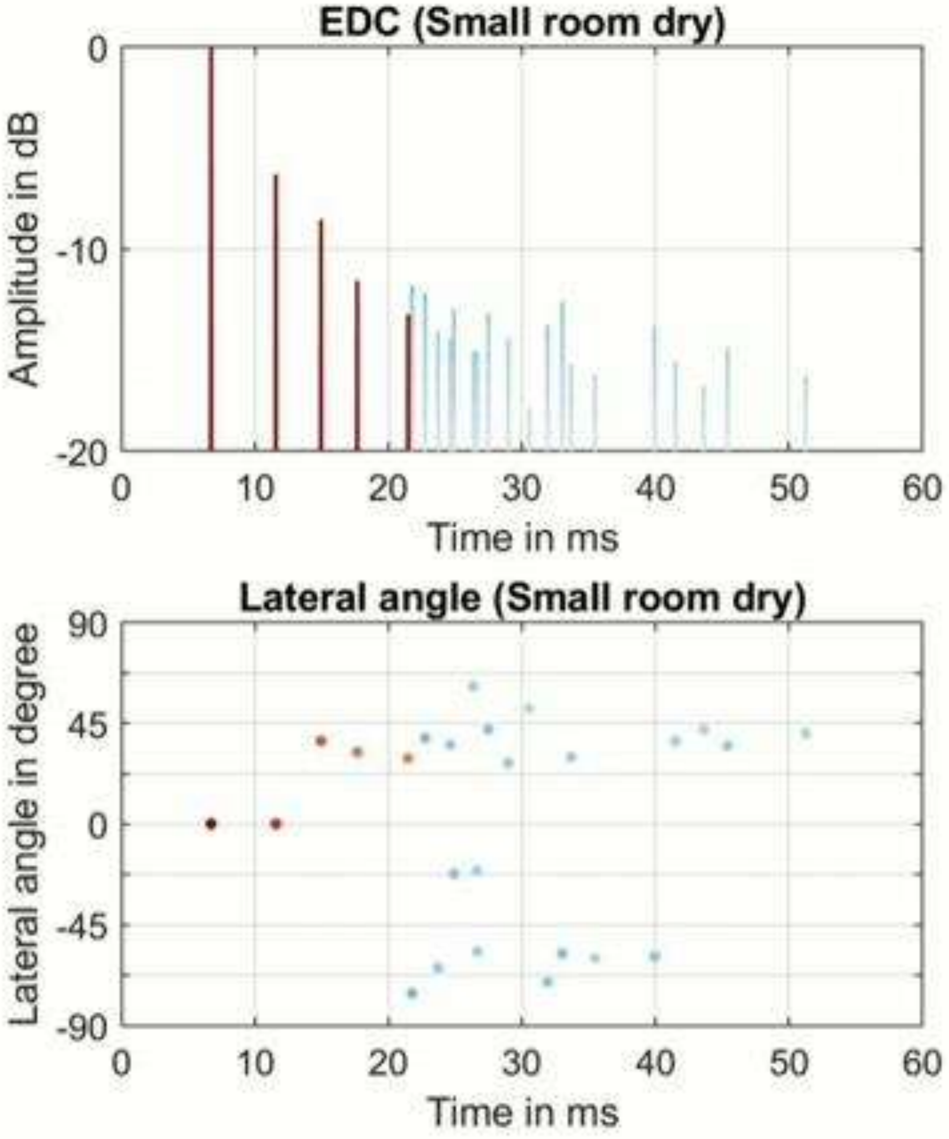

Polar angle (Small room, dry)

Triton


Lateral angle (EmptyBox dry 8000Hz eq (228 cm))

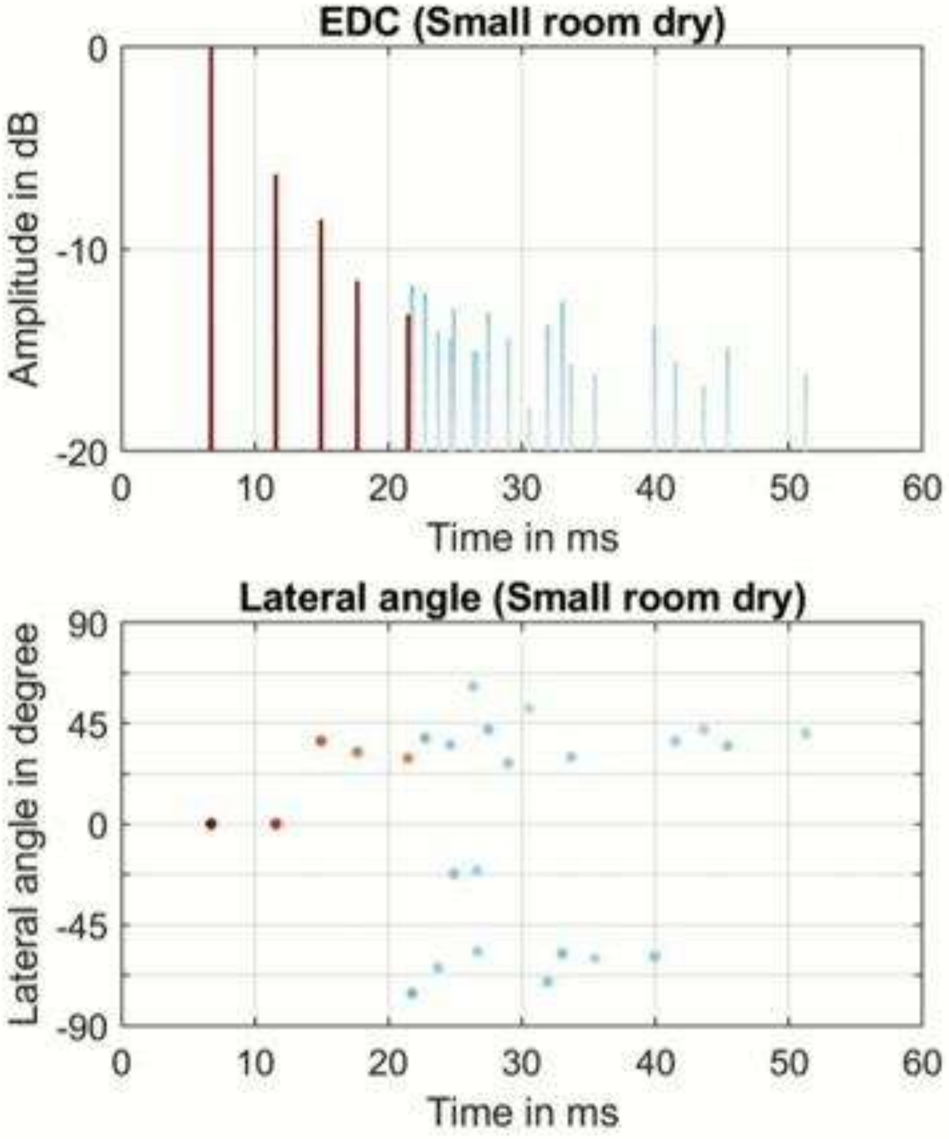

Polar angle (EmptyBox dry 8000Hz eq (228 cm))

PROPOSED ENCODING: SELECTION

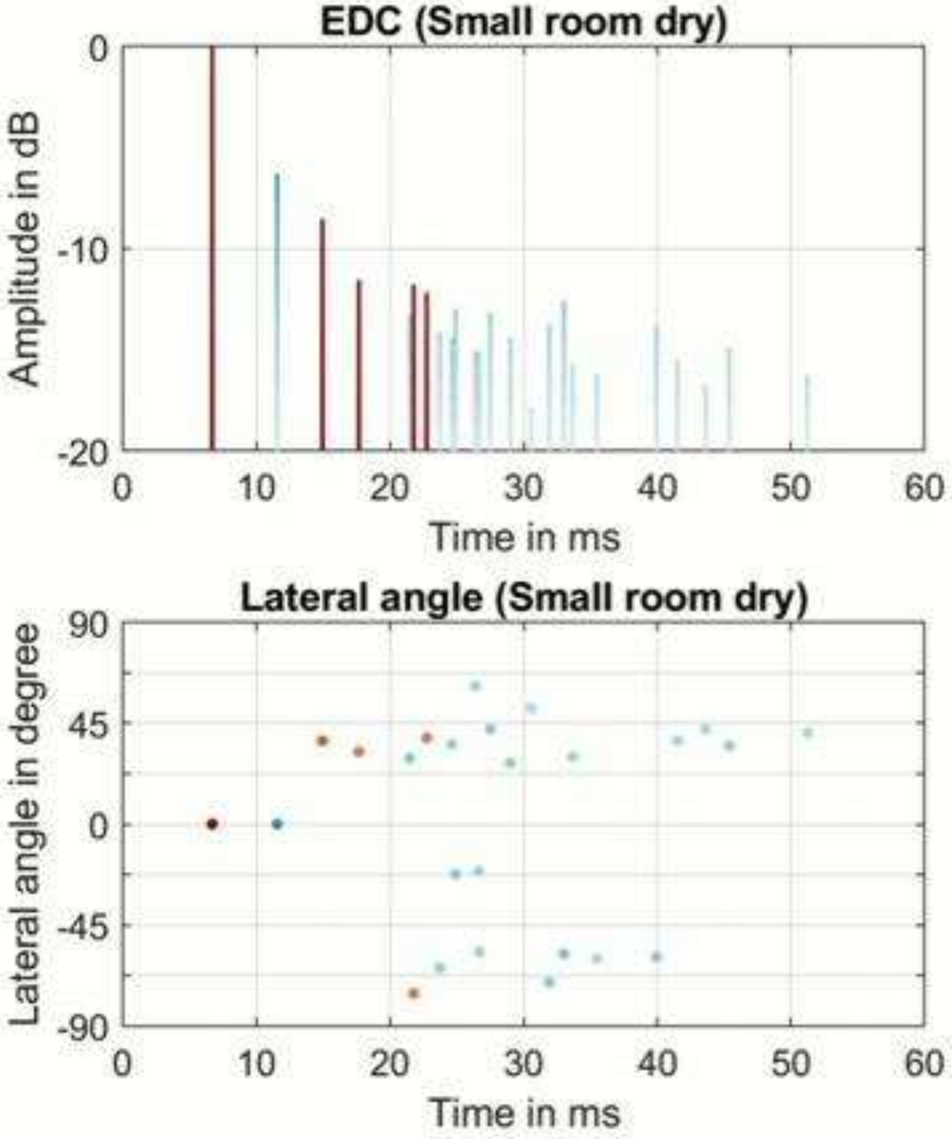


First

PROPOSED ENCODING: SELECTION

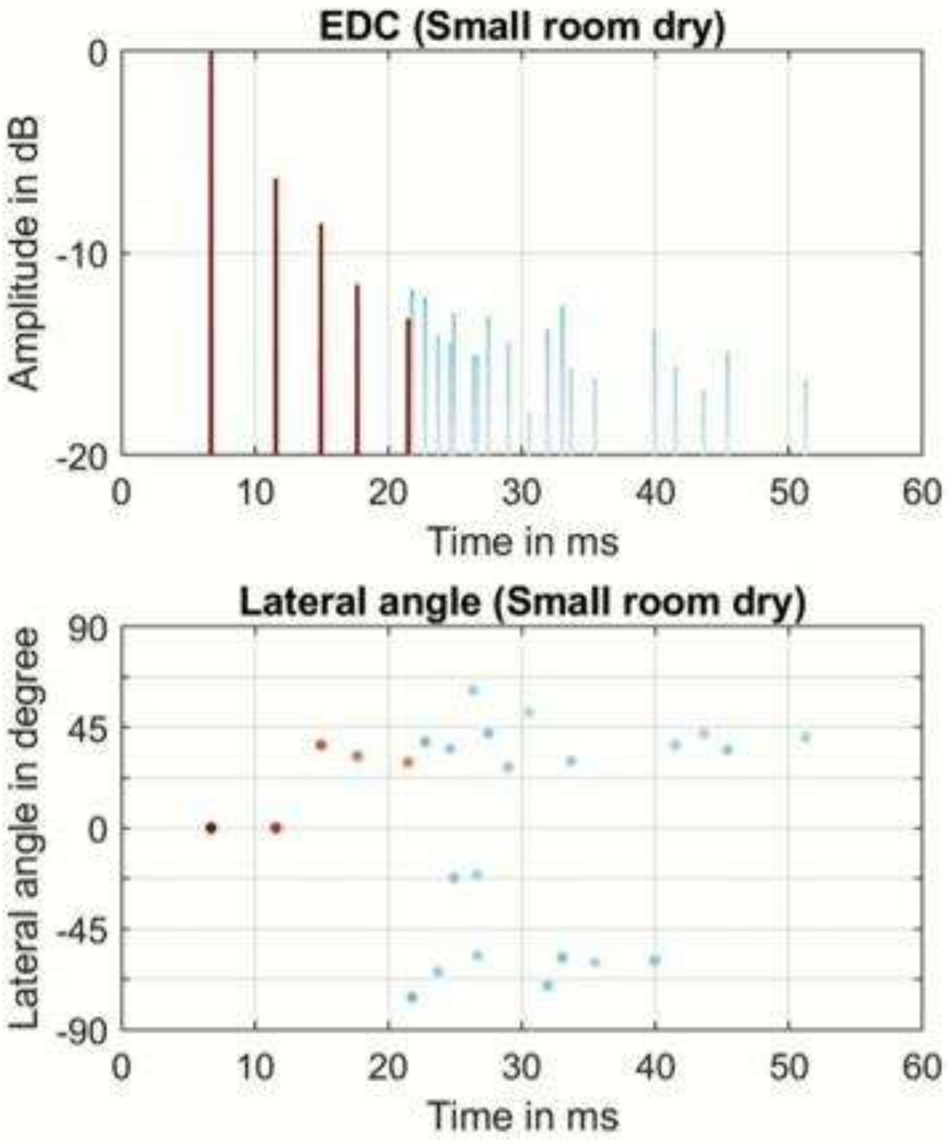


First

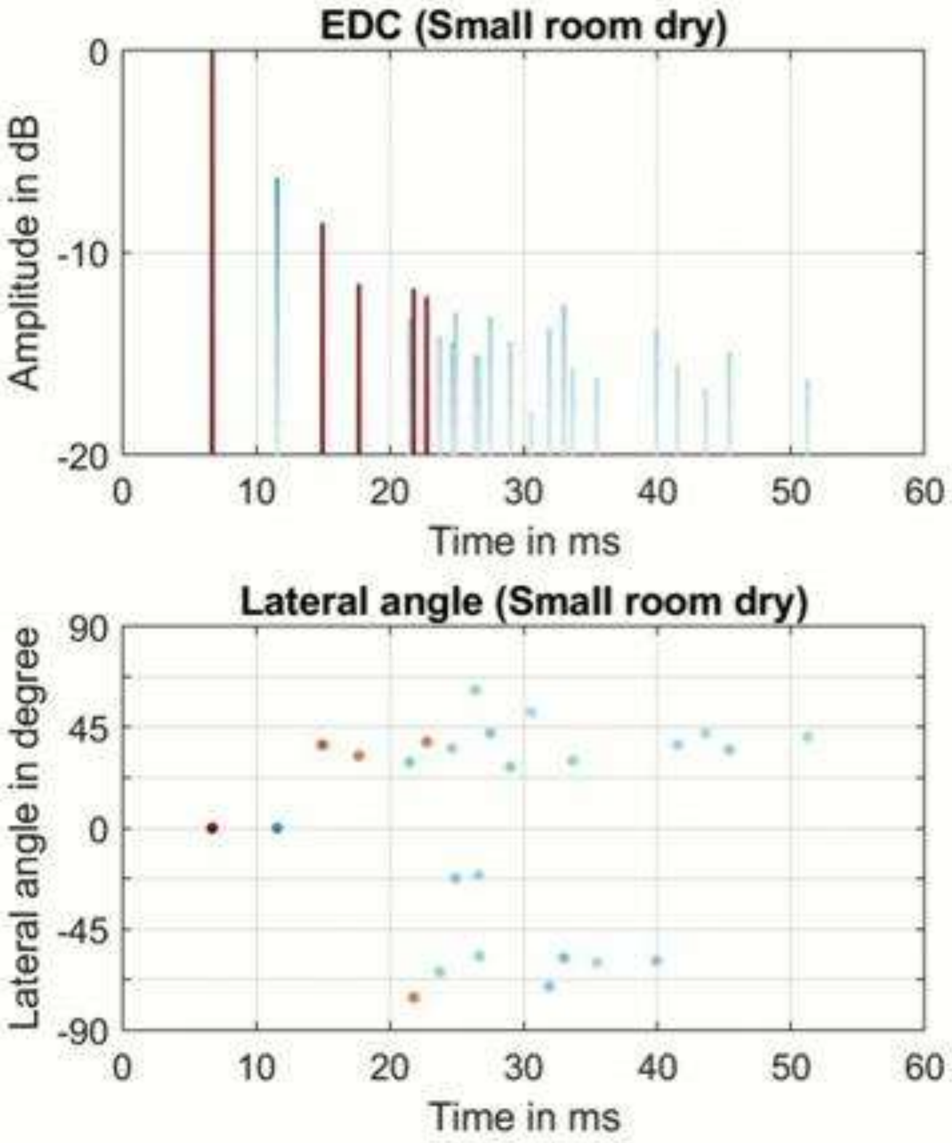


Exceed

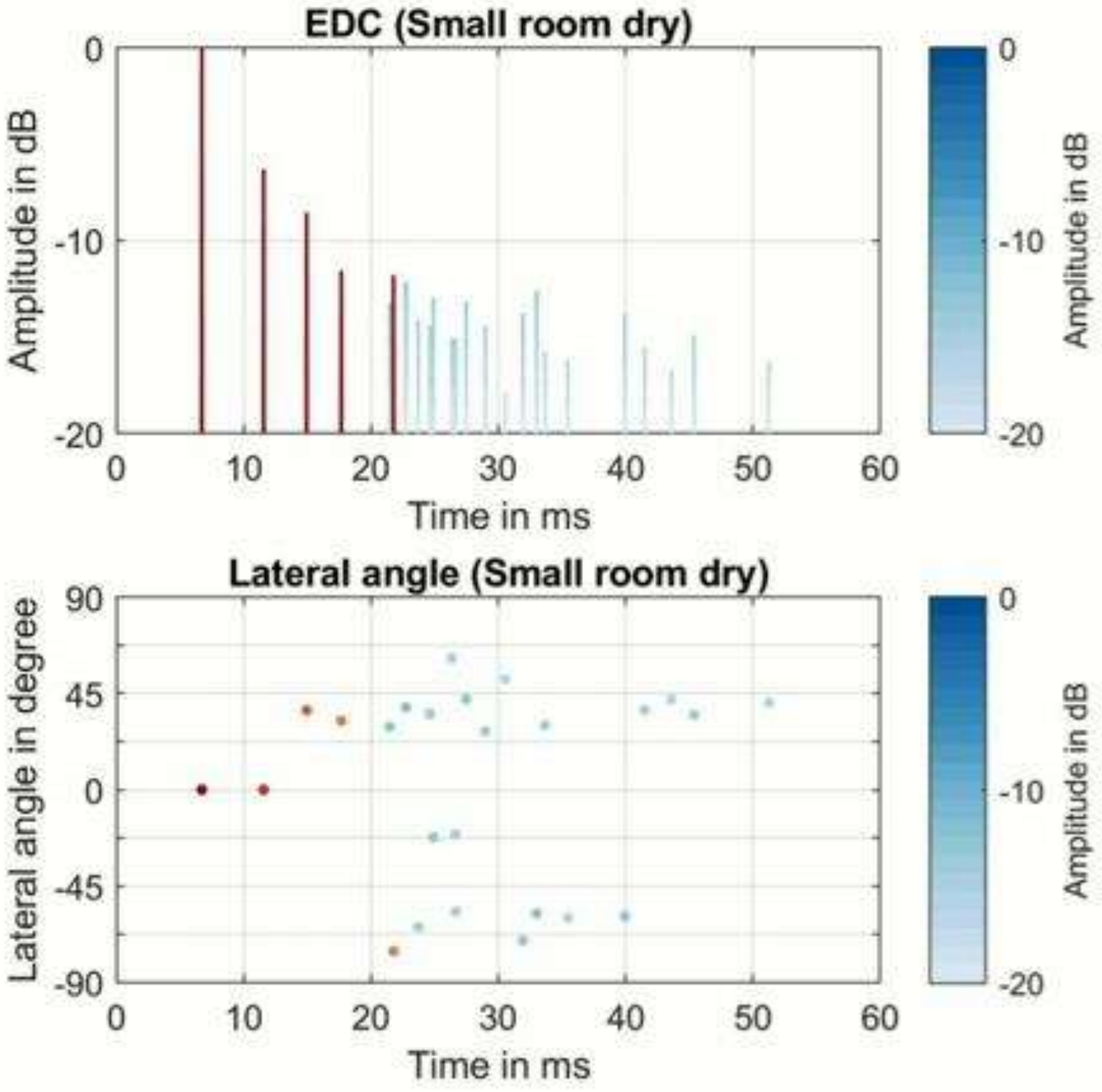
PROPOSED ENCODING: SELECTION



First

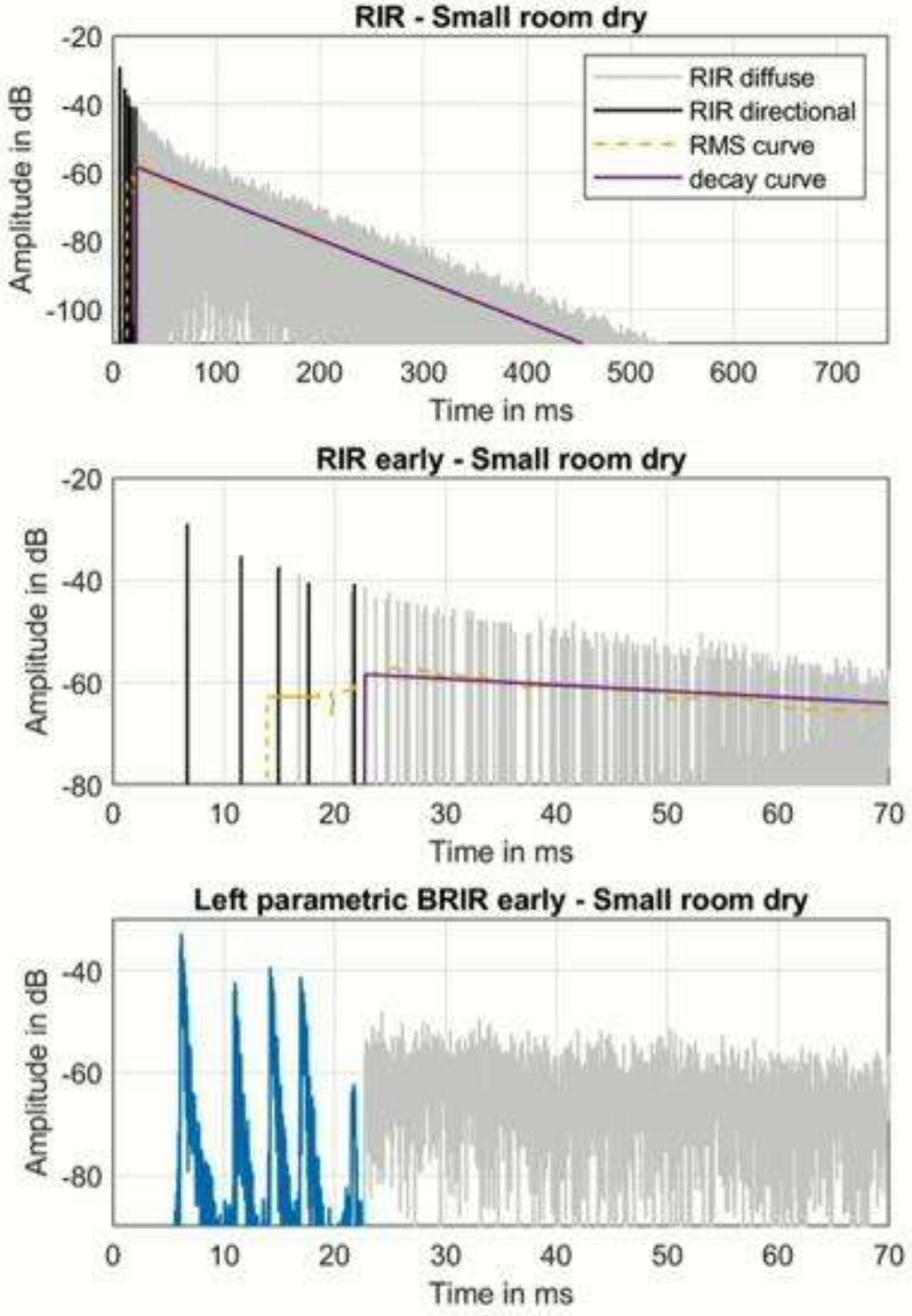


Exceed

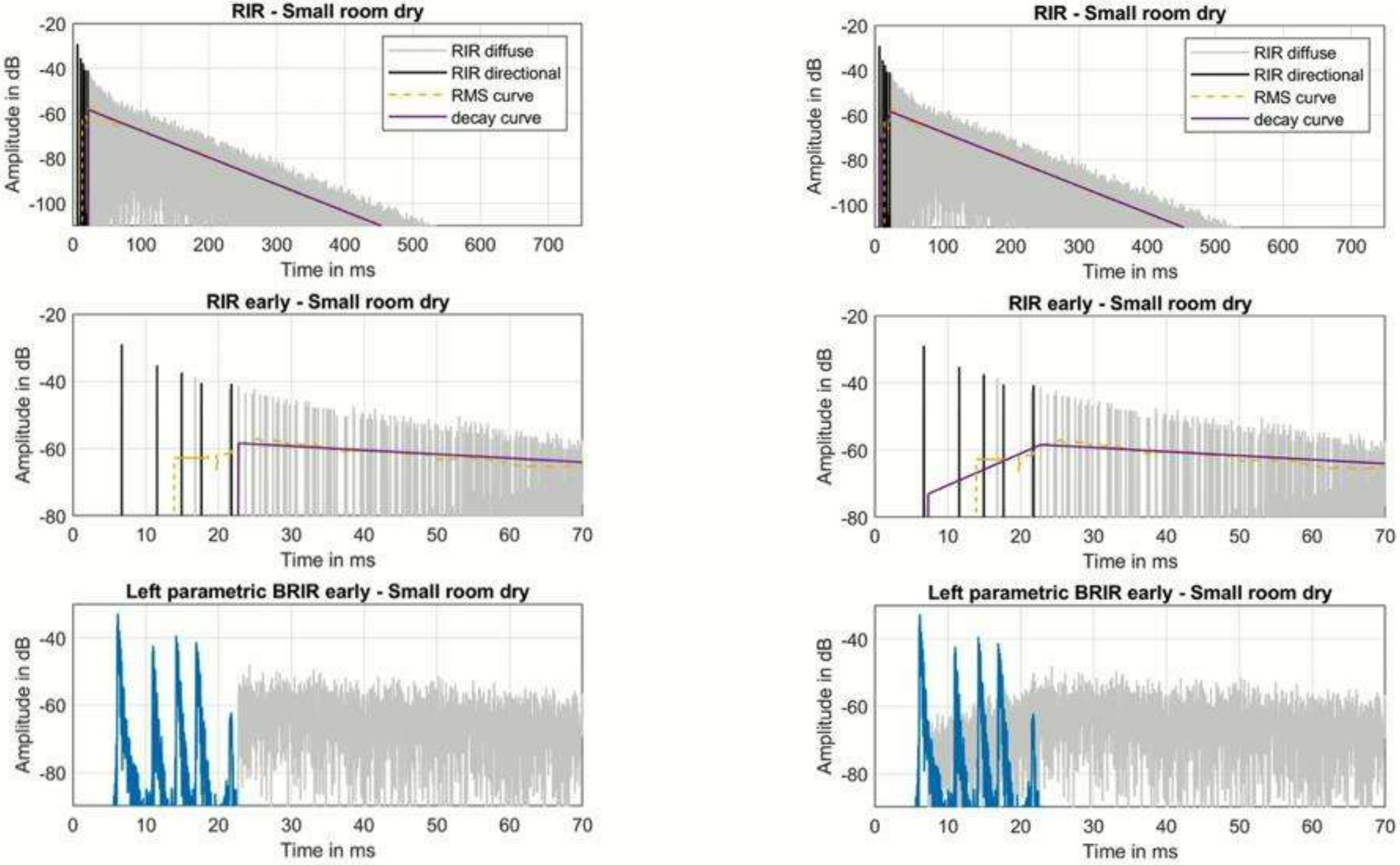


Loudest

PROPOSED ENCODING: LATE REVERBERATION



PROPOSED ENCODING: LATE REVERBERATION



INTRODUCTION

METHOD

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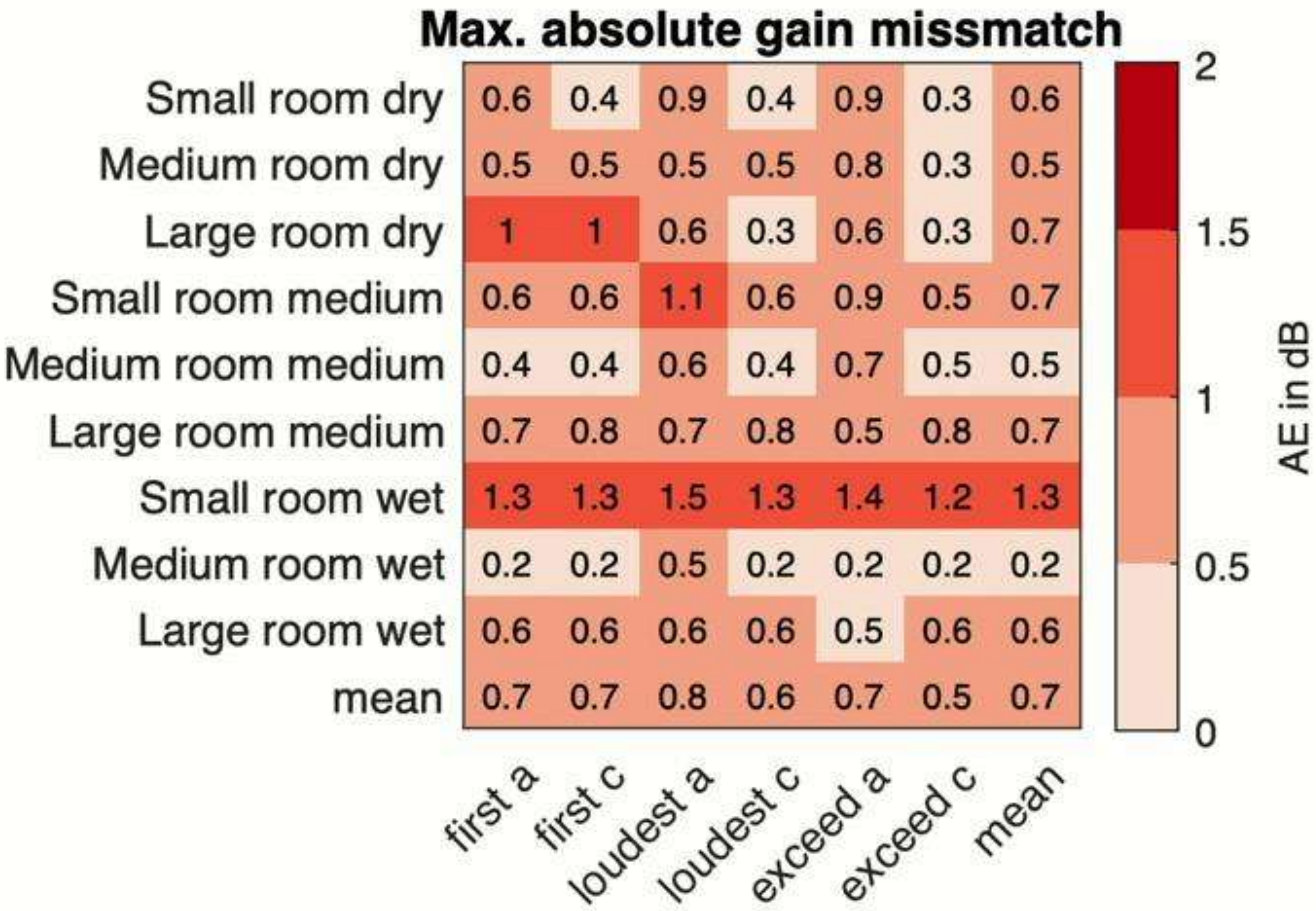
DISCUSSION

PHYSICAL EVALUATION

- 0, 1, 2, 4, 6, 8, 10 and 15 reflections
- Three selection methods (first, exceed, loudest)
- Two late reverberations (single, double ramp)
- Comparison against reference

PHYSICAL EVALUATION

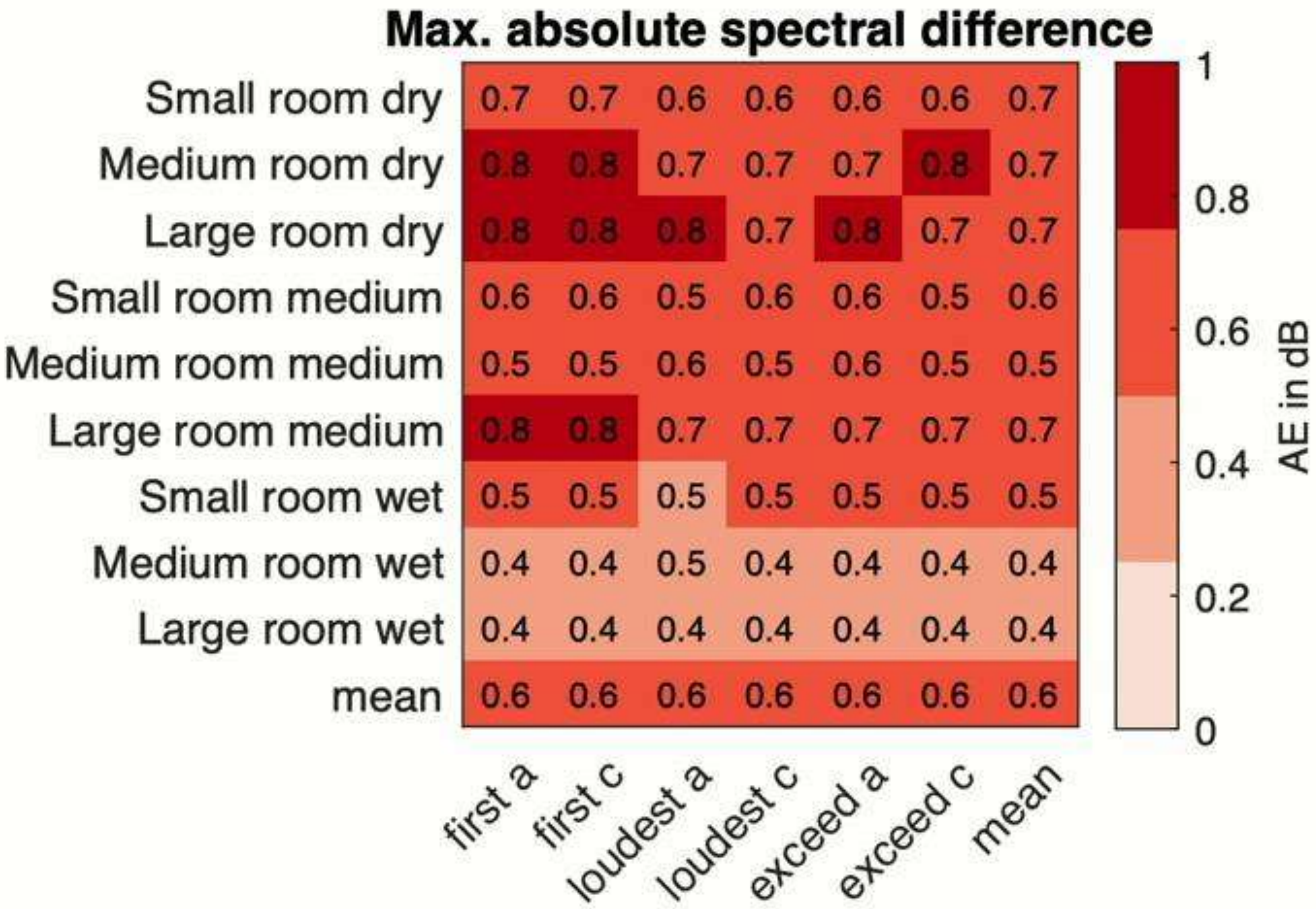


Max. absolute gain missmatch

	first a	first c	loudest a	loudest c	exceed a	exceed c	mean
Small room dry	0.6	0.4	0.9	0.4	0.9	0.3	0.6
Medium room dry	0.5	0.5	0.5	0.5	0.8	0.3	0.5
Large room dry	1	1	0.6	0.3	0.6	0.3	0.7
Small room medium	0.6	0.6	1.1	0.6	0.9	0.5	0.7
Medium room medium	0.4	0.4	0.6	0.4	0.7	0.5	0.5
Large room medium	0.7	0.8	0.7	0.8	0.5	0.8	0.7
Small room wet	1.3	1.3	1.5	1.3	1.4	1.2	1.3
Medium room wet	0.2	0.2	0.5	0.2	0.2	0.2	0.2
Large room wet	0.6	0.6	0.6	0.6	0.5	0.6	0.6
mean	0.7	0.7	0.8	0.6	0.7	0.5	0.7

- Good level preservation
- Slightly audible differences
- Minor differences across algorithms

PHYSICAL EVALUATION

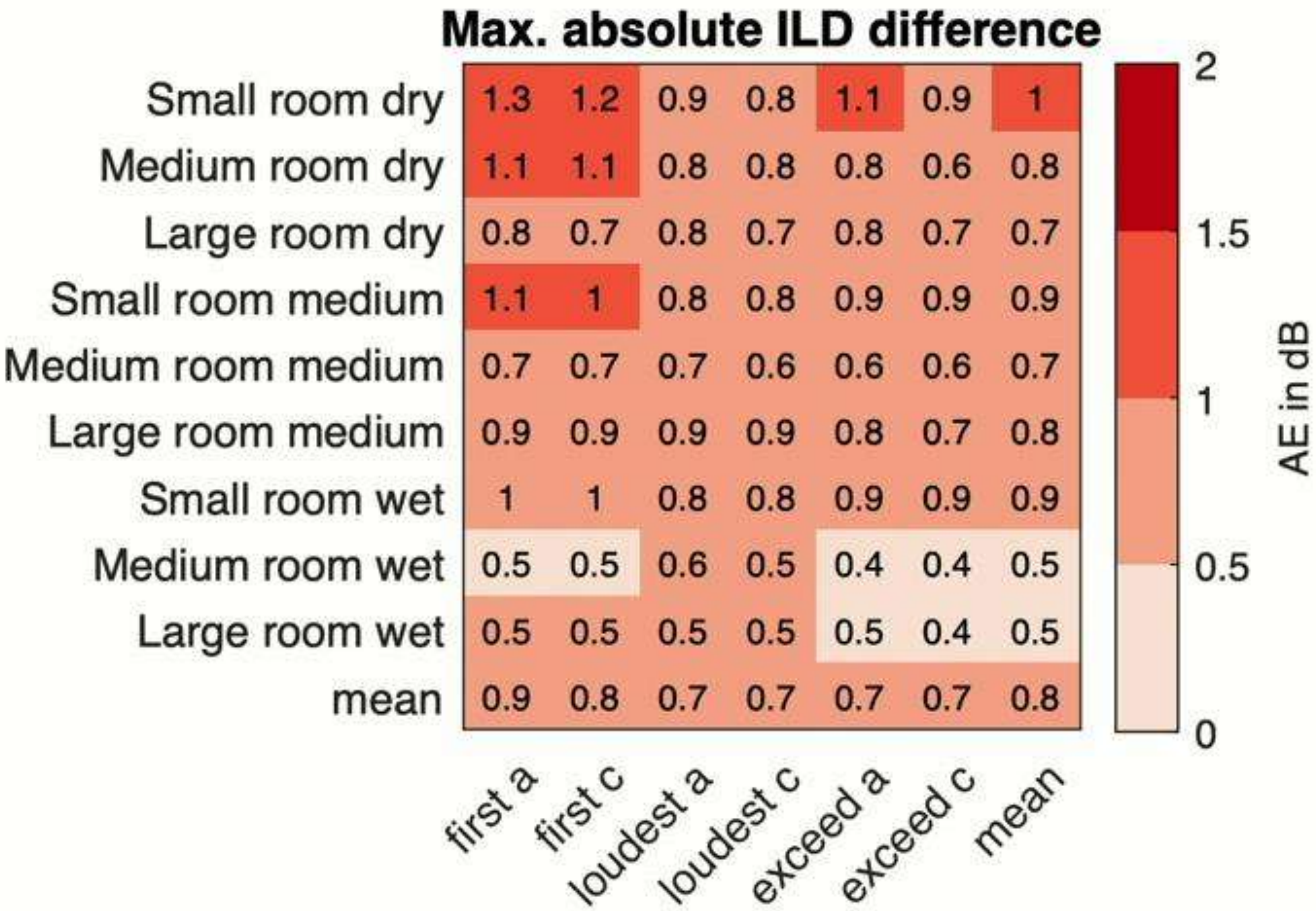


Max. absolute spectral difference

	first a	first c	loudest a	loudest c	exceed a	exceed c	mean
Small room dry	0.7	0.7	0.6	0.6	0.6	0.6	0.7
Medium room dry	0.8	0.8	0.7	0.7	0.7	0.8	0.7
Large room dry	0.8	0.8	0.8	0.7	0.8	0.7	0.7
Small room medium	0.6	0.6	0.5	0.6	0.6	0.5	0.6
Medium room medium	0.5	0.5	0.6	0.5	0.6	0.5	0.5
Large room medium	0.8	0.8	0.7	0.7	0.7	0.7	0.7
Small room wet	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Medium room wet	0.4	0.4	0.5	0.4	0.4	0.4	0.4
Large room wet	0.4	0.4	0.4	0.4	0.4	0.4	0.4
mean	0.6	0.6	0.6	0.6	0.6	0.6	0.6

- Slightly audible coloration
- Minor differences across algorithms

PHYSICAL EVALUATION

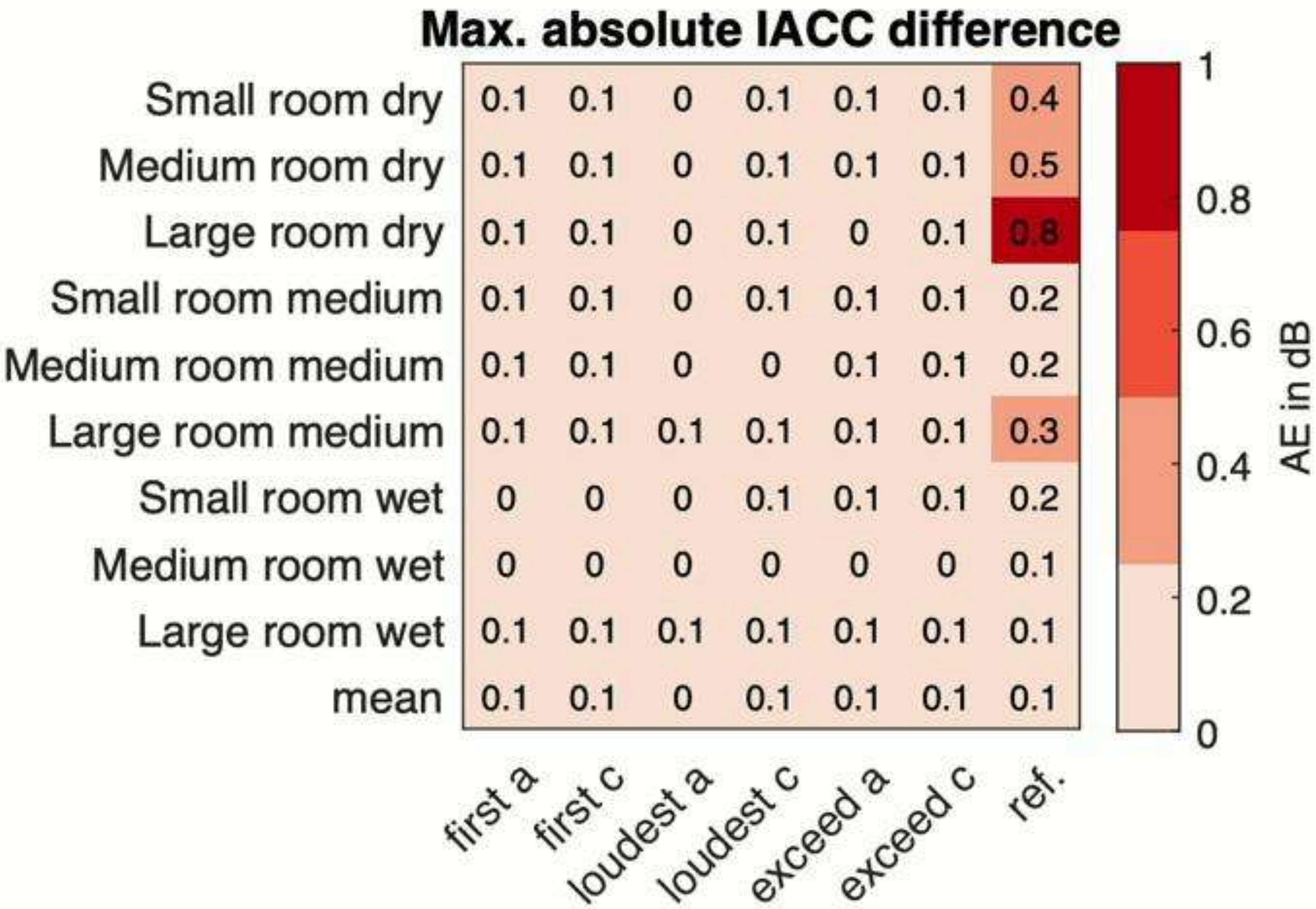


Max. absolute ILD difference

	first a	first c	loudest a	loudest c	exceed a	exceed c	mean
Small room dry	1.3	1.2	0.9	0.8	1.1	0.9	1
Medium room dry	1.1	1.1	0.8	0.8	0.8	0.6	0.8
Large room dry	0.8	0.7	0.8	0.7	0.8	0.7	0.7
Small room medium	1.1	1	0.8	0.8	0.9	0.9	0.9
Medium room medium	0.7	0.7	0.7	0.6	0.6	0.6	0.7
Large room medium	0.9	0.9	0.9	0.9	0.8	0.7	0.8
Small room wet	1	1	0.8	0.8	0.9	0.9	0.9
Medium room wet	0.5	0.5	0.6	0.5	0.4	0.4	0.5
Large room wet	0.5	0.5	0.5	0.5	0.5	0.4	0.5
mean	0.9	0.8	0.7	0.7	0.7	0.7	0.8

- Slight mismatches in source position
- Minor differences across algorithms

PHYSICAL EVALUATION



Max. absolute IACC difference

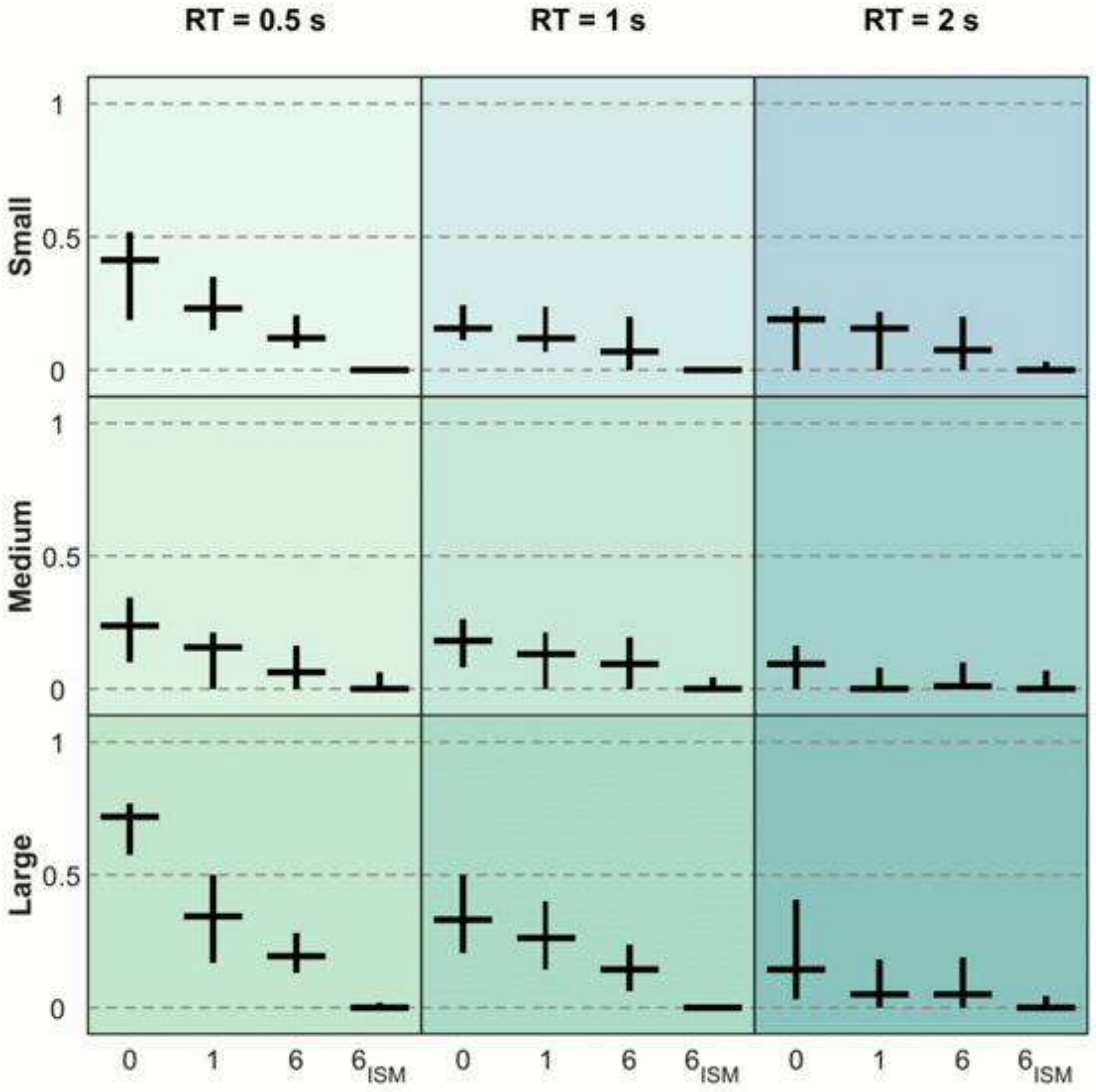
	first a	first c	loudest a	loudest c	exceed a	exceed c	ref.
Small room dry	0.1	0.1	0	0.1	0.1	0.1	0.4
Medium room dry	0.1	0.1	0	0.1	0.1	0.1	0.5
Large room dry	0.1	0.1	0	0.1	0	0.1	0.8
Small room medium	0.1	0.1	0	0.1	0.1	0.1	0.2
Medium room medium	0.1	0.1	0	0	0.1	0.1	0.2
Large room medium	0.1	0.1	0.1	0.1	0.1	0.1	0.3
Small room wet	0	0	0	0.1	0.1	0.1	0.2
Medium room wet	0	0	0	0	0	0	0.1
Large room wet	0.1	0.1	0.1	0.1	0.1	0.1	0.1
mean	0.1	0.1	0	0.1	0.1	0.1	0.1

- Slight mismatches in source width & envelopment
- Minor differences across algorithms

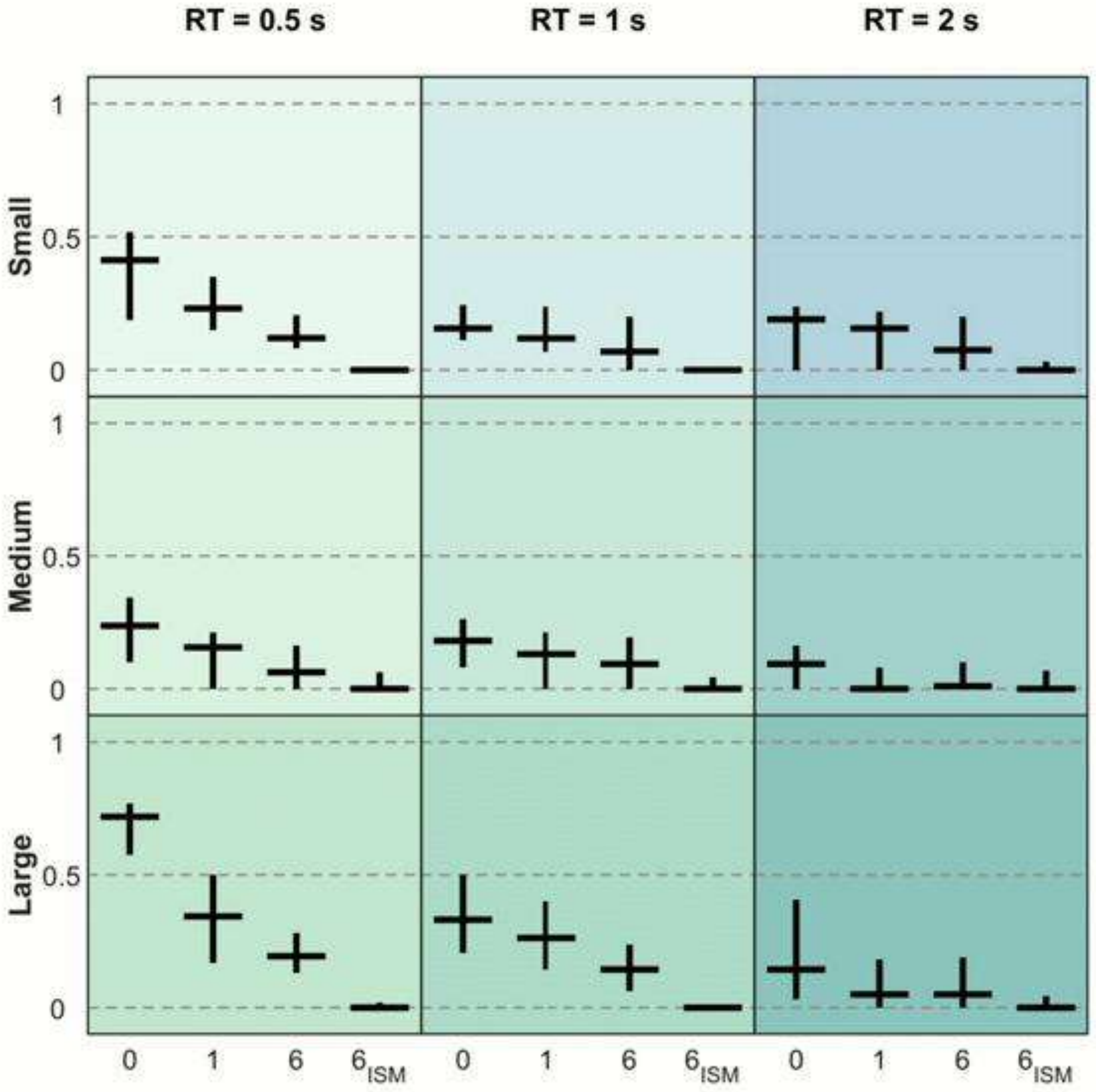
PERCEPTUAL EVALUATION

- 27 participants (5 female, 22 male, 38 yrs.)
- 0, 1, and 6 reflections
- First order image source model as anchor (6_{ISM})
- ‘Loudest’ selection method
- ‘Double sloped’ late reverberation
- Running anechoic speech
- Rated against reference

PERCEPTUAL EVALUATION

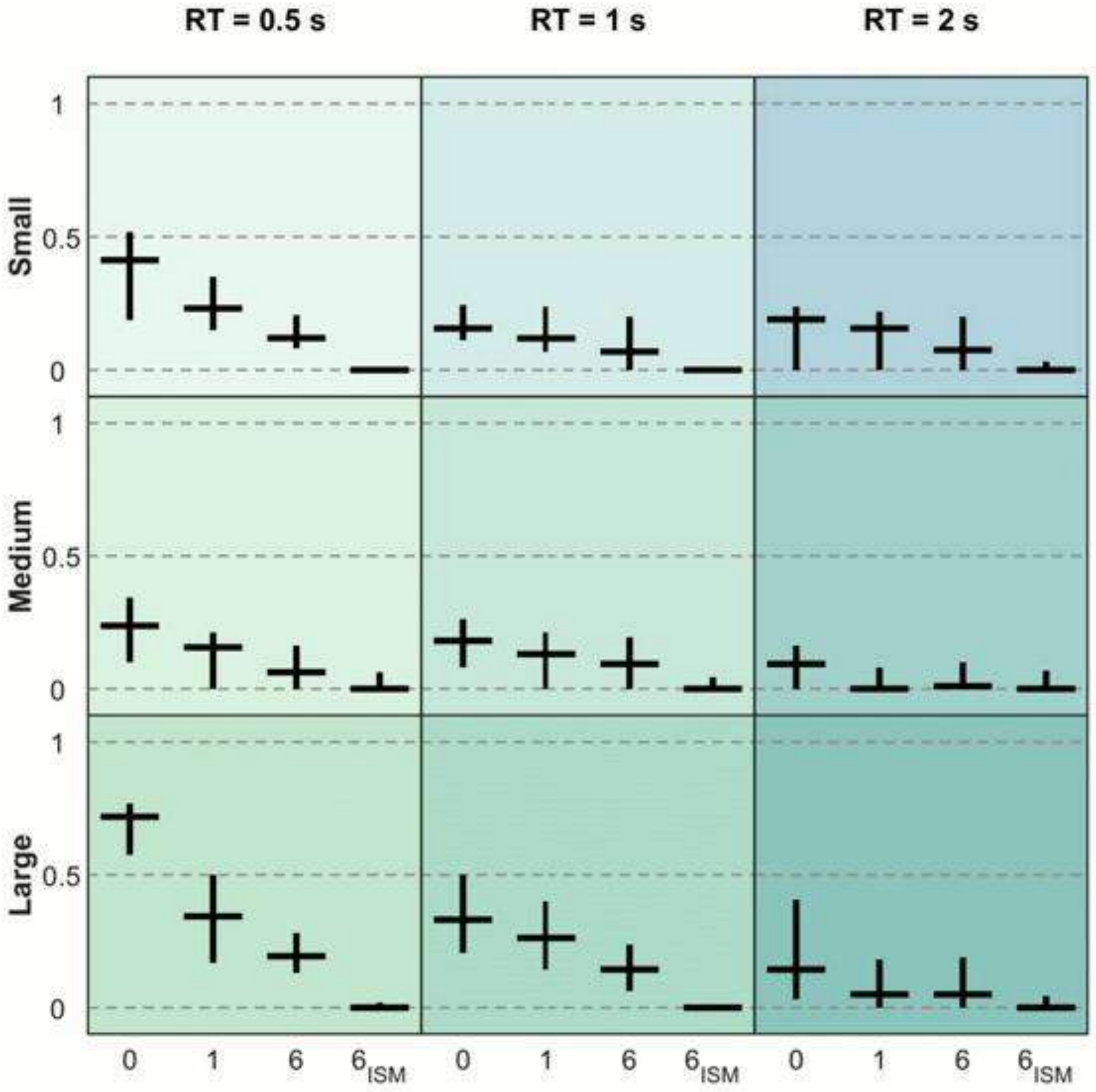


PERCEPTUAL EVALUATION



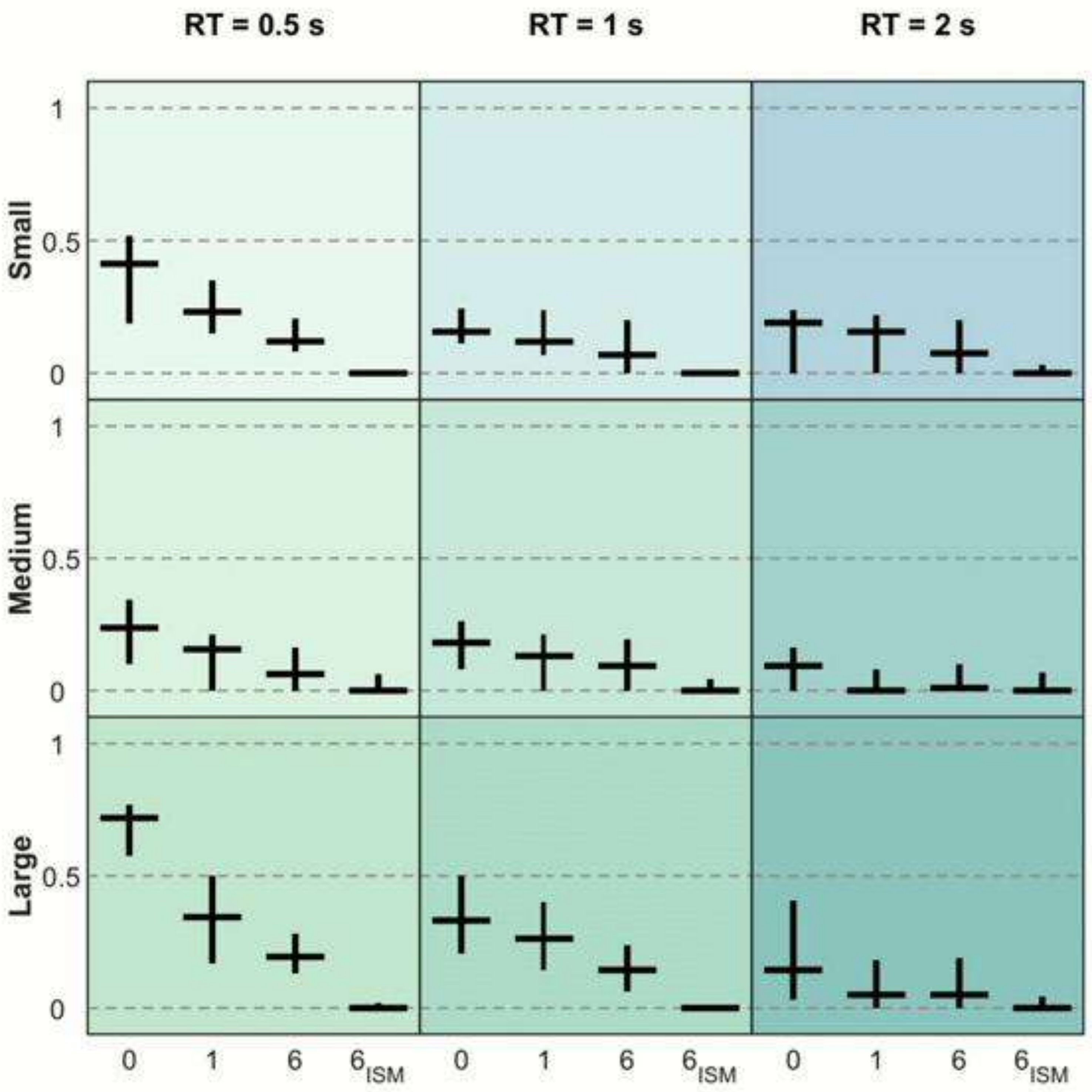
- Differences decrease with **N**

PERCEPTUAL EVALUATION



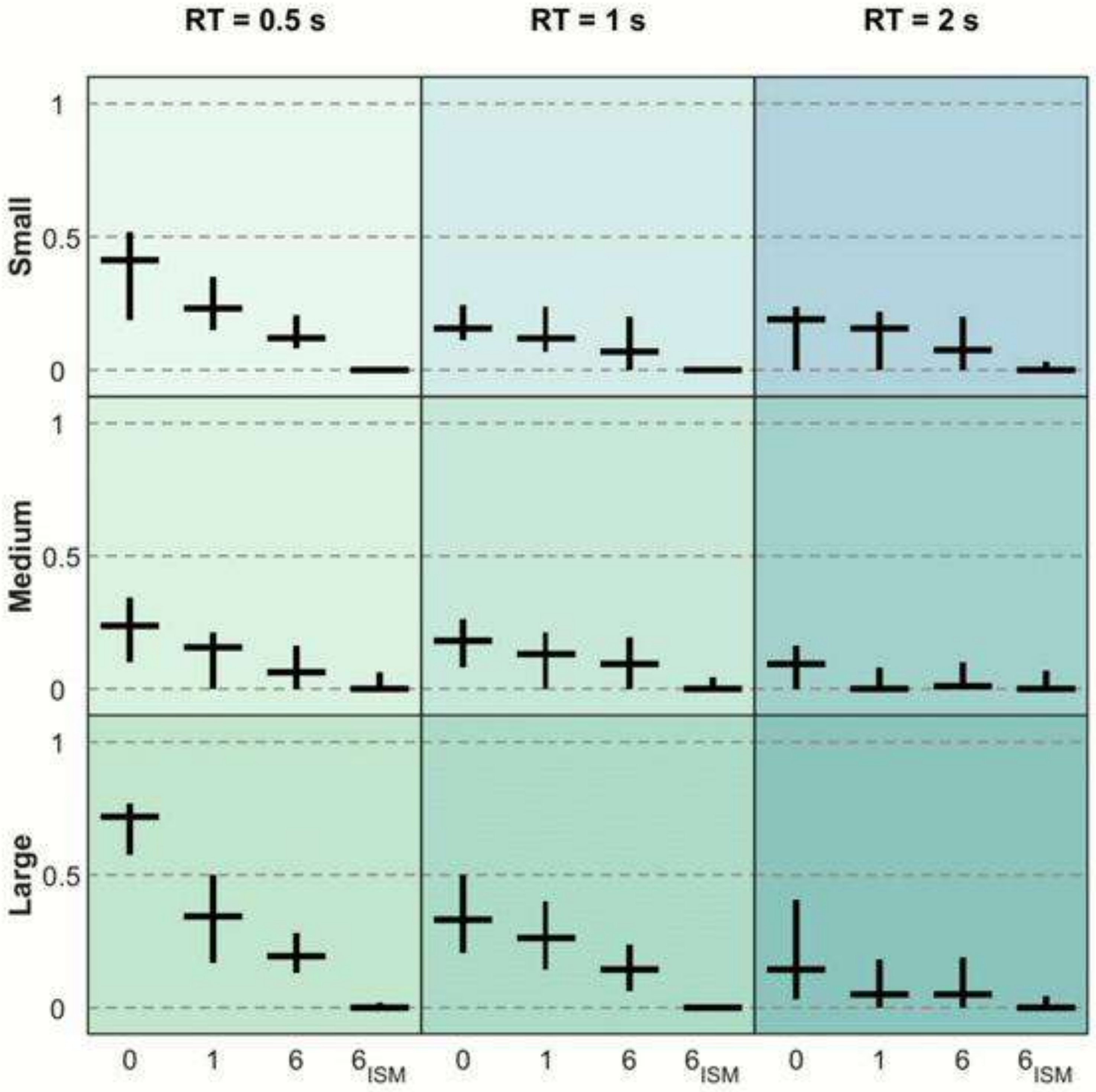
- Differences decrease with **N**
- 6_{ISM} is always rated 0

PERCEPTUAL EVALUATION



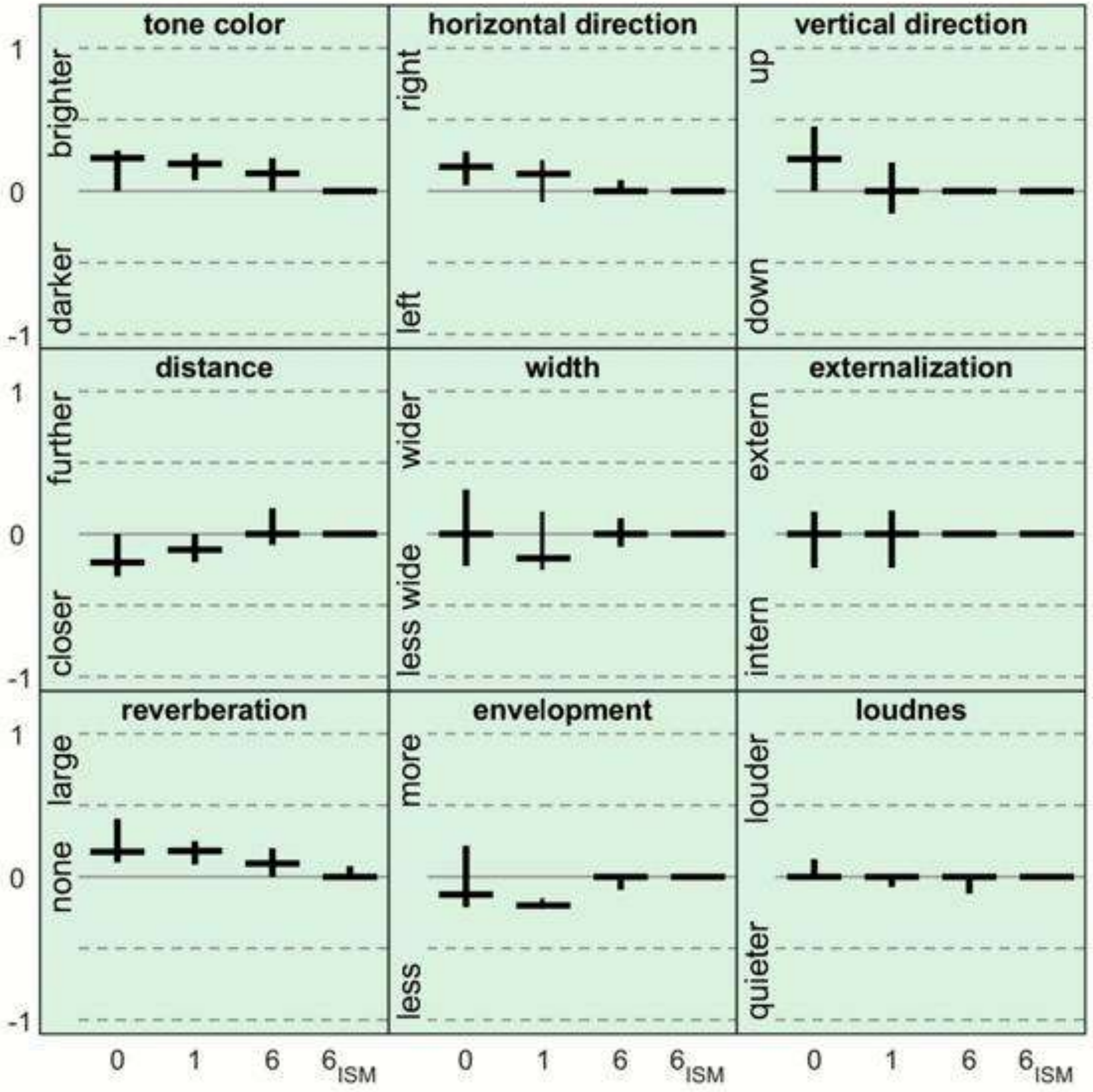
- Differences decrease with **N**
- 6_{ISM} is always rated 0
- Differences decrease with **RT**

PERCEPTUAL EVALUATION

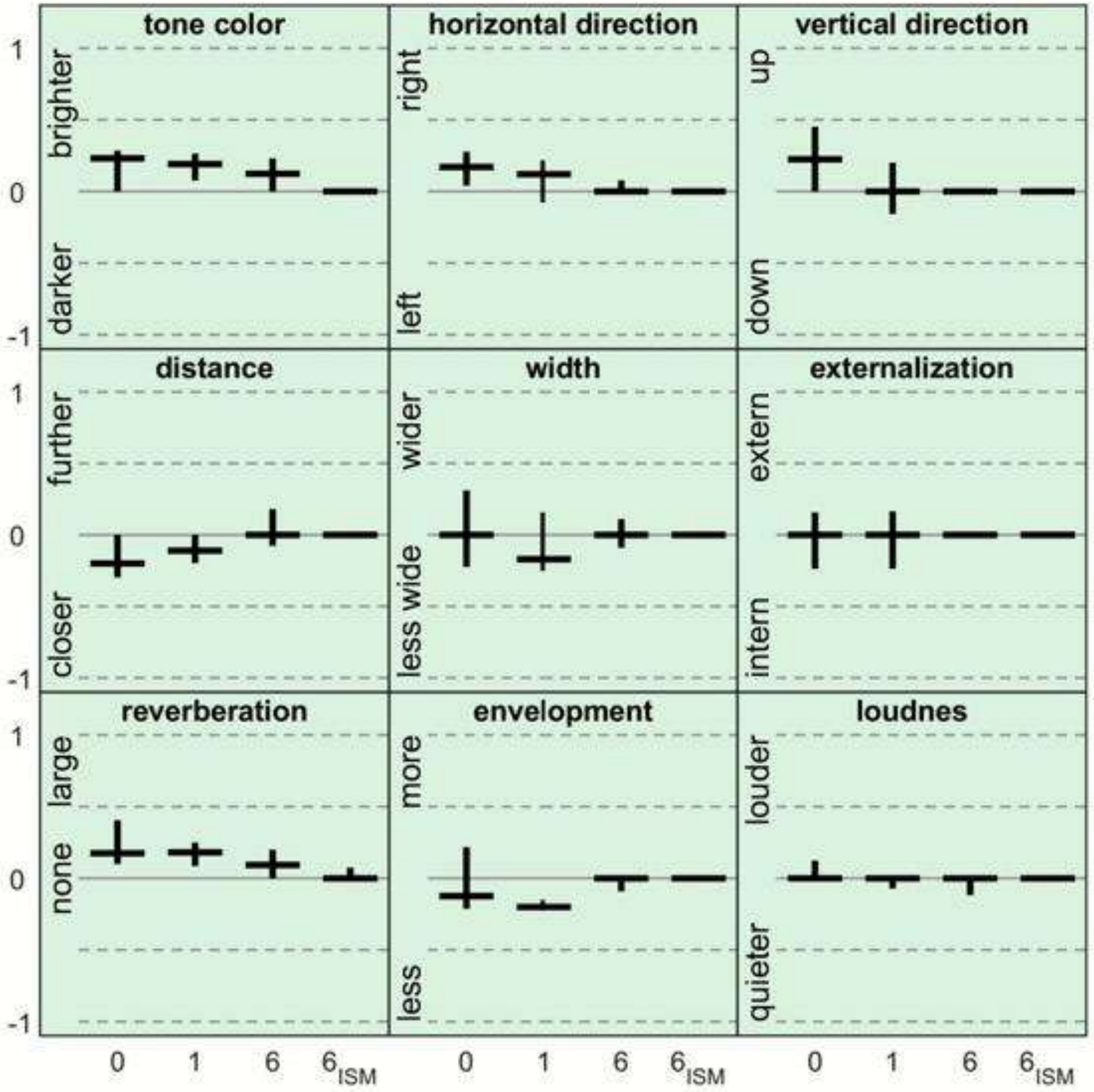


- Differences decrease with **N**
- 6_{ISM} is always rated 0
- Differences decrease with **RT**
- Effect of **V** (?)

PERCEPTUAL EVALUATION



PERCEPTUAL EVALUATION



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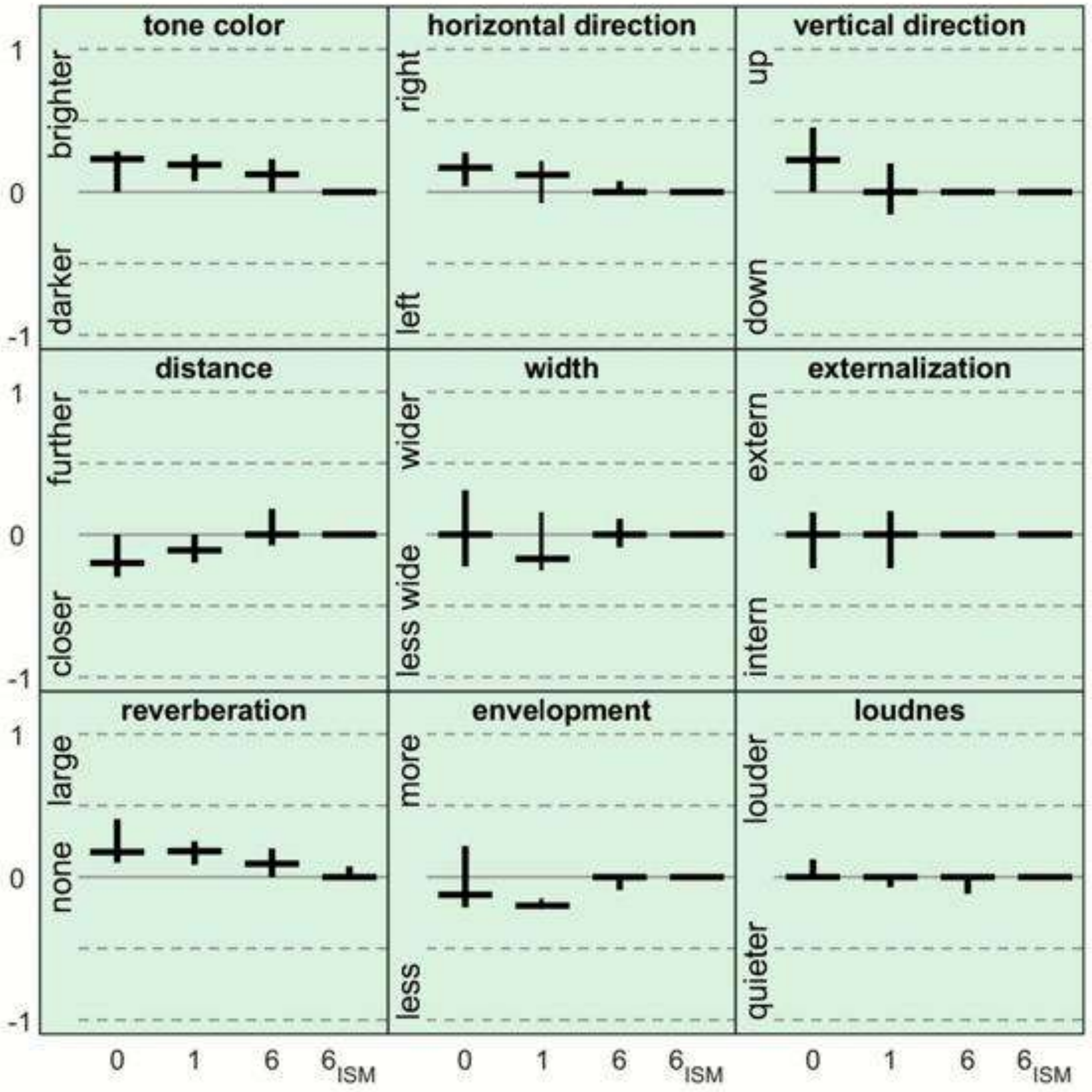
PERCEPTUAL EVALUATION



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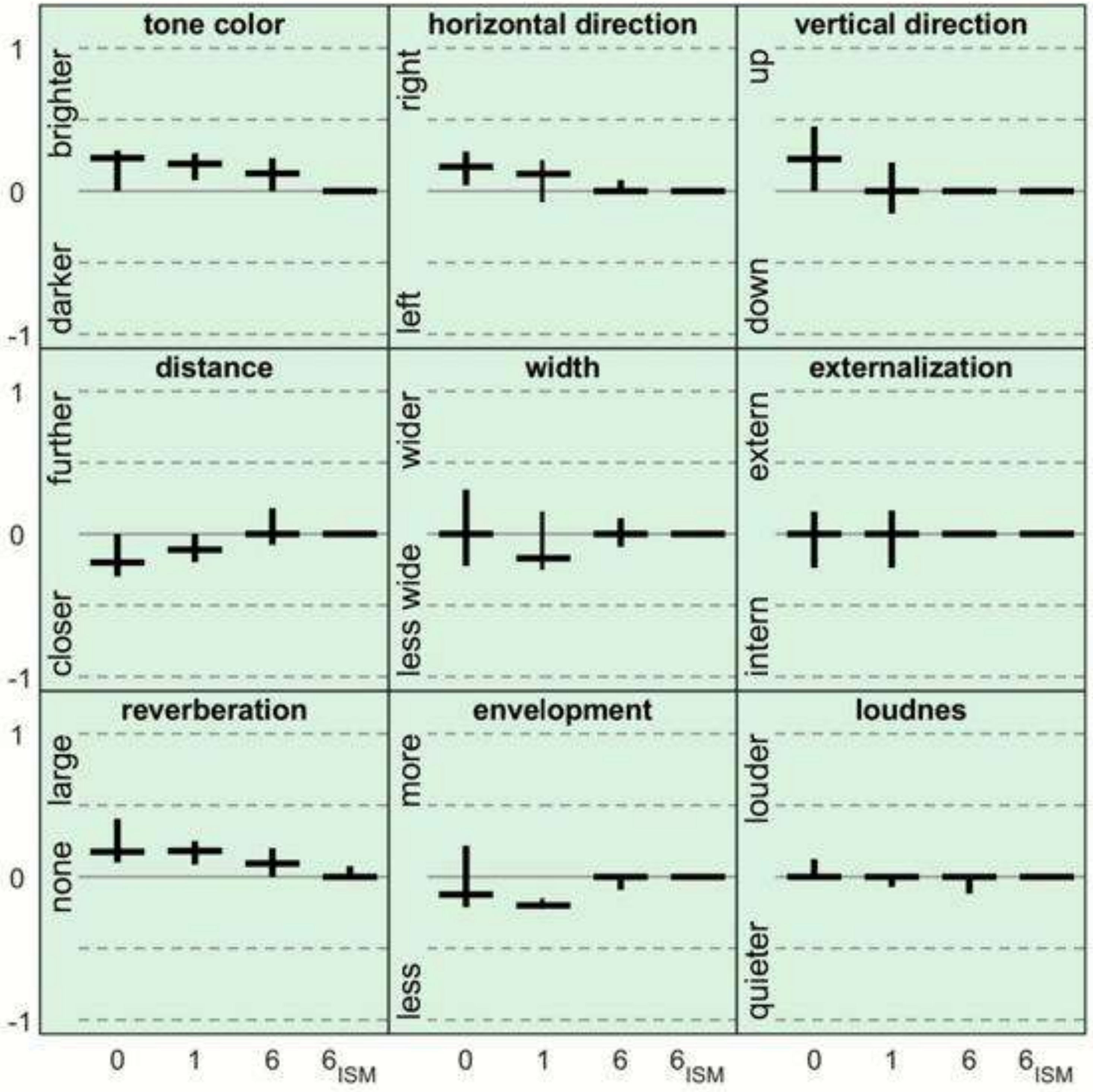
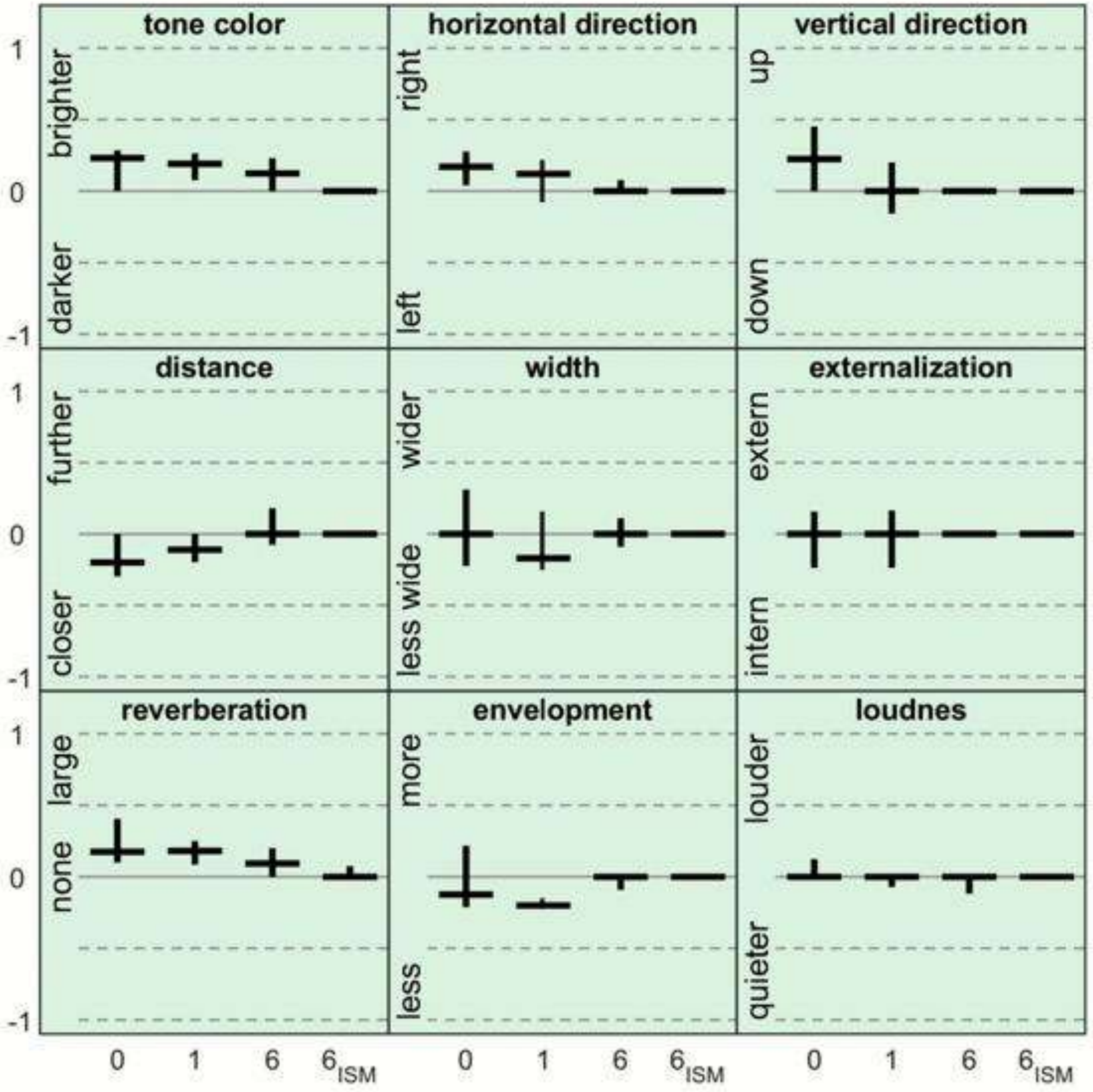
PERCEPTUAL EVALUATION



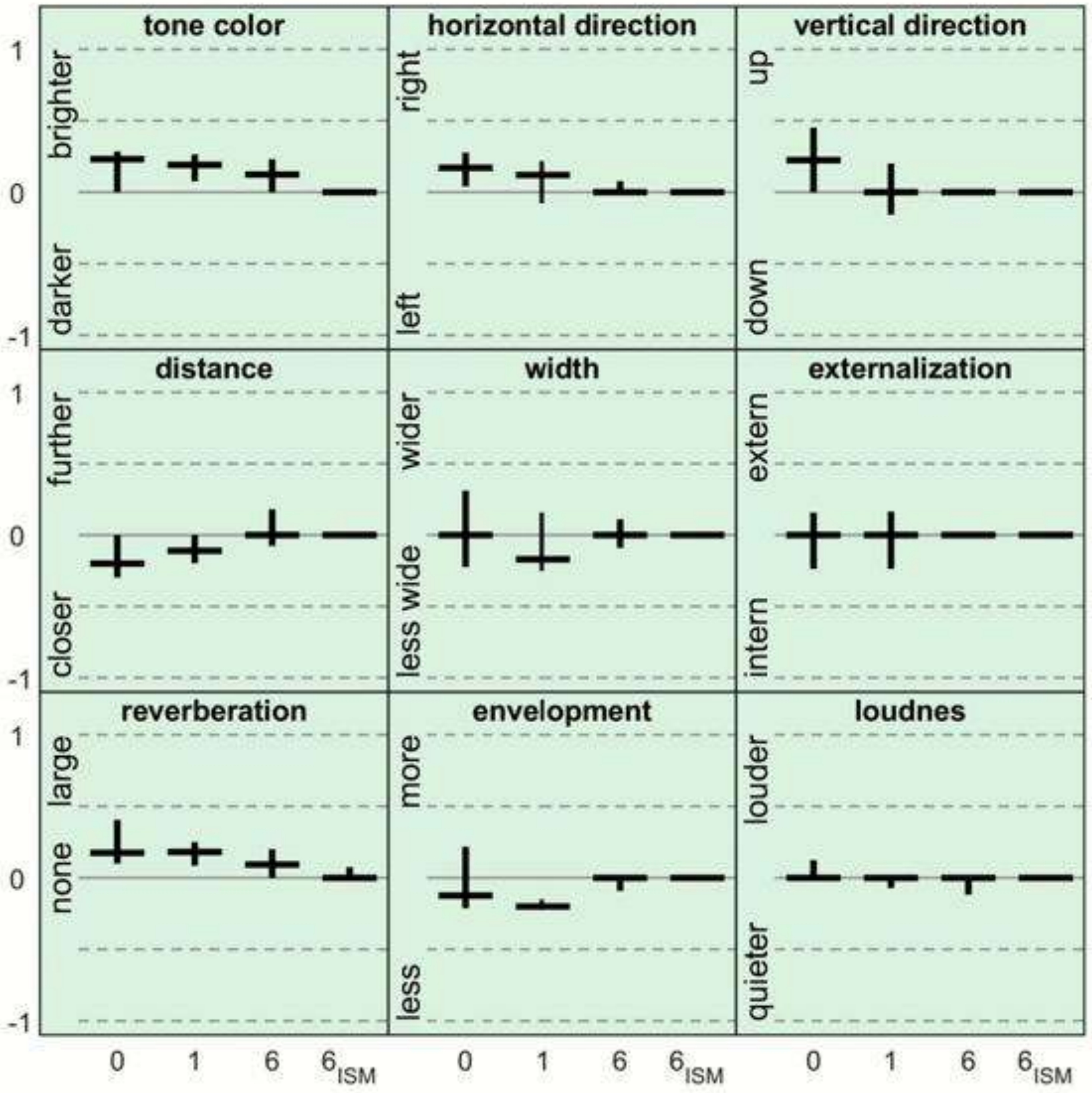
- Differences decrease with **N**
- 6_{ISM} is always rated 0
- 6 Cis overlap with 0

PERCEPTUAL EVALUATION



- Differences decrease with **N**
- 6_{ISM} is always rated 0
- 6 Cis overlap with 0
- Small differences in every tested Quality

PERCEPTUAL EVALUATION



- Differences decrease with **N**
- 6_{ISM} is always rated 0
- 6 Cis overlap with 0
- Small differences in every tested Quality
- Loudness not problematic

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SUMMARY

- End-to-end parametric audio system including early reflections

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- Evaluated on two different models

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- 6 early reflections sufficient in most cases

SUMMARY

- End-to-end parametric audio system including early reflections
- Evaluated on two different models
- Detected reflections agree across models
- Early reflections important in large and dry rooms
- Differences decrease with increasing reflections
- 6 early reflections sufficient in most cases
- Floor reflections seems important

CONTRIBUTIONS

- Detecting and selecting early reflections

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- Double sloped parametric late reverberation

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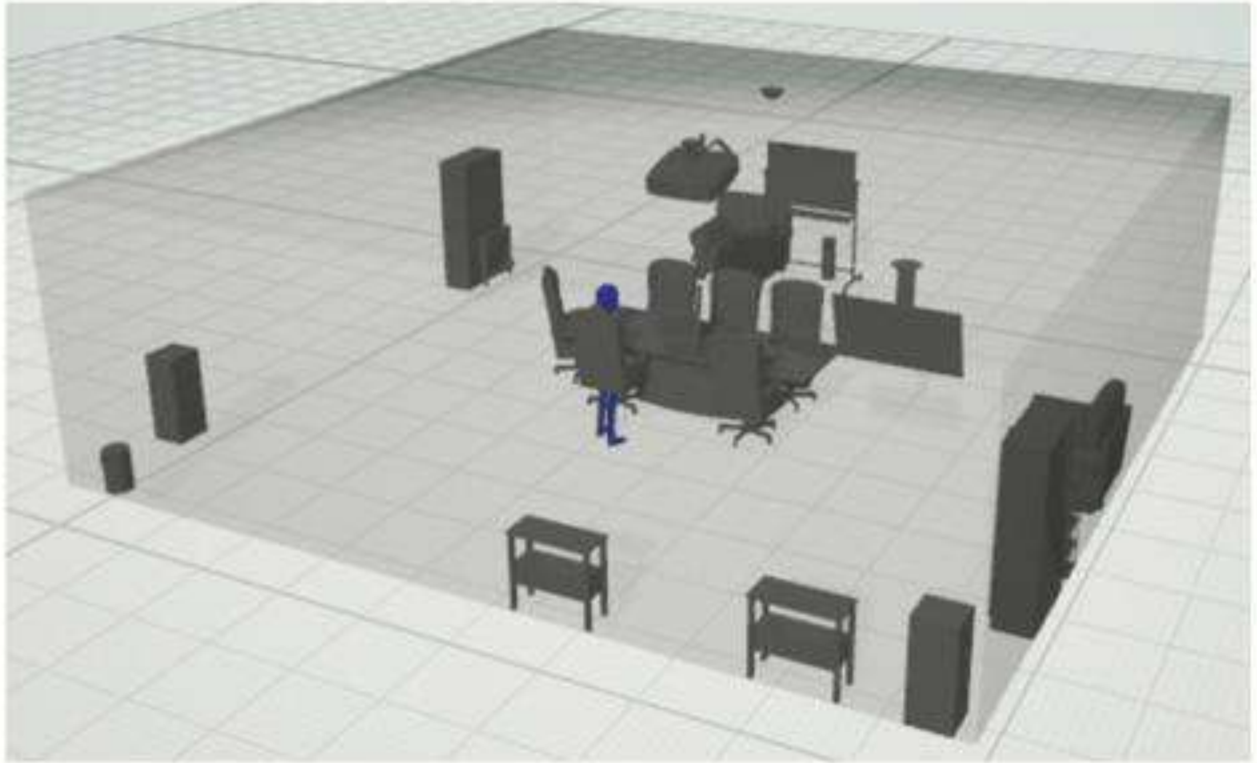
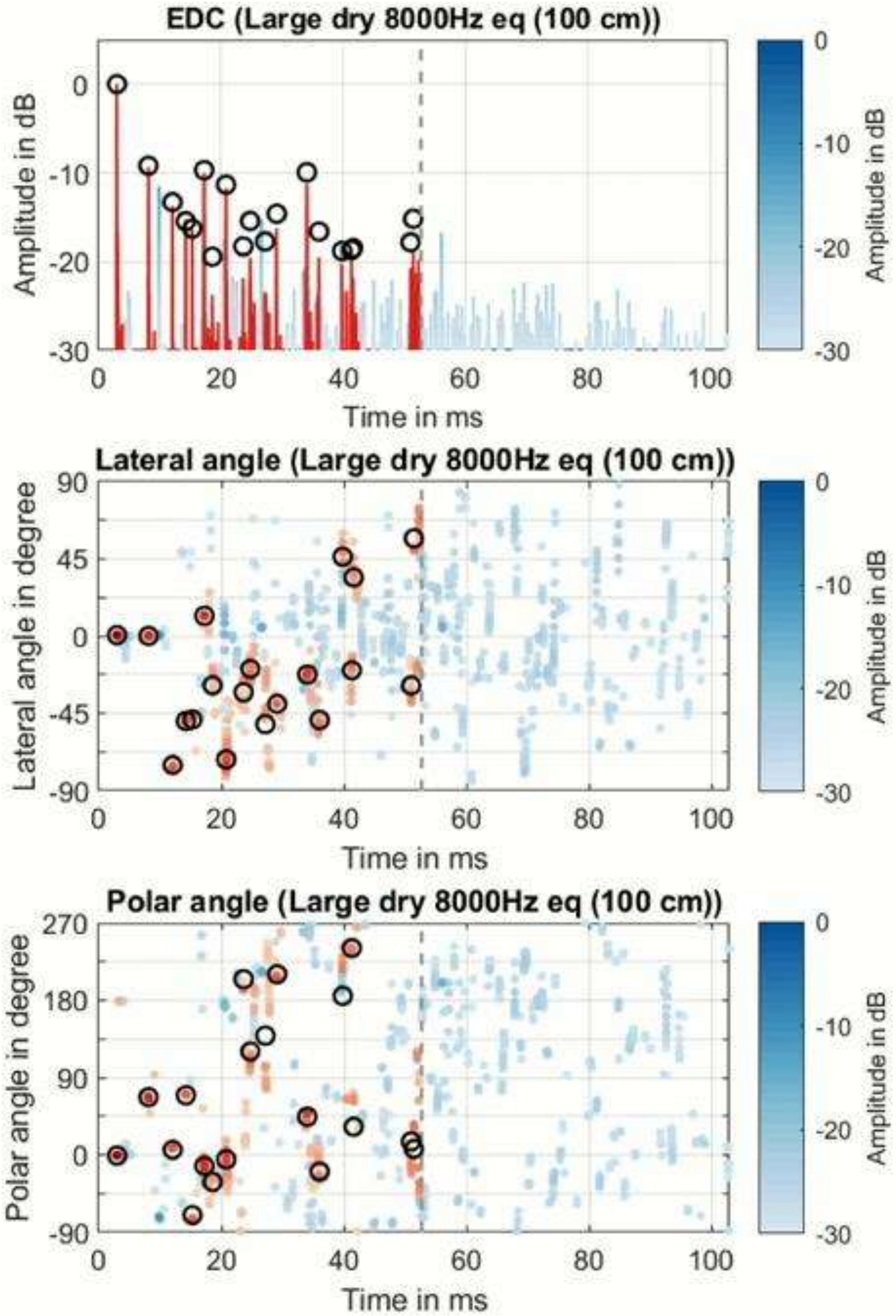
➢ More efficient, and higher perceptual quality

OUTLOOK

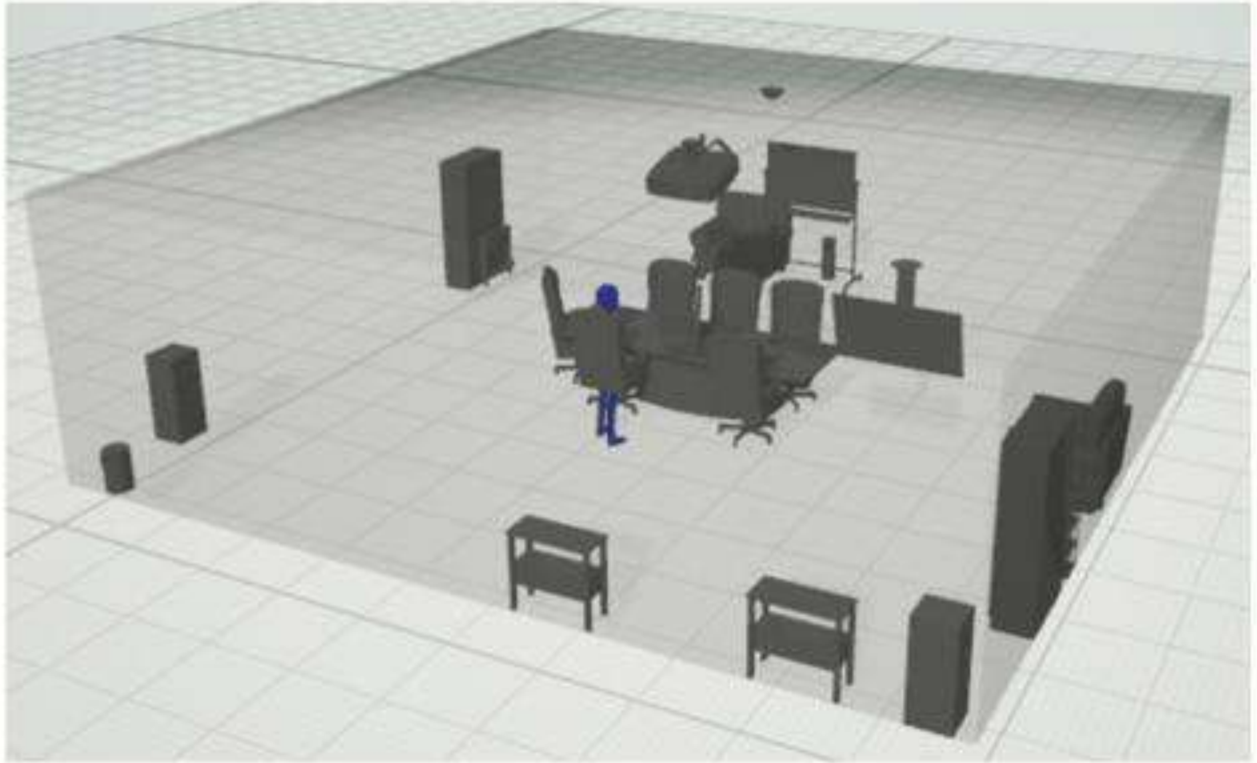
- Non-empty rooms

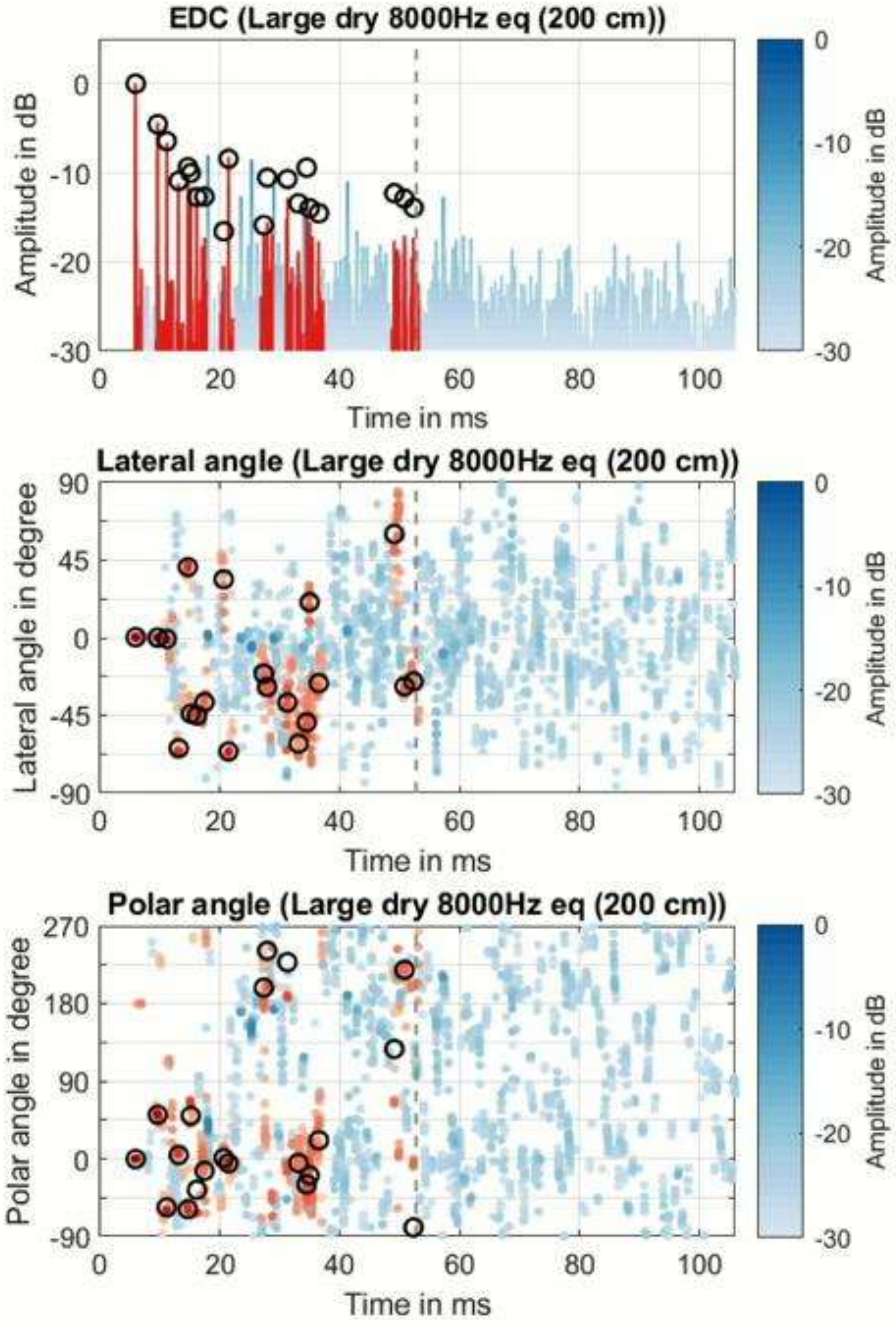




OUTLOOK

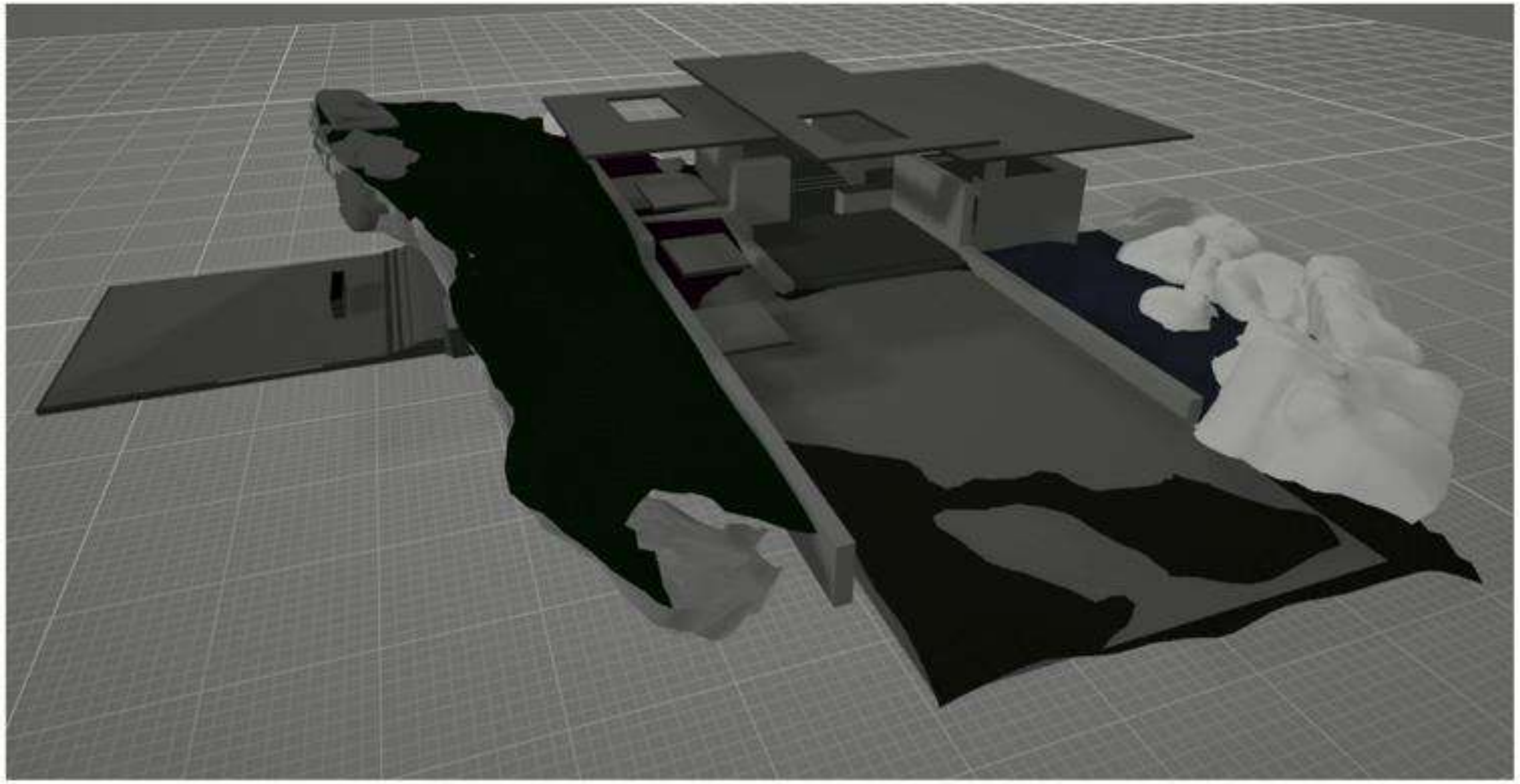
- Non-empty rooms
- Spatial smoothness




EDC (Large dry 8000Hz eq (200 cm))
Amplitude in dB
0
-10
-20
-30
Time in ms
0
20
40
60
80
100
Lateral angle (Large dry 8000Hz eq (200 cm))
Lateral angle in degree
90
45
0
-45
-90
Polar angle (Large dry 8000Hz eq (200 cm))
Polar angle in degree
270
180
90
0
-90

OUTLOOK

- Non-empty rooms
- Spatial smoothness
- Outdoor Environments



OUTLOOK

- Non-empty rooms
- Spatial smoothness
- Outdoor Environments
- Parametric rendering
  - Discover first order reflections

OUTLOOK

- Non-empty rooms
- Spatial smoothness
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  - Detect reflections with short memory

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  - Room dependent search time

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OUTLOOK

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OUTLOOK

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  - Discover first order reflections
  - Detect reflections with short memory
  - Room dependent search time
  - Directional variance
  - Frequency dependent rendering
  - Directional reverberation

THANKS!

Ivan Tashev for having me

Hannes Gamper for mentoring, critical feedback and help

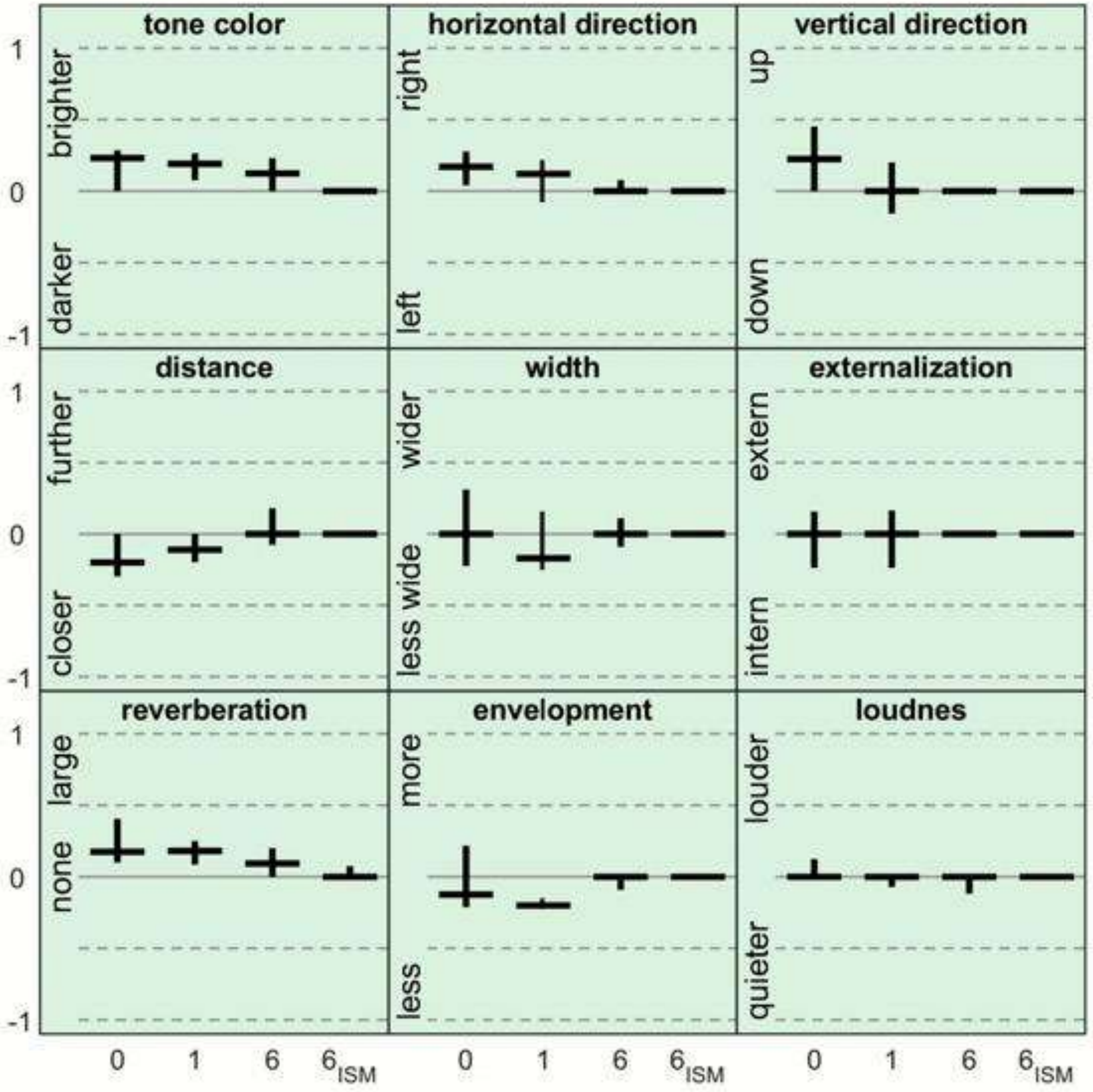
Nikunj Raghuvanshi for critical feedback and help

Acoustics Team for help with Triton

Audio and Acoustics Group for the warm welcome

All subjects that participated in the listening test

PERCEPTUAL EVALUATION



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