DOI: 10.61782/fa.2025.0837

FORUM ACUSTICUM EURONOISE 2025

SUBJECTIVE EVALUATION OF THE FIRST INCOMING REFLECTION - REVISITING AND EXTENDING BARRON'S STUDY

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ABSTRACT

In 1971, Barron published a study on *The subjective effects of first reflections in concert halls*, comprising a lead/ lag paradigm experiment with two loudspeakers set up in an anechoic room. As a result, he presented the determined audibility threshold, as well as a figure showing the audible effects caused by the first reflection (lag) depending on its delay and level relative to the direct sound (lead). This study gave an inspiring first insight into prominent perceptual effects like spatial impression, colouration, image shift, and 'disturbance'. However, the diagram was created based on the responses of only two listeners, evaluating the various attributes of a single item of programme material. To assess the reproducibility and generalisability of the results, we repeated and extended Barron's experiment with a larger panel of participants and a slightly revised test method. Besides ensemble music, a solo piece played by an electronic bass guitar was considered. The analysis confirmed a signal dependency of the estimated thresholds. Furthermore, despite intense training, mapping the specific attributes to the perceptual effects remained challenging for the complex signals. Considerable individual differences were observed. We present an updated version of Barron's graph as a result of our study.

Keywords: *First reflection, Perception, Audible effects, Lead/ lag paradigm.*

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1. INTRODUCTION

Prominent early reflections can introduce audible effects that influence the acoustic attributes perceived by listeners. Understanding the thresholds at which a reflection modifies each perceived attribute is key to control the perceptual implications of music reproduction in rooms and off-centre listening in spatial audio loudspeaker systems.

In 1971, Barron published a highly influential study [1] investigating the perceptual implications of adding a first reflection while varying the relative level and delay with respect to the direct sound. He used two loudspeak-

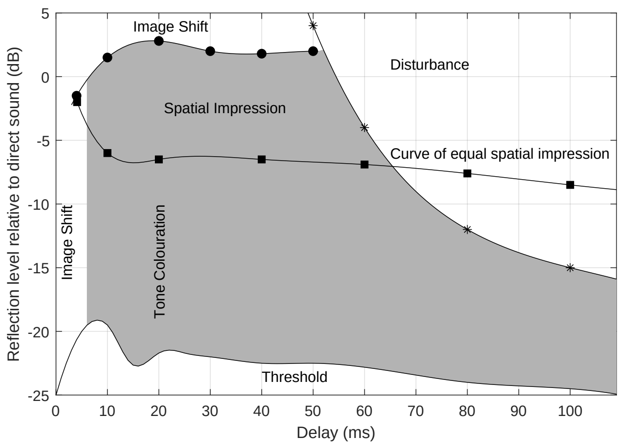

Figure 1. Barron's diagram visualizes the "Subjective effects of a single side reflection (α = 40°) of variable delay and level using music" [1, p. 481], Redrawn after [1, Fig. 5].

ers which were placed in an anechoic chamber, one in front of the listener and the other one located to the left of the listener at the same distance, with a lateral angle $\alpha = 40°$ with respect to the median plane. The signal emitted by the side loudspeaker could be controlled in its level and delay relative to the loudspeaker in the front. Two participants evaluated and documented the audible effects caused by the addition of the lateral reflection, simulated by the lateral loudspeaker. First, the audibility threshold of the lag was established. The two subjects then consulted and agreed on the main effects at play: *image shift*, *disturbance*, *tone colouration*, and *spatial impression*. The subjects were then asked to determine the maximum or minimum delays and levels at which each of the effects occurred. Fig. 1 shows Barron's original diagram, summarising their main observations.

Since its publication, Barron's study has been serving as a benchmark for the perceptual effects induced by a single lateral reflection. The study has been referenced more than 400 times and is part of many established textbooks on room acoustics [2–5]. However, it comes with some limitations. For example, only two subjects participated in the experiment, which were also the experimenter and his supervisor [6]. In addition, the methodology that was used for the experiment is not documented in detail. For example, while it was specified that a training was conducted, its design and content were not further described.

The goal of our investigation is to repeat and revise Barron's study. The new design was guided by two main principles. First, the experiment should follow Barron's setup and procedure as closely as possible. Second, the design aimed at extending the validity of the results of the original test in terms of methodology as well as in the documentation. Therefore, we tested more participants, documented each of the steps in depth, and revised some minor aspects of the study. The main objective of our investigation is to learn more about the generalisability of Barron's findings.

2. BACKGROUND

Room acoustics is the field that studies the propagation of sound in enclosed spaces and its effect in auditory perception [4]. Researchers in the field aim at understanding how the geometry of a room and its materials influence the sound attributes perceived by a listener. Early reflections, i.e. delayed versions of the direct sound that arrive shortly after, are known to influence the perception of the sound source. In 1951, Haas [7] conducted the first study on analysing the effect on intelligibility of adding a simulated early reflection to a speech source. Since then, numerous studies analysed the effect on spatial and timbral aspects of adding one or more reflections and varying their level and delay with respect to the direct sound [8–11].

In 1974, Barron published his PhD thesis "The effects of early reflections on subjective acoustic quality in concert halls" at the University of Southampton [6]. Therein, subjective concert hall acoustics are described as a multidimensional process. Barron proposed the effect of *spatial impression* as it is produced by early lateral reflections, as the only desirable effect of early reflections. His work also extracted the first links between perceptual effects of early reflections and what became known as the *early lateral energy fraction*. He also explored 'the height of the maximum of the cross-correlation function' as a perceptual predictor. *Spatial Impression* was later established as a perceptual construct based on Barron's and Marshall's work [12].

Simulating specular room reflections with loudspeakers in an anechoic room with one loudspeaker serving as the 'lead' and one or more reproducing the later 'lag' stimulus, has been a popular test paradigm to investigate their perceptual implications of prominent early room reflections. The precedence effect has been investigated thoroughly over years for a wide range of conditions, using the lead-lag paradigm. For example, Litovsky et al. [10] and Brown et al. [11] provide comprehensive literature reviews on the phenomenon. It addresses fusion effects between the direct sound and early reflections, the localisation dominance of the first arriving wavefront, and discrimination suppression for later arriving sound [10]. Despite the extensive accumulated knowledge on the topic, open questions related to the phenomena formation and perception still remain.

3. METHODOLOGY

To reassess the documented psychoacoustic effects, a methodology as similar as possible to Barron's was implemented.

3.1 Test Setup

In an anechoic room compliant with the DIN EN ISO 3745 [13] regulations, instead of Quad electrostatic loudspeakers, we used two Genelec 1030A loudspeakers and placed them at a height of 1.30 m (average ear height of a seated person). As in Barron's study, the loudspeakers were positioned in a distance of 3 m from the listener, one of them at 0° and one at 40° to the left as shown in Fig. 2.

The participant could de-/activate the lag and control the its level via a tablet PC with a user interface developed using the *AVrateVoyager* framework [14]. Fig. 3 shows the GUI designed to control the lag level.

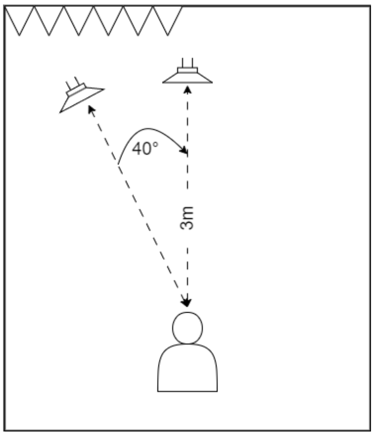

Figure 2. Overview of the test setup with the loudspeakers and listening position in the anechoic room.

The audio processing was implemented using simple FIR filters created in Matlab, which were selected and convolved with the signal using the Python rendering tool *pyBinSim* [15].

Barron's study examined lag levels up to +5 dB relative to the lead. Early reflections of directional sound sources in small rooms can have relative levels far beyond +5 dB [16]. Therefore, we extended the tested level range to +10 dB.

3.2 Definition of Attributes

Barron observed noticeable changes in localisation, sound level, colouration, spatial impression, and so-called "disturbances". Some of these terms have evolved in meaning over time. Therefore, for our experiment, we updated the corresponding attributes. An example is spatial impression, which was later found to be an ambiguous term that was split into apparent source width and listener envelopment [17]. Listener envelopment refers more to late reverberation, while apparent source width is related to effects induced by early reflections. Therefore, we decided to replace *spatial impression* with *apparent source width* for the evaluations within this lead/lag paradigm.

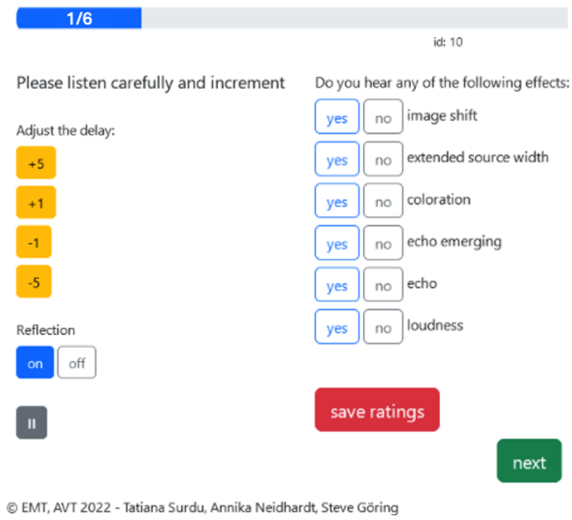

Figure 3. Graphical user interface designed for the experiment to modify the lag-level, switch the lag on and off, and indicate the noticed audible effects.

Meanwhile, the term *echo* has been established in the literature, describing the effects Barron called *disturbance*. Therefore, the updated terminology was used in the test. Furthermore, during the pre-test for this experiment, we noticed that with complex signals like music played by a jazz ensemble, the transition between *echo*, *image shift*, and *apparent source width* is rather smooth and continuous. As a consequence, we added *echo emergence* to better capture the transition range. We also added the attribute *loudness*, since already Haas [18] documented changes in loudness as a perceptual effect of a prominent reflection. The list below describes the selected attributes with their corresponding definitions, as they were presented to the participants:

- **Image Shift** - the auditory event's position will move towards the lateral loudspeaker. It does not have a stable position at the main central loudspeaker. The perceived sound can be anywhere between the two playing loudspeakers. The effect cannot occur during the formation of an echo or once a full echo is present.
- **Apparent Source Width (ASW)** - the extent of the sound source becomes broader and more diffuse. Instead of a point-like auditory event concentrated in one spot, the source will spread out in space. To

clarify the expected change in ASW, the GUI label was given as "*Extended* source width" rather than *apparent*.

- **Colouration** - the timbre of the sound changes. For example, it starts sounding more/less dark or more/less muddy or more/less sharp. It is a phenomenon related to the spectral structure of the sounds.
- **Echo Emergence** - some of the main sound components are incoming from a lateral side. However, a full second auditory event is not produced. A stereo-like effect can be heard. Additionally, a resonance effect can be observed. The effect cannot happen simultaneously once an echo is present.
- **Echo** - two distinctive auditory events are being played simultaneously. This implies that each sound source comes from a specific direction one of them being delayed. The two sound sources are independent of one another.
- **Loudness** - the reproduced sound appears louder.

3.3 Test Stimuli

The anechoic recording of the Mozart motif used by Barron could not be found anywhere despite an intense research. As a consequence, the two different stimuli were chosen: The first signal is the jazz sample *It don't mean a thing* recorded by Thery and Katz [19] [1] . The jazz ensemble consists of three instruments, a saxophone, a guitar, and a double bass. The second signal is a self-produced solo bass guitar recording with many rhythmic and transient elements, which will be provided online.

The participants were invited to adjust the sound level to their individual preference to support critical listening and reduce fatigue effects during the test.

3.4 Test procedure

In the experiment, the delay was fixed at 0, 1, 2, 5, 10, 20, 40, 60, 80 and 100 ms. The level could be varied in ±1 or ±3 dB steps from +10 to -25 dB using the graphical user interface shown in Fig. 3. The initial level was set to +10 dB. The delays were presented in a randomized order.

For each delay, the participants were asked to vary the level until a difference for at least one of the attributes was perceived. Pretests suggested that the formation of two separate auditory events occurs over a longer time frame. Thus, capturing the start and ending point for this acoustic phenomena is of great interest. During the test, for each considered trial, the subjects had the possibility to switch the lag on and off as desired. This feature was integrated to better facilitate the phenomena evaluation and reduce build-up effects [20].

3.5 Training

Before the actual test, participants completed an extensive training session to get used to the GUI, as the interface is rather complex. In addition to providing the definitions of the attributes, their practical meaning and the related audible cues were studied with them together by going through some listening examples. Different signals, for example, a solo saxophone and an orchestral piece served as stimuli in during the training, excluding those used in the following experiment. After an accommodation phase and after the subject's understanding of the task, terminology, and evaluation tool was confirmed, the candidate was invited to start the test.

3.6 Participants

In total, eleven participants, eight male and three female, with self-reported normal hearing, completed the experiment. Their average age was 29.6 years, with subjects aged 22 to 40 years. All participants were experienced listeners, either studying or working in the field.

4. RESULTS AND DISCUSSION

The experiment captures a 10×36-matrix of binary data per participant and attribute, indicating whether the corresponding effects were audible for the specific delay-level-combination. As an example, Fig. 4 shows the raw binary answering data of two participants for Apparent Source Width distributed according to the corresponding tested delay value. A comparison of the individual results of the participants reveals quite large differences. Potential reasons are discussed in the next paragraph.

4.1 Differences between participants

Clear definitions and the specific conducted training session were provided to the participants, aiming at reducing potential differences in individual interpretations of the constructs and related audible cues. Despite this effort, the

[1] `www.lam.jussieu.fr/Projets/index.php?page=AVAD-VR`.

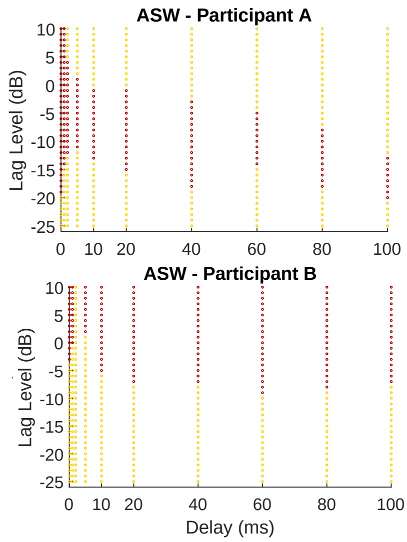

Figure 4. Example of the discrete binary data obtained for Apparent Source Width with the Jazz-Ensemble signal by one participant. Red marks the delay-level where the participant perceived changes in Apparent Source Width.

occurrence of the specific construct varied considerably among the participants. Fig. 4 shows the ASW ratings of two participants in comparison. These two participants showed quite consistent results each for themselves, but they rated differently especially the level-range beyond -5 dB. This example is a pronounced case of differences between two participants. However, for ASW and all other attributes, such deviation was not uncommon.

4.2 Combined visualisation

The binary data captured in the experiment is combined by summation to map out the occurrence of the individual attribute over all eleven participants and both signals. The resulting grid of values between 0 and 22 is interpolated linearly over the lag-level (with function *interp1* in Matlab) to create the graphs shown in Fig. 6. The colour indicates the number of participants who noticed a change in the specific attribute.

4.2.1 Differences between the signals

Fig. 5 shows the interpolated visualisation for Image shift, Colouration and Loudness, separated by the two stimuli *Jazz ensemble* (top) and *Bass guitar* (bottom). The Image shift is more pronounced for the bass guitar than for the jazz stimulus for levels beyond 0 dB. Colouration and Loudness are perceived more prominently with the jazz than with the bass guitar. For Colouration, the delay-level-ranges of most prominent occurrence differ between the two signals. These three examples highlight that level-delay ranges, where specific audible effects occur, depend on the signal.

4.2.2 Overview of the attributes

The main results of this study are presented in Fig. 6, visualising the occurrence of the specific audible cues caused by the added lag signal.

The **Image shift** effect documented in Barron's original diagram occurs in the level range above the audibility threshold for delays below about 7-8 ms (see left side of Fig. 1) and for levels beyond about 2 dB up to delays of 50 ms (top part of the figure). In our experiment, the range where participants perceived an image shift was much smaller, largely limited to levels above 0 dB and lags below 5-6 ms (top left corner). For lag levels below 0 dB, the effect is limited to the 0 ms delay case until around -10 dB, and for levels above 0 dB no effect is observed beyond around 10 ms (as opposed to 50 ms for Barron's).

Apart from the *curve of equal spatial impression*, the original diagram remains vague in indicating changes of **Spatial Impression**. It was indicated to occur in a wide range of level-delay combinations. Our new findings highlight prominent extensions in **Apparent Source Width** for short delays from 0 to about 45 ms.

Originally, **(Tone) Colouration** was indicated to occur mostly for delays ranging from about 10 ms to 50 ms for audible levels. In the new results, the most prominent colouration effects were reported in a similar range, but several participants also reported colouration for considerably larger delays.

Disturbance was indicated for delays starting from 50 ms, increasing towards lower levels. In the new investigation, disturbance, now called **Echo**, aligns textbook-like with Barron's disturbance. The border follows almost exactly the original threshold. **Echo emergence** marks the transition between the Colouration/ASW area towards the echo area.

In our instructions to the participants, we defined image shift, echo emergence and echo in a way that they cannot occur at the same time. However, in complex signals, it can happen that different effects occur in different fre-

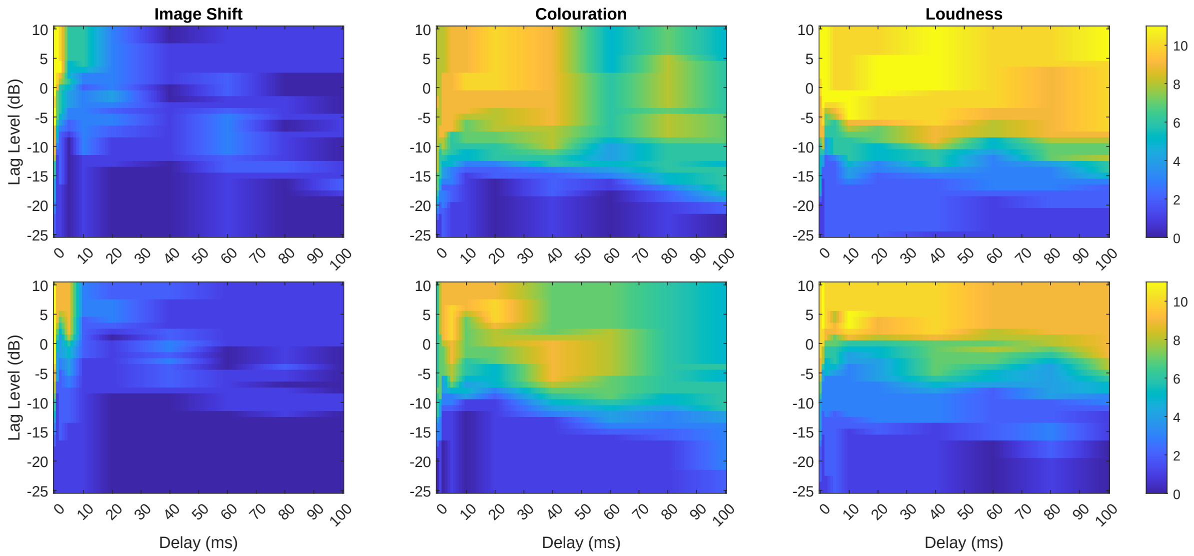

Figure 5. Comparing the effects for the two test stimuli **Jazz Ensemble (Top)** and the **Bass guitar (Bottom)** for the three example attributes Image Shift, colouration and loudness.

quency bands. This was particularly observed for the bass guitar stimulus, where transient components were clearly separated already, while the low frequencies still appeared as one fused image.

Loudness was not part of the original visualisation. In our experiment, Loudness is most prominent starting from -5 dB upwards. Fig. 5 shows that the perceived increase in loudness strongly depends on the stimulus, with the effect being noticeable at much lower levels for the jazz ensemble compared to the bass guitar.

The lead-lag test paradigm is popular, but it is also known to be a keen abstraction of reality. For example, spectral variation or [21], a more natural spatial and or an increased diffuseness of the reflection [22, 23] are known to influence the manifestation of the audible effects.

Since Barron published the results of his experiment, numerous further studies examined the perceptual effects, also considering the impact of the type of signal, for example with speech, noise bursts, or click trains. Our study helps adding ecological validity by providing new insights into the manifestation of otherwise well-studied effect in complex music signals.

5. SUMMARY AND CONCLUSION

We conducted a study reproducing and extending Barron's impactful investigation on the perceptual effects of early reflections conducted in a lead-lag paradigm in 1971. As main findings, we present an updated visualisation for the occurrence of the six tested attributes–image shift, apparent source width, colouration, echo, echo emergence, and loudness. The results show considerable differences among the participants in the evaluation of the various attributes. Moreover, the occurrence of specific auditory effects also varied with the signal and partly also within the same music signal. This study provides valuable insight into perceptual effects for (complex) music signals reproduced in rooms or for off-center listening in multichannel-loudspeaker systems.

6. ACKNOWLEDGMENTS

This work was funded by EPSRC Challenges in Immersive Audio Technology (EP/X032914/1), Carl-Zeiss-Stiftung *Co-Humanics*, and DFG SPP2236 AUDICTIVE *APlausE-MR*. The authors would like to thank Steve Göring for his support in designing the user interface, and our participants and students of the 2022 module "Advanced Psychoacoustics" at TU Ilmenau for their help.

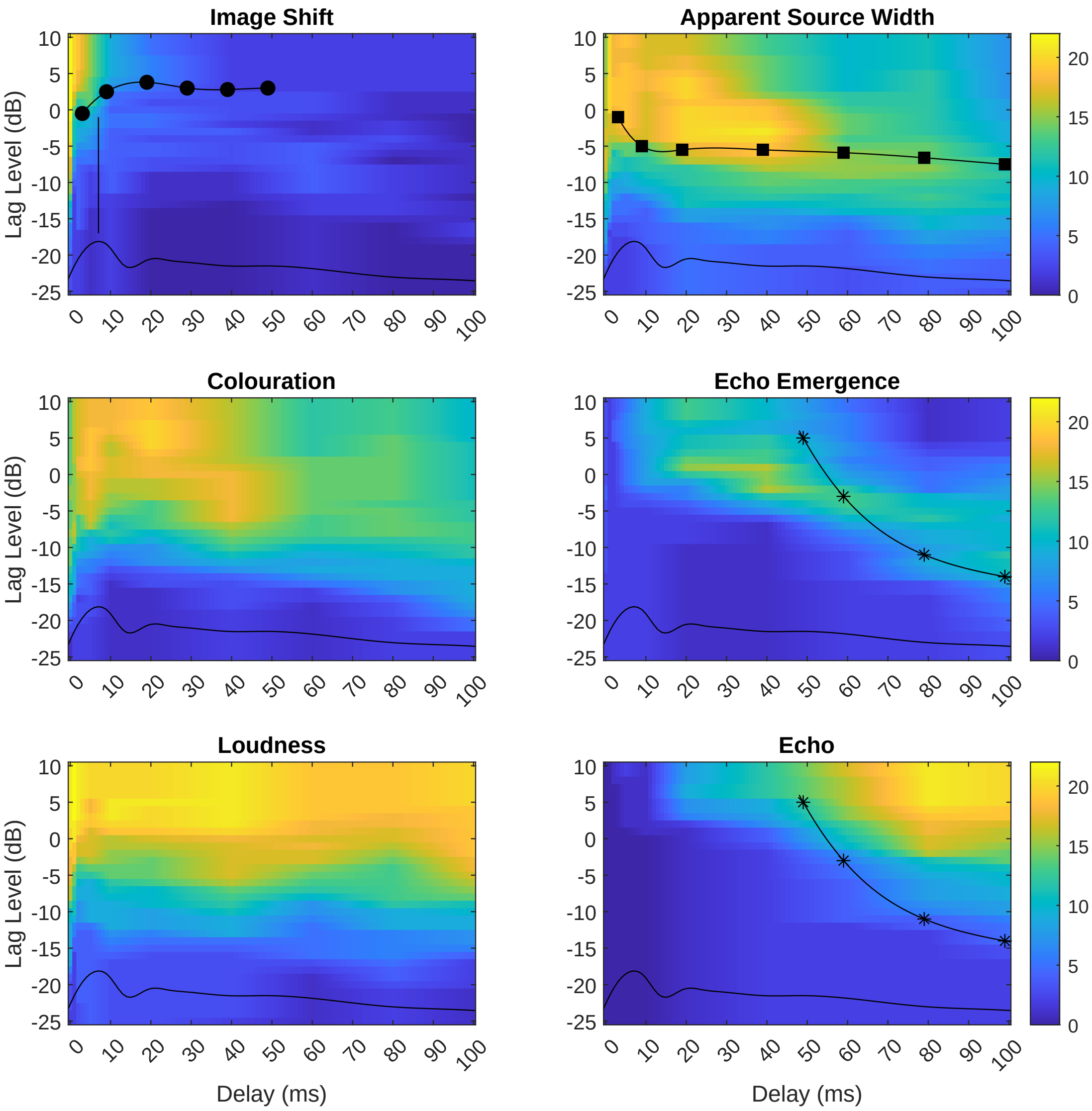

Figure 6. Overview of attributes over all participants and for both signals obtained in our experiment. The colorbar indicates the number of responses that reported the associated effect as occurring (the maximum possible is 22, i.e. 11 subjects times 2 signals). For comparison, Barron's original thresholds and curves are overlaid here. The solid curve present in all plots is Barron's audibility threshold. In the "Image Shift" plot, the two additional curves indicate Barron's thresholds beyond which image shift was observed (to the left of the vertical line and above the horizontal curve). In the "Apparent Source Width" plot, the additional line indicate the "curve of equal spatial impression," which was obtained by Barron as the locus of points with the same spatial impression as the 40 ms delay reflection at -6 dB, relative to the direct sound. The curve in the "Echo Emergence" and "Echo" plot represents Barron's "Disturbance" threshold.

Furthermore, we would like to thank Matthias Frank for sharing his Matlab-Version of Barron's diagram, which we integrated in Fig. 6.

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