The 8th International Congress on Sound and Vibration
2-6 July 2001, Hong Kong, China

OBJECTIVE COMPARISON OF MEASURED AND MODELED BINAURAL ROOM RESPONSES

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Abstract

In this paper the measured and modeled binaural room impulse responses are analyzed. The analysis is carried out to the responses of each ear monaurally. Calculated parameters are such as reflection density, T20, EDT, and C50 as room acoustical attributes, and an auditorily motivated time-frequency plot. The analysis showed that with simplified modeling techniques, suitable for dynamic auralization, the impulse responses are close to measured ones, especially at frequencies between 400 and 8000 Hz.

INTRODUCTION

Virtual auditory environments (VAE) are an essential part of virtual reality applications. Traditionally, the design of VAE has been divided into physical and perceptual modeling. The aim in physical modeling of VAE is to reproduce acoustic space on the basis of room geometry (including material absorption data) and information of sound source(s) and listener placements. The ultimate goal is to reproduce an authentic sound field to observer's ear drums. It cannot be done perfectly with current modeling techniques. However, the authentic sound field is not needed if the perception of the observer is identical with the perception in real environments. This fact allows us to use simplified room acoustics modeling techniques as long as the perceived VAE is considered authentic. Blauert [1] and Pellegrini [2] have discussed the quality of VAE and they have claimed that in many applications perceptual plausibility of the VAE is more important than authenticity.

Despite of the fact that perceptual plausibility is enough for VAE creation, it is interesting to know what are the differences between authentic and simulated auditory environment. These differences can be studied in many ways, in this paper we try to find differences in room impulse responses with traditional room acoustic criteria as well as with a new auditorily motivated time-frequency analysis method [3]. As a case study, a lecture room is binaurally measured and modeled with the DIVA room acoustics modeling and auralization software [4, 5].

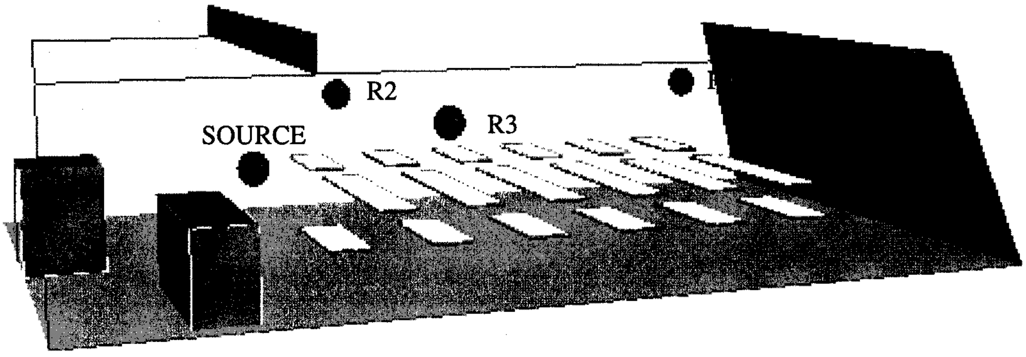

Figure 1: *Model of the studied lecture room and the positions of the sound source and listening points R1-R4.*

THE BINAURAL ROOM IMPULSE RESPONSES AND THEIR COMPARISON

In this section the measurement procedure and the modeling schemes of the binaural room impulse responses under study are described. The responses are measured with a real head with known HRTF characteristics which are applied in modeling.

Measurement of binaural room impulse responses. Binaural room impulse responses were measured in the studied room (12m x 7.3m x 3m) with MLS-based multichannel measurement equipment [6]. The sound source was a small active loudspeaker and the microphones, placed in the entrances of the blocked ear canals, were high quality electret microphones. The listener's head has been held as stable as possible during a measurement to avoid time variance which is crucial for MLS-based system. The responses were collected from four listening points (see Fig. 1).

Room acoustics modeling. The simulated room impulse responses were created with a modeling technique suitable for dynamic real-time auralization. The applied DIVA auralization system is based on the image source method (for direct sound and early reflections up to third order) and a parametric recursive late reverberation algorithm. From the modeling point of view, the applied software is not the most accurate one. However, given that our goal is to make perceptually plausible VAEs the choice is reasonable. The DIVA software implements such acoustical phenomena as sound source directivity, material and air absorption, and binaural cues with HRTFs. The detailed description of applied algorithms and digital signal processing are presented in a previous paper [5].

Objective analysis methods used in comparison. The best possible method to study binaural room impulse responses is to use a complete binaural auditory model. Unfortunately, this kind of model has not yet been developed. In this case the comparison between measured and modeled responses is performed monaurally for each ear. Similar measurements could have been made with

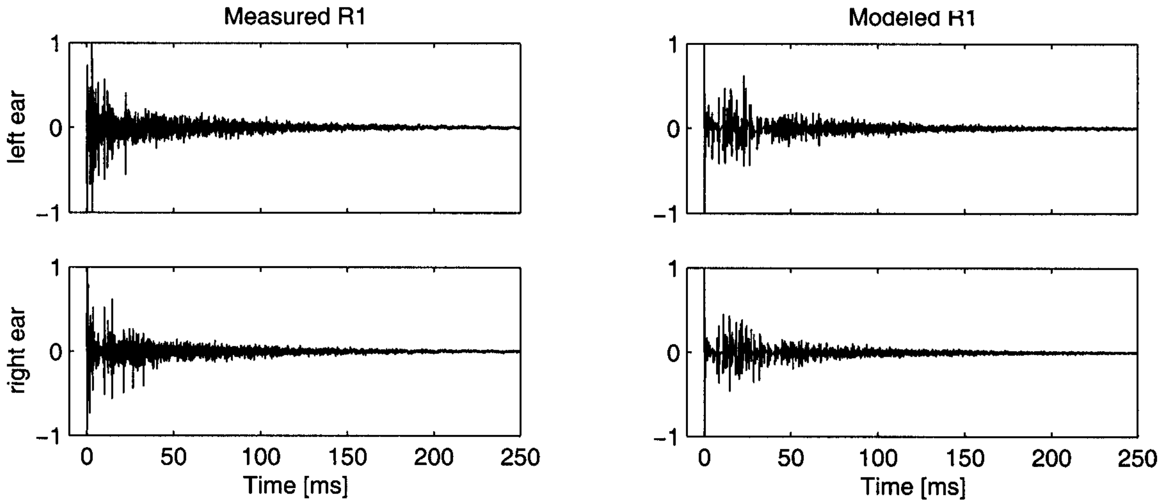

Figure 2: *The measured and modeled impulse responses at point R1. Each response is normalized.*

monophonic microphone, but when measured at the entrance of ear canals, the effect of human head is included to the responses.

Griesinger [7] has proposed several tests with which a monaural reverberation quality can be judged. Such tests applied in this case are:

1) *Plots of reflection density versus time.* Reflection density can be calculated by computing the individual reflections in a 20 ms sliding window (with 10 ms hops) in each of which the peaks within 20 dB from the strongest reflection are counted for defining the density. The algorithm has been implemented by detecting the absolute values of the response which exceed the neighboring values as proposed by Väänänen *et al.* [8].

2) *Plots of energy at different frequencies as a function of time.* The corresponding quality measure is the room acoustical criteria, defined in ISO3382 standard [9]. The standardized monaural parameters, such as reverberation time (T20), early decay time (EDT), or clarity index (C50), are based on the decay of the energy at different frequencies.

3) *Sonograms, for detecting long ringing modes.* In this case traditional time-frequency sonograms are not used, instead an auditorily motivated analysis [3] is applied monaurally to the responses of both ears, to obtain a perceptually relevant visualization of impulse responses. In this method the frequency resolution of human hearing is simulated with the Equivalent Rectangular Bandwidth (ERB) filterbank [10]. The method implements also a coarse approximation for time resolution of human hearing with a 15 ms long triangle-like integrating time window. With this method the impulse responses can be studied with the perceptually reasonable time-frequency resolution.

A CASE STUDY: FOUR IMPULSE RESPONSE PAIRS

In this section four measured and modeled impulse response pairs are analyzed with the above mentioned methods. The wideband impulse response pairs at listening point R1 is depicted in Fig. 2. Clear differences can be seen in the early part of the responses, but the reverberation tail decays uniformly. The first analyzed parameters, namely the reflection densities, were calculated and the results are depicted in Fig. 3. Obviously, no differences in reflection densities between left and right ears were found and only left ear densities in points R1, R2, R3, and R4 are depicted. Figure 3 shows that reflection density grows faster in real room responses than in modeled responses. However, after 50 ms the reflection densities are very similar in all listening points.

To obtain more information of the decay of reverberation at each frequencies, the room acoustical attributes, such as T20, EDT, and C50 were calculated at one-third octave bands from 100 Hz to 10 kHz. The four topmost plots in Fig. 4 show reverberation times at each listening point. It can be seen that over 315 Hz the T20 values are very close to each other. The errors in modeling are within limits of normal inaccuracy of measurements (0.1 s). Next two plots in Fig. 4 are the clarity values at points R1 and R2. The difference between measured and modeled values is bigger than with T20 values, although at mid frequencies errors are not very severe. The last two plots show EDTs at the same points R1 and R2. The similar trend than with T20s can be seen at low frequencies. There is quite a lot of fluctuation in EDT values at different frequency bands, even in measured responses.

The most detailed information about the reverberation decay is found with an auditorily motivated analysis, presented in Figs. 5 and 6. The topmost plot in Fig. 5 shows a sonogram type presentation of measured left ear impulse response at point R1. Next plot is at same point (R1, left ear), but at this time the difference between measured and modeled responses is visualized. The figure is calculated so that first both responses are analyzed with proposed method and then the results are subtracted from each other. In the resulting plot the black areas correspond the situation when measured energy is more than 3 dB stronger than energy in modeled response. Similarly, the white areas tell us the moments (and frequencies) when the modeled response is over 3 dB stronger. If the energy difference at certain time and frequency is less than 3 dB the areas are gray. Similar analysis has been made with the responses of right ear and results are shown in the two bottom plots in Fig. 5.

Reasons of differences between measured and modeled responses

The applied image-source method for the direct sound and early reflections is based on ray-based modeling that neglects the wave-like behavior of sound. Due to this limitation there is no model for diffraction and diffusion. This fact obviously caused some error, especially at low frequencies (smaller T20 and EDT values and bigger C50 values with modeled responses as seen in Fig. 4).

The other clear difference between measured and modeled responses is in the high frequencies (over 8 kHz) of the direct sound and early reflections. This is very well seen in Figs. 5 and 6.

Despite of these and other possible errors the analyzed responses are quite similar. Of course, the calculated parameters do not tell anything about the spatial characteristics of the impulse responses. The spatial characteristics as well as other features will be evaluated subjectively with listening tests and these results will be reported in near future [11].

CONCLUSIONS

The comparison of measured and modeled binaural room impulse responses are presented with a case study of a lecture room. The comparison showed that at mid frequencies the responses

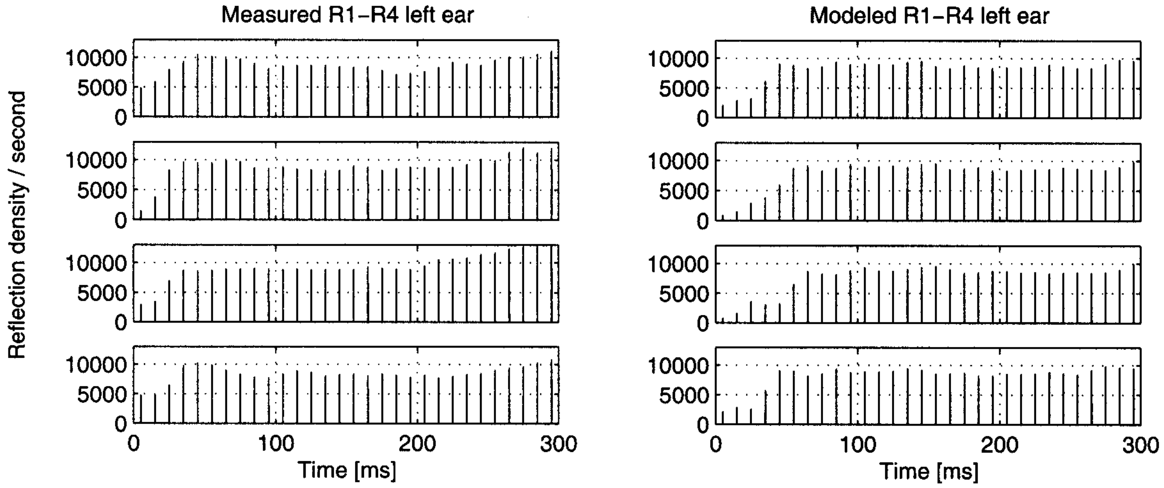

Figure 3: *Reflection densities at different listening points. Only the left ear densities are plotted because the right ear densities have similar characteristics.*

obtained with ray-based modeling technique combined with statistical late reverberation are close to measured responses. For example the difference between measured and modeled T20 values are within the limits of measurement accuracy of 0.1 s. The analysis included an auditorily motivated analysis with which the room impulse responses can be visualized with time and frequency resolutions that respect human hearing.

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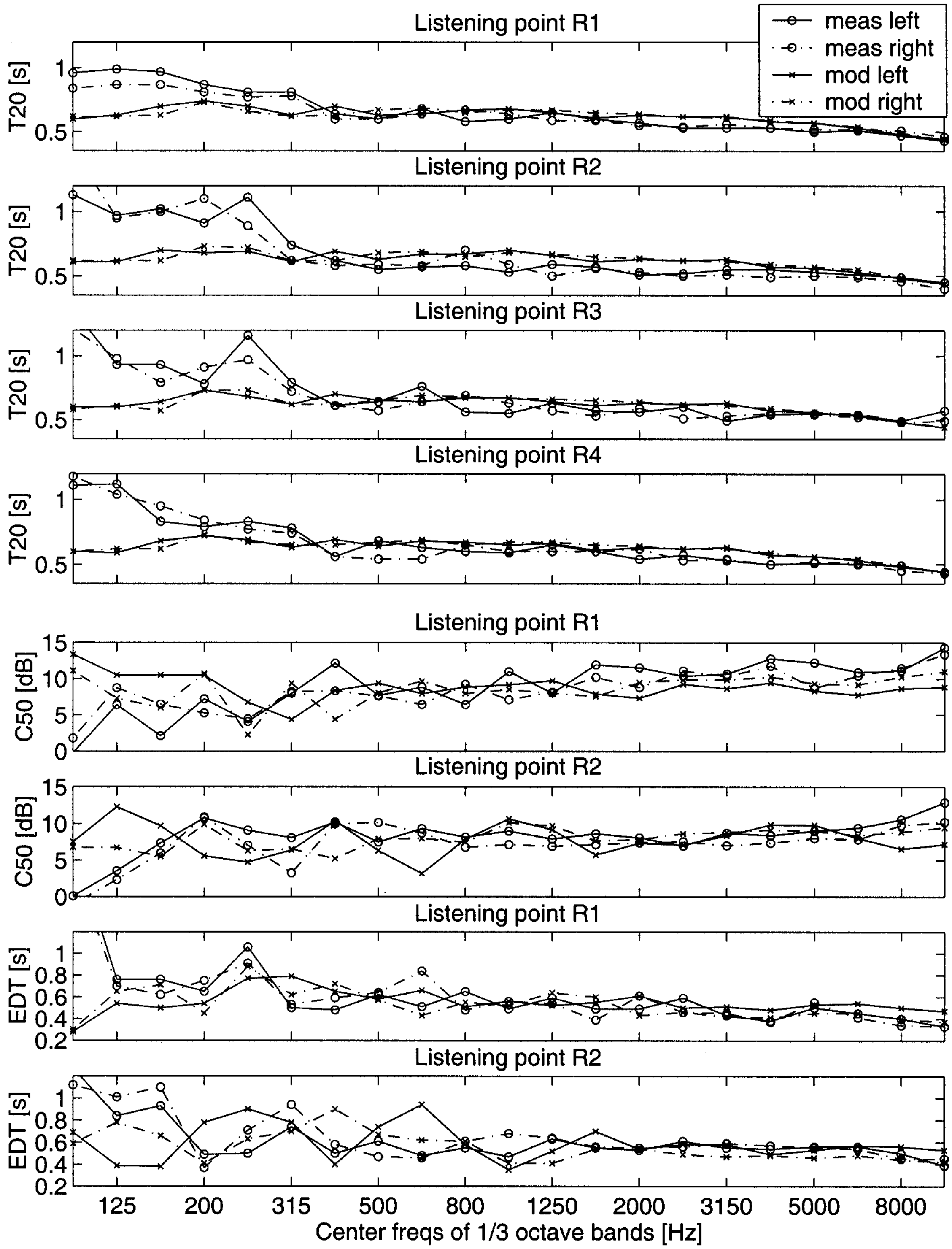

Figure 4: *Reverberation time (T20) at four measurement points and C50 and EDT at two measurement points. Acronyms "meas" means value from measured response and "mod" from modeled impulse responses.*

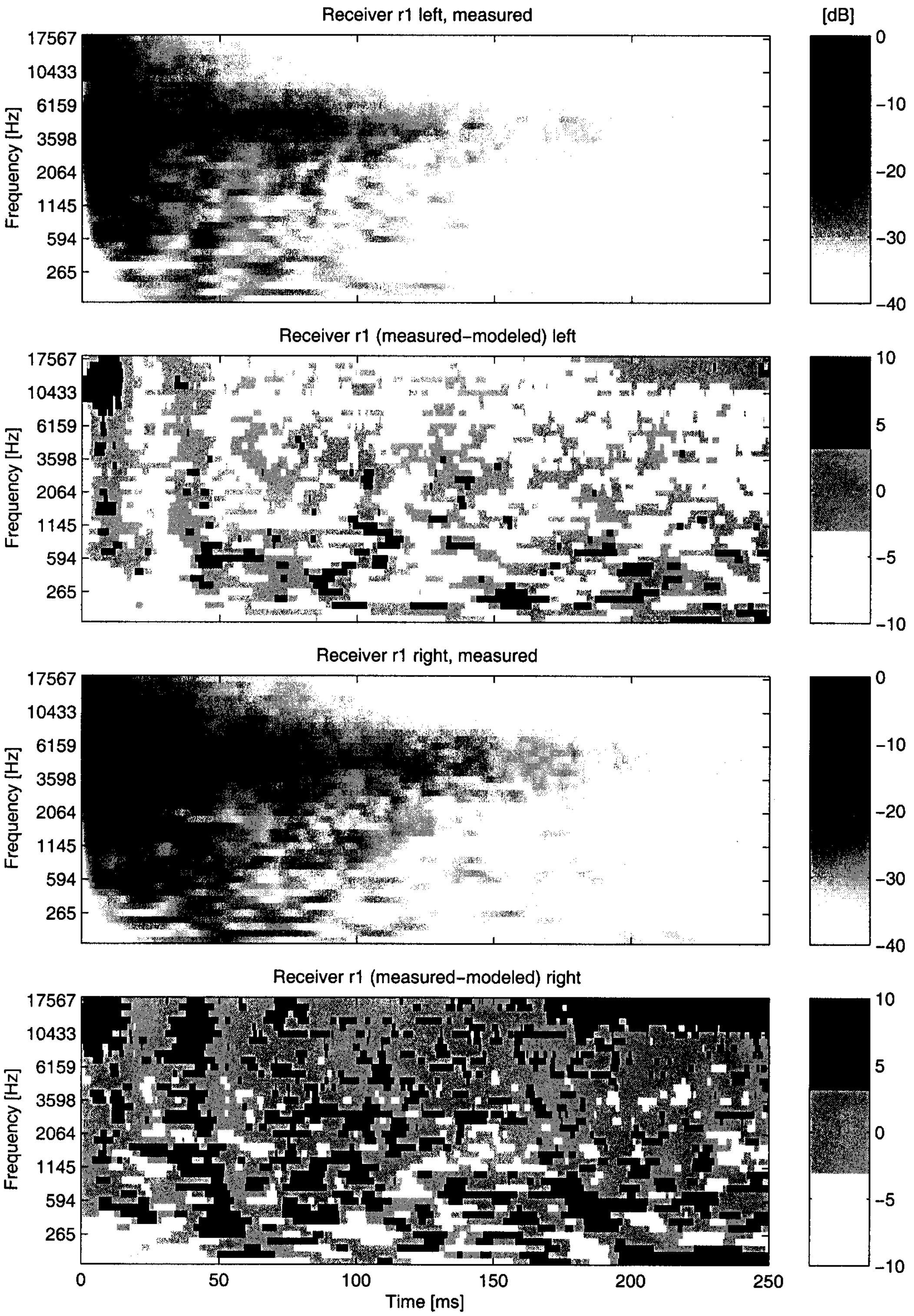

Figure 5: *Auditorily motivated analyses of the responses obtained in point R1. The darkness in the plot indicates energy in decibels.*

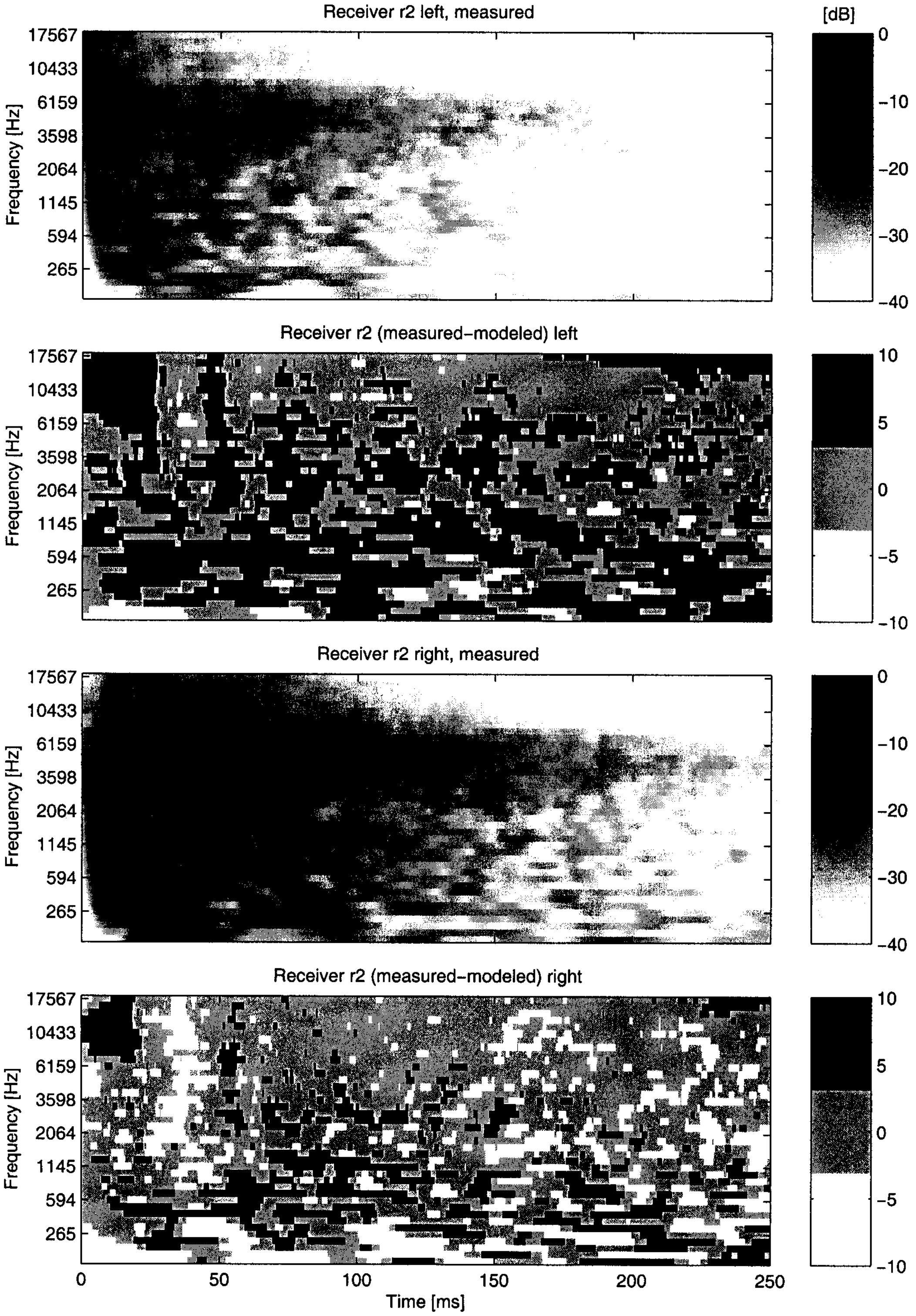

Figure 6: *Auditorily motivated analyses of the responses obtained in point R2. The darkness in the plot indicates energy in decibels.*