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PAPER

An active free-field equalizer for headphones used in functional magnetic resonance imaging

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Abstract: The free-field response of *NordicNeuroLab AudioSystem* electrostatic headphones for use in functional magnetic resonance imaging (fMRI) is determined by loudness comparisons with free-field equalized *Beyerdynamic* DT 48 headphones. Based on these measurements, an active equalizer with resonances at 0.55, 1.5, and 6.9 kHz is developed, realized, and tested. A free-field equivalent level independent of frequency within ±3 dB between 63 Hz and 10 kHz is obtained when using the *AudioSystem* headphones with the described free-field equalizer.

Keywords: headphones, free-field, equalization, fMRI, audio-visual interactions

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1. Introduction

To help obtain controlled, comparable, and repeatable conditions during psychoacoustic experiments, headphones used to present acoustic stimuli are generally calibrated with reference to a free sound field. For electrodynamic headphones such as DT 48, TDH 39, and TDH 49, free-field equalizers in both passive (Zwicker and Maiwald [1], Killion [2], Fastl and Zwicker [3]) and active (Schorer [4], Fastl and Zwicker [5]) design have been proposed.

However, for experiments involving functional magnetic resonance imaging (fMRI), standard electrodynamic headphones cannot be used due to the strong magnetic field that exists in the MRI scanner. Therefore, special headphones are available which do not contain any ferromagnetic parts. For example, an external transducer can be connected to plastic headphone capsules via rubber tubes (e.g. Meuli et al. [6]). This method is mainly used for speech communication, as the achievable frequency-range is limited. Modified electrodynamic headphones which use the existing magnetic field of the MRI scanner (Baumgart et al. [7]) or electrostatic headphones are alternatives which provide better sound-quality (e.g. Palmer et al. [8]).

For one particular electrostatic headphone, a *NordicNeuroLab AudioSystem*, a free-field equalizer was developed in order to provide an acoustical reproduction system with a frequency independent free-field response for use in psychoacoustic experiments in MRI environments. The *AudioSystem* is a closed circumaural headphone which also functions as hearing protection.

2. Procedure

As the specimen of *AudioSystem* headphones to be tested was in use in a clinical MRI facility, it could not be removed to be measured in an anechoic chamber. Thus, following the method described in DIN 45619-2 [9], the free-field response of the *AudioSystem* headphones was determined by diotical loudness comparison to free-field equalized reference head-phones (*Beyerdynamic* DT 48 with passive free-field equalizer as described by Fastl and Zwicker [5], p. 7) in a quiet office room with a background noise level of about 45 dB(A). Pure tones in third octave intervals between 63 Hz and 10 kHz were used as stimuli. This method is also similar to the loudness balancing procedure employed to compare different headphones during development of ISO 389 [10], as described by Weissler [11].

In contrast to determining headphone responses via measurement devices like artificial heads (e.g. Kulkarni and Colburn [12]), using real heads has the advantages of presenting the headphones with a realistic load due to the compliance of the flesh (Corliss and Snyder [13], Els and Schröter [14]) and, more importantly, ensuring a realistic fit of the headphone cushions around the ear. For closed headphones, as used in this study, leaks between the cushion and an artificial head can impair the transmission especially of low frequencies (Schröter and Els [15], Hirahara [16]).

Because the *AudioSystem* headphones use an electrostatic transducer principle, high voltages may occur at

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the headphone inputs. For safety reasons, all measurements were to be performed in a non-laboratory environment; therefore, the input voltage to the *AudioSystem* headphones was not measured directly. Instead, the input voltage to the *AudioSystem* headphone amplifier was used and was kept constant at an effective value of −20 dBV. The amplification was then adjusted so that sound pressure levels of around 70 dB were produced during the experiment.

At the start of the experiment, a pure tone of a certain frequency is presented diotically to a subject over the *AudioSystem* headphones. The subject then takes the headphones off and puts on the reference headphones. The same tone is presented again. The task of the subject is now to decide which pair of headphones produces a louder sound. The voltage to the equalizer of the reference headphones is then varied according to the subject's answer while the voltage to the *AudioSystem* amplifier is kept constant. The procedure is repeated until both pairs of headphones are judged equally loud to within a precision of 1 dB. The voltage to the equalizer of the reference headphones is noted and the experiment continues with the next frequency.

The free-field response of the *AudioSystem* headphones without equalizer was determined with 16 normal hearing subjects aged 23 to 38 years (median 27 years). A second group of three subjects, aged 24, 27, and 38 years, verified the free-field response of the *AudioSystem* headphones *with* equalizer.

Thus, for each test tone frequency, 16 voltages are obtained for the free-field response. As the calibration of the reference headphones is known (0 dBV at the equalizer corresponds to 80 dB SPL), these voltages can be converted into free-field equivalent sound pressure levels.

3. Results

3.1. Free-field response

Figure 1 shows the free-field response of the *AudioSystem* headphones. The free-field equivalent sound pressure level as measured by 16 subjects for an effective voltage of −20 dBV to the amplifier is given as medians (circles) and interquartiles. The solid line indicates the attenuation characteristics of the equalizer, which will be described in the next section.

Two maxima can be seen in Figure 1, a first broad maximum at about 1.25 kHz and a second, somewhat narrower maximum at about 6.3 kHz with a dip of nearly 8 dB around 3.15 kHz. Towards lower frequencies, the free-field equivalent level drops and at 63 Hz is down more than 10 dB in comparison to the mid-frequency range.

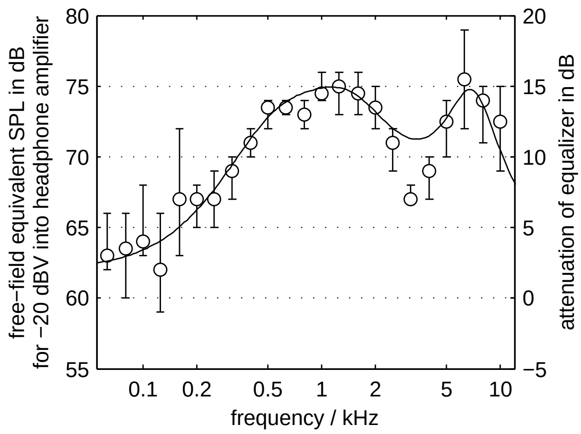

Figure 1 Free-field response of the *AudioSystem* headphones. Circles: medians and interquartiles obtained via loudness comparisons with free-field equalized DT 48 headphones; solid curve: attenuation characteristics of the proposed free-field equalizer.

3.2. Free-field equalizer

The prototype of the free-field equalizer for the *AudioSystem* headphones is based on an existing implementation of the active-filter version of the equalizer for DT 48 headphones (Fastl and Zwicker [5], p. 7, Fig. 1.5 e). This allowed for the quick development of a first version of the filter. In the future it would also be possible to use digital implementations based on FIR or IIR designs. As can be seen in Figure 2, the current electrical network consists of three sections: the input amplifier, the filter section, and the output stage.

The filter section provides three resonances at 0.55, 1.5, and 6.9 kHz. The values of the resistors and capacitors given in Fig. 1.5 e in Fastl and Zwicker [5] were adapted accordingly: the resonances at 0.55 and 1.5 kHz correspond to the broad maximum of the free-field response at 1.25 kHz, while the filter resonance at 6.9 kHz accounts for the narrower maximum at 6.3 kHz. The narrow dip in the free-field response at 3.15 kHz could not adequately be modeled in the active filter section without sacrificing phase coherence. A digital version of the equalizer with linear phase response could be used in the future to optimize the frequency response. The frequency dependent attenuation of the current filter is plotted as solid line in Figure 1, the phase response is shown in Figure 3.

The input amplifier and the output stage are based on the design shown in Schorer [4]. The input stage is a differential amplifier with high input impedance, so that the filter can be directly connected to standard audio equipment (e.g. line output of computers). Accordingly, the output section was modified as there is no need to directly drive electrodynamic headphones connected to

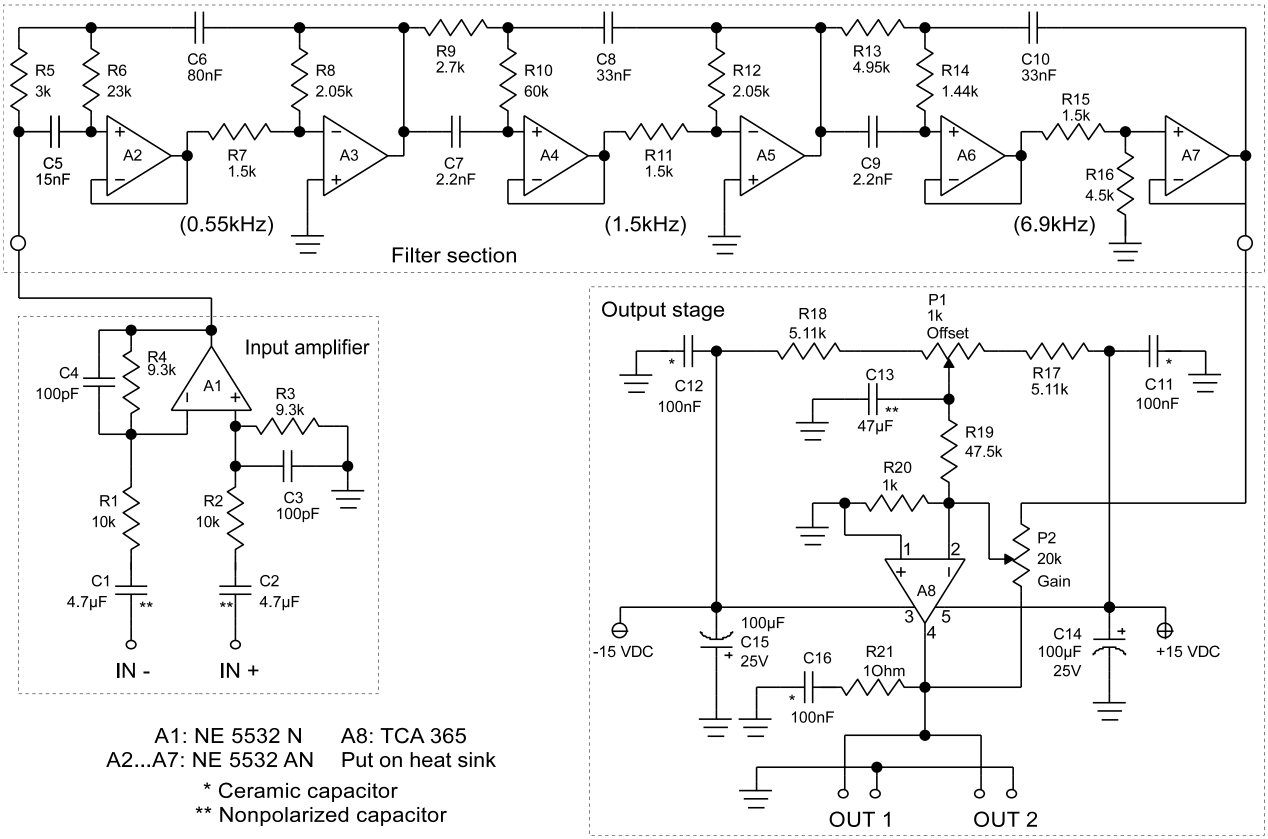

Figure 2 Circuit diagram of an active free-field equalizer for the *AudioSystem* headphones.

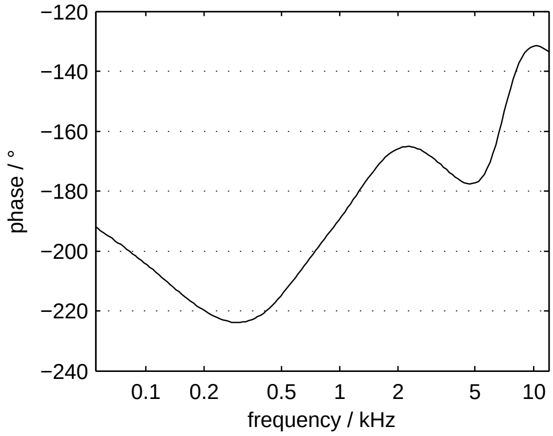

Figure 3 Phase response of the proposed free-field equalizer.

the filter. Instead, the output of the proposed equalizer is connected to the amplifier input of the *AudioSystem* headphones.

3.3. Free-field response with equalizer

For the following measurements, the equalizer was calibrated by means of the potentiometer P2 (see Figure 2) so that a voltage of 0 dBV at 1 kHz at the input of the equalizer produces a voltage of −15 dBV at the output of the equalizer, which in turn corresponds to a free-field equivalent sound pressure level of 80 dB of the headphones.

As mentioned above, three subjects, who also participated in the first experiment, measured the free-field response of the *AudioSystem* headphones with equalizer. A constant input voltage to the equalizer of -5 dBV was used which should produce an equivalent sound pressure level of 75 dB. Figure 4 shows the results of this experiment. The free-field response is independent of frequency within ±3 dB between 63 Hz and 10 kHz. The free-field equivalent level is −2 to +6 dB with the expected value.

4. Conclusion

The free-field response of a pair of *AudioSystem* headphones was measured by means of subjective loudness comparison with a reference headphone. On the basis of the resulting psychoacoustic data, a free-field equalizer for the *AudioSystem* headphones was developed, realized, and verified. The free-field equalizer now enables the use of the *AudioSystem* headphones in an MRI environment for psychoacoustic experiments which require free-field equivalent conditions for stimulus presentation.

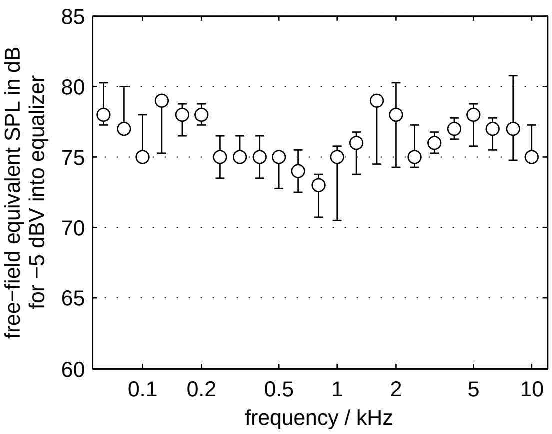

Figure 4 Free-field response of the *AudioSystem* headphones with free-field equalizer as shown in Figure 1.

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