The Effect of Objective Room Acoustic Parameters on Auditory Steady-State Responses

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Introduction

Auditory Steady-state Responses (ASSRs) are routinely used to estimate hearing threshold in pre-lingual hearing impaired infants in order to fit a hearing aid (HA). This objective HA fitting procedure requires verification in order to determine whether the subject has access to auditory input with the prescribed gain settings. Inappropriate HA amplification can lead to delayed development of language skills [1], and therefore a verification step in the fitting procedure could lead to significant clinical benefits. Since young infants are unable to express their perception of auditory events, traditional behavioural tests are highly unreliable, and validation of HA fitting becomes challenging. Thus a reliable objective test for verification of HA fitting is needed in the clinic. Some studies have already demonstrated that sound-field ASSR can be used to verify the prescribed gain of the HA device. Good correlation has been observed between aided and unaided thresholds, and provided evidence of the utility of ASSR in this application [2-6].

A novel method for verification HA fitting using ASSR where the stimuli has been designed to ensure that the HA operates in a normal speech-mode has been developed [7, 8]. The test involves sound field stimulation via a loudspeaker, since sound delivery via insert earphone (directly into the patient's ear canal) cannot be used when HAs are worn. Sound-field ASSR should ideally be measured in anechoic conditions, but for practical and economic reasons this is impossible in clinics or hospitals. Therefore, the stimuli used to elicit an ASSR will be heavily influenced by room acoustical conditions of the test rooms.

The stimulus used to elicit an evoked potential from the auditory system has certain features that must be preserved. If these are altered, the electrophysiological response will also change. One of the most important features of the signal is the modulation depth, where ASSR amplitude reduces as it decreases [9]. Modulation depth is easy to control in the electrical stimulus presented to a set of transducers, and is not adversely affected when these are insert-earphones. However, if the goal is to use sound-field stimulation, the modulation depth is in fact influenced by factors such as the reverberation time and background noise of the room [10, 11] in which the signal is reproduced. The detection of the ASSR could therefore become more difficult depending upon the acoustics of the room. The test subject may hear the stimulus perfectly (i.e. it is completely audible), but the effect of the room renders the stimulus inefficient in eliciting an ASSR, making the clinical test unreliable.

The present study aims to investigate ASSR measurements in non-ideal room conditions via an auralization approach. In this preliminary study, only the effect of the reverberation time on the ASSR amplitude was investigated. For this purpose, a room acoustic model was implemented, and the impulse responses of three different rooms were simulated and convolved with the stimuli. The resulting signals were then presented via insert earphones to the subjects and ASSRs were recorded.

Theory

Cosine room acoustic model

When modelling small rooms, it is important to consider that these have higher Schroeder frequencies and their modal behaviour thoroughly. On this basis, a cosine room acoustic model using a modal approach was used.

The frequency response of the enclosures were calculated based on a truncated Green's Function, Eq. (1), which is the complex ratio between the volume acceleration of a point monopole source at an arbitrary position and the sound pressure at another given position [12].

$$G(r, r_0) = -\frac{1}{V}\sum_{m}^{M} \frac{\Psi_m(r)\Psi_m(r_0)}{k^2 - k_m^2 - jk/(\tau_m c)} \quad (1)$$

$$\Psi_m(x, y, x) = \sqrt{\varepsilon_{n_x}\varepsilon_{n_y}\varepsilon_{n_z}} \cos\left(\frac{n_x \pi x}{l_x}\right)\cos\left(\frac{n_y \pi y}{l_y}\right)\cos\left(\frac{n_z \pi z}{l_z}\right) \quad (2)$$

Each term, represented by Eq. (2), characterizes a mode in the usual Cartesian coordinate system. The coefficients ε_{n_i} are normalization constants that take values of 1 and 2, when $i = 1$ and $i \neq 0$, respectively. The location of the source is represented by $r_0 = (x_0, y_0, z_0)$, whereas $r = (x, y, z)$ is the position where the sound pressure is determined. $V = l_x l_y l_z$ is the volume of the enclosure in cubic meters, c is the speed of sound (343m/s) and the time constant τ_m is given by $\tau_m = T_{60}/13.8$. The parameter k_m is the wavenumber corresponding to the natural frequency of the room. In order to produce a subjectively more natural sounding auralization, a small random factor $\varepsilon_m \backsim N(0,1)$ was added to the natural frequencies given by Eq. (3).

$$k_m := (1 + 0.01\varepsilon_m)k_m \quad (3)$$

The Green's function is an analytical solution to the wave equation with the boundary conditions imposed by the rigid surfaces, thus forming a cosine mode shape for each direction. This approach is appropriate for lightly damped rectangular enclosures, and specifically at low frequencies [13]. Its main advantage is that the model accurately calculates the individual modes of the rooms, which are prominent in small enclosures at low frequencies [14]. The approximation allows a realistic frequency response to be calculated that corresponds to a real-valued casual impulse response, which is obtained from the inverse Fourier transform of the simulated frequency response [12].

Auditory Steady State Responses

Auditory Steady-State Responses (ASSRs) are a compound auditory evoked potential, made up of many sources located along the auditory pathway that provides an objective assessment of the hearing system [15]. They are recorded from surface mounted electrodes, and are elicited by specific groups of neurons firing in a phase-locked manner to the envelope of an acoustic stimulus.

ASSR is a following response elicited by acoustic stimuli whose amplitude and frequency content remain constant over time having a periodic repetition modulation rate. Although amplitude modulated sine tones have traditionally been used, octave narrow-band (NB) CE-Chirp® trains are currently a popular stimulus used for ASSR recordings in the clinic. These stimuli are designed to compensate for the inherent wave traveling delay in the basilar membrane. This delay is an epiphenomenon of a relatively normally functioning inner ear, which results as a consequence of the cochlea's role in frequency selectivity. By using stimuli that compensate for the cochlear delay, a broader region on the basilar membrane is excited at the same time resulting in a synchronization of auditory nerve firing patterns and hence a larger and more reliable evoked ASSR response [16]. The CE-Chirp® family for ASSR recording consists of four NB chirp trains, with centre frequencies of 500, 1000, 2000 and 4000 Hz. Each single stimulus is presented at a slightly different repetition rate around 90 Hz.

When this signal excites the auditory system, the centre frequency of the stimulus determines the specific place in the basilar membrane that is excited. Then, the inner hair cells attached to that particular place transduce the envelope information producing a bioelectrical response that follows the repetition rate of the acoustic stimulus. The evoked potential signal is then a mixture of the ASSR and the background noise from the brain activity. ASSRs are analysed in the frequency domain, showing typically a tall peak at the modulation/repetition rate of the stimulus, and background noise dominating at all other points in the spectrum, see Figure 1.

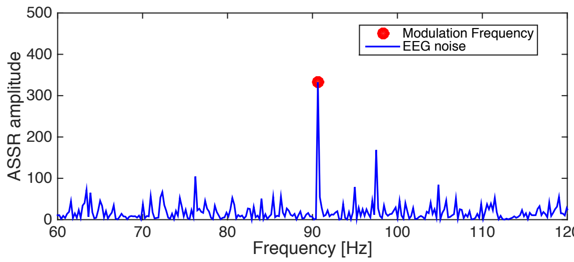


Figure 1. Example of ASSR spectrum elicited by an acoustic stimulus with modulation frequency of around 90 Hz.

Method

In this study, a monaural room auralization approach was used to simulate sound-field ASSR using insert earphones. The experiment measured ASSR where the stimuli were presented via insert earphones. The stimuli were processed in real time with the simulated impulse responses for three different rooms. The room acoustic model was implemented in MATLAB. This was validated comparing the measured and simulated impulse response for a specific source and receiver position of a given room with dimensions 3.29 × 4.38 × 2.39 m. The room was a rectangular lightly damped room with a volume of 42.8m^3, an overall reverberation time of 2.5s and a Schroeder frequency (f_{Sch}) of 412Hz.

For the experiment, the Interacoustics Eclipse platform was used. This generates the auditory stimuli, and records and processes the EEG signal. ASSRs were recorded from 15 normal-hearing subjects (7 females and 8 males) with a mean age of 24 years (range, 20 to 26 years). The stimuli were sent to an RME Fireface UCX sound card that was connected via USB to an external computer running the free version of LiveProfessor v1.2.5 software. This software serves as host program for virtual studio technology plugins (VST-plugins). The plugin SIR v1.011 was used, which is an impulse response processor that works based on the mathematical convolution operation. Then, the simulated room impulse responses were fed into the plugin for a real time processing. Finally, the acoustic stimuli were presented to the test subject via Tucker-Davis Technologies HB7 headphone driver and the ER-3A earphones, using foam ear tips.

A total of 16 conditions were tested, and defined based on the stimuli and the room condition under consideration. The four octave band CE-chirp stimuli were presented individually. Reference conditions (*Ref*) were recorded presenting the anechoic samples of the stimuli to the subjects, and three additional room conditions were studied. The rooms simulated were an audiology testing booth (*Room1*), a room recommended by the British Society of Audiology for sound-field audiometry test for paediatric assessment (*Room2*) [17, 18], and a loudspeaker listening room designed according to the standard IEC 268-13 (*Room3*) [19], summarized in Table 1. The three conditions represent potential real scenarios in health-care facilities that are likely to exist.

Table 1: Reverberation time, volume and Schroeder frequency of room conditions.

	T_{60} [s]	Volume [m^3]	f_{Sch} [Hz]
Room1 – Audiology testing booth	0.09	10.97	184
Room2 – Audiology testing room for sound-field audiometry for paediatric assessment	0.25	66.24	123
Room3 – standard listening room	0.41	98.38	128

Results

Validation of Room Acoustic Model

The room acoustic model was validated by comparing the measured and simulated impulse response in Control Room, and the reverberation time derived from them. Figure 2 shows the simulated and measured impulse response with frequency range between 10 and 10k Hz for a source position at (*1.9, 1.0, 2.48*) m and a receiver position at (*1.9, 1.0, 1.68*) m. In general, it can be observed that the model correctly simulates the rate of decay of the impulse response. However, differences in the arrival times and the amplitudes of the reflections are observed, and can be explained by the imperfections of the rectangular geometry in practice.

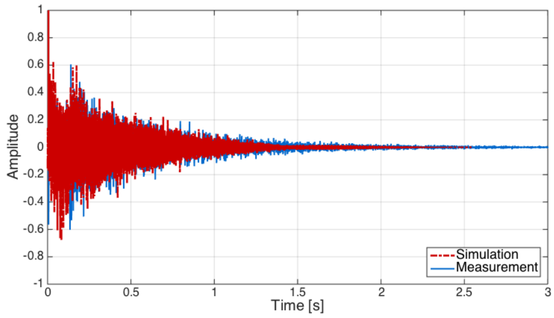


Figure 2. Measured (blue) and simulated (red) impulse response of Control Room.

Figure 3 shows the reverberation time per third octave bands derived from the simulated (red) impulse response, and obtained from spatially averaged measurements (blue) in the Control Room. A good agreement between the two curves is observed, although the model slightly underestimates the reverberation time of the room, where the biggest differences are in the middle frequency range.

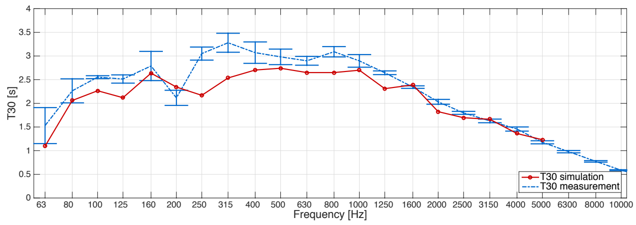
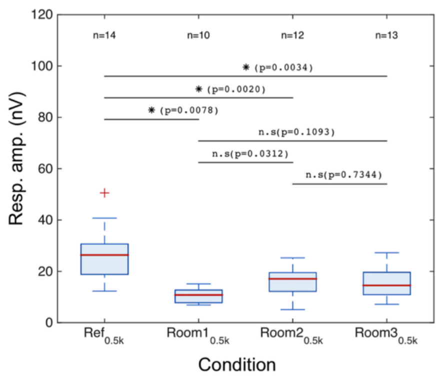


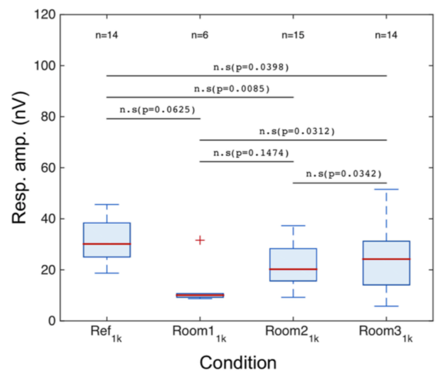
Figure 3. Reverberation time derived from the simulated (red) impulse response and obtained from spatially averaged measurements (blue) of Control Room.

Electrophysiological Recordings

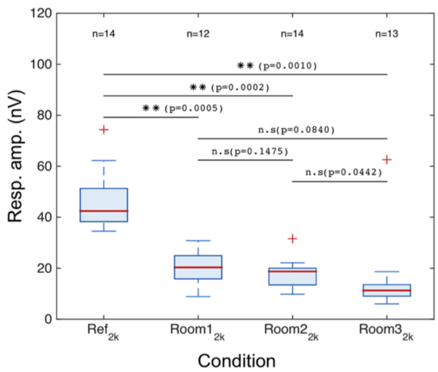
The effect of the room on the amplitude of the auditory steady state responses is analysed per each frequency narrow band CE-chirp. Figure 4 shows the summary data presenting the range of variation of response amplitudes per condition as boxplots. An ASSR response here is defined as the amplitude (nV) of the fundamental frequency of the ASSR spectrum. Each boxplot accounts for the data collected used in the analysis, where n stands for the number of test subjects in which was possible to detect the ASSR for the given condition. The statistical results are also presented in the plot. The Wilcoxon signed-rank test was used, for which more information is found in Ref [20]. This test was implemented to determine significance differences across each paired data. To do so, a Bonferroni correction of 6 was used with a significance level of $p=0.05$, resulting in a $p=0.0083$.



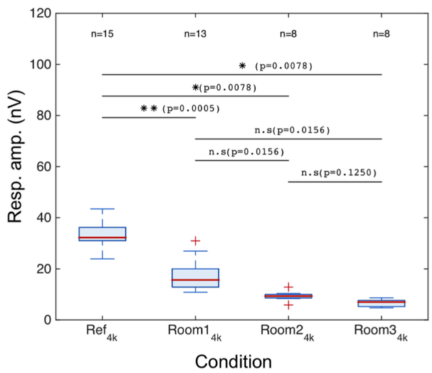
(a) 500 Hz Octave Band



(b) 1000 Hz Octave Band



(c) 2000 Hz Octave Band



(d) 4000 Hz Octave Band

Figure 4. Experimental results of ASSR recording. Highly significant differences are represented by **($p \leq 0.0017$) and significant differences are represented by *($0.0017 < p \leq 0.0083$).

It is easy to see from visual inspection of the results that there is a change in the ASSR amplitude due to the effect of the enclosures. Figure 4.(a) illustrates the results for the 500 Hz octave band chirp. The response amplitude is clearly affected by the room conditions, especially for Room1. A marked tendency is presented for the 2 kHz and 4 kHz CE-Chirps, sub-figures 4.(c) and 4.(d), respectively. Here, it can be observed that the longer the reverberation time, the lower the amplitude of the response. For 500 Hz, 2 kHz and 4 kHz narrow band CE-Chirps the statistical test revealed significance differences between the baseline condition and the room conditions. However, between the different room conditions a significant effect was not observed. For the 1 kHz octave band Chirp, in Figure 4.(b), the ASSR amplitude is reduced for the room conditions, particularly for Room1. Nevertheless, no significant differences were observed due to an unbalanced sample number between the rooms.

Discussion

Overall these preliminary results suggest that room acoustic conditions can highly influence the amplitude of the auditory steady-state response, which, in turn, could reduce detectability and hence clinical utility. The ASSR recordings showed a clear reduction in the response amplitude due to the room effect that was also reflected in the statistical analysis, where significant difference were obtained between the reference conditions and room conditions for the octave bands of 500 Hz, 2 kHz and 4 kHz. For the pair Ref_{1k} – $Room1_{1k}$ there were no statistical differences, which can be explained by the fact that the power of the Wilcoxon signed-rank test goes down when unbalanced data is compared. For condition $Room1_{1k}$, the ASSRs of only 6 test subject were obtained, whereas for condition Ref_{1k} the responses were detected for 14 subjects.

For further work, it will be analysed the effect of the room on the envelope of the acoustic stimuli, which is essential for eliciting ASSRs. The envelope spectrum of the original stimuli and the stimuli filtered by the rooms will be examined to quantify the changes, and correlate this with the outcome of the ASSR test. It is expected that the ASSR results can be explained by linking the potential degradation of the acoustic stimuli due to the room with the reduction in the ASSR amplitude.

Conclusions

This study showed that the room acoustics can affect directly the response amplitude of sound field ASSR, which is a promising tool for hearing aid fitting verification. However, before this test can be implemented routinely, it should be properly characterized and quantified the effect of objective room acoustic parameters on the electrophysiological response.

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