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Effect of Head-Movement on Sound-Field Auditory Steady State Response Measurement

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ABSTRACT

Sound-field auditory steady-state response (sound-field ASSR) measurement is an objective alternative for hearing aid fitting validation in infants. For including the hearing aid in the signal path, the stimulus is presented via a loudspeaker. In this case, ASSR can be affected by the head orientation of the participants and the measurement room resulting from the change in degree of modulation of the stimulus in the measurement room. Eleven normal hearing participants were tested for three static head-orientations relative to the loudspeaker in two different rooms. A speech modified NB CE-Chirps stimulus was used to eventually force the hearing aid under test to provide the correct gain. The rooms chosen for measurement were an IEC listening room (T30 of about 0.5 s) and an anechoic chamber (reference condition). A dynamic head-orientation condition comparable to a real head-movement was simulated by randomly combining the responses from the three static head-orientation measurements. The results show a limited influence of head orientation on ASSR level. However, at 4 kHz, a significant reduction in ASSR level was observed when the test ear was oriented away from the loudspeaker. The overall mean ASSR level in the IEC room was reduced by 2.5 dB with reference to the anechoic condition.

Keywords: auditory steady-state response (ASSR), hearing-aid validation, head-movement

1. INTRODUCTION

The improvement in newborn hearing screening has resulted in infants being prescribed with hearing aids at a tender age down to two months. The standard validation tools like aided audiometry or questionnaires are ineffective in these circumstances. Hence, an objective electrophysiological method called steady-state auditory response (ASSR) measurement is considered (1). In sound-field ASSR, the stimulus is presented through a loudspeaker to include the hearing aid in the signal path. This approach comes with several challenges. The reverberation time and background noise of the measurement room can affect the modulation depth of the signal resulting in a reduced ASSR level (2). The head-orientation of the infant during the recording may also affect the ASSR level. These two challenges associated with the sound field ASSR were investigated in this study.

The effect of the room on the ASSR was first examined using simulated room environments (2). This study instead measured sound-field ASSR in two real rooms to investigate the effect of the room. The two rooms were an anechoic chamber and an IEC standard listening room (T_{30}~0.5 s) The ASSR was recorded at three pre-defined static head-orientations to investigate the effect of head-movement. The static head-orientations were considered as the analysis blocks ("epochs") will be rejected during the actual head-movement due to increase in EEG noise floor resulting from the muscle activity and strain during the movement. Hence, the resultant ASSR in this condition would be an average across the different static head orientations over the whole measurement period. A dynamic head-orientation

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condition was simulated from the static head-orientation responses for mimicking the response of natural head-movement during the measurement.

The recorded responses were post-processed and statistically analyzed for comparing the ASSR level, detection time, EEG-noise levels, and detection rate for the defined measurement conditions. For choosing a favorable position for the ASSR measurement in the room, modulation power analysis, a useful tool in characterizing the efficacy of the stimuli for ASSR measurement (3), was performed.

2. METHODS AND MATERIAL

The measurements were carried out on 11 normal hearing test subjects (6 males and 5 females) with a mean age of 25 years. All the participants gave written informed consent and were compensated for their participation. The study was conducted under the approval of the Science-Ethics Committee for the capital region of Denmark.

The stimulus used for the measurement was an ISTS-modified NB CE-Chirp (3). This stimulus has speech like properties, which is critical in the validation of hearing aids in their normal mode of operation, to ensure that correct gain and signal processing features are activated. Each one-octave band CE-chirp (4) was modified by applying the frequency-specific envelope of the International Speech Test Signal (5). The response evoked by each octave-band is identified by the repetition rate at which it was presented. Four-octave band CE-chirps were used, centered at 0.5, 1, 2, and 4 kHz with repetition rates of 90.8, 94.7, 102.5 and 96.7 Hz, respectively. The basic NB-CE chirp was created with a 32-kHz sampling frequency and 65536 samples per epoch, corresponding to a period of 2.048 seconds.

The participants were lying down comfortably on a bed, and the room was darkened during the measurement. Only one ear was stimulated at a time, while the other ear was blocked using an earplug. Standard 4-electrode montage (high forehead reference, ipsi- and contra-lateral mastoids active, and cheek ground) were used for the ASSR recording. A custom-made MATLAB software loaded to a laptop controlled the playback and recording. The stimulus was routed to an in-house built two-way coaxial loudspeaker, placed 1 meter above the test subject's head, through an audio chain comprising of an RME Fireface UC soundcard, a graphic equalizer, a custom-made crossover filter, two attenuators, and an audio power amplifier. The Interacoustics Eclipse unit was used as the front-end to deliver the line-level EEG signal to the RME Fireface UC soundcard.

To evaluate the effect of head-movement, three static head-orientation conditions were defined, namely, No Head-Movement (NHM), Towards the Speaker (TS) and Away from the Speaker (AS). These head-orientation conditions were characterized concerning the position of the test ear in relation to the loudspeaker. In the NHM condition, the participants were instructed to not to move their head and look straight at the speaker for the entire duration of the measurement. Then, the participants were asked to move the test ear towards the speaker and hold that position for the TS condition. For AS, the participants moved the test ear away from the speaker. This is illustrated in Figure 1. The head-orientation of the participants for the TS and AS conditions were not constrained to a specific angle but were left to the test subject's comfort and convenience, to keep muscle artifacts in the EEG signals to a minimum.

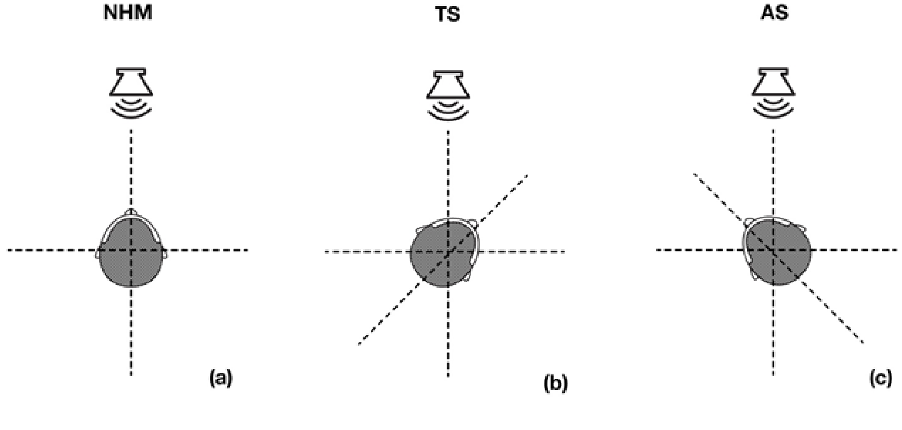

Figure 1: Static head-orientation conditions with reference to left ear (stimulated ear): (a) No Head-Movement (NHM), (b) Towards the Speaker (TS), and (c) Away from the speaker (AS)

Two room conditions were identified to understand the effect of the room on the ASSR measurement. The first one was an anechoic chamber of dimension 4.8m x 4.1 m x 2.9 m (L x W x H). This chamber is considered anechoic from 100 Hz to 10 kHz. The second one was IEC 60268-13 standard listening room henceforth referred to as the IEC room. The IEC room (7.52 m x 4.74 m x 2.76 m) with a T_{30} of about 0.5 seconds is comparable to a clinical room, albeit somewhat larger than a typical clinic. The anechoic chamber was considered the reference condition. The results from the IEC room were compared with those from the anechoic chamber to understand the effect of the room.

Before conducting the actual ASSR measurement, an un-normalized modulation power analysis of the stimulus was performed. This analysis intends to predict the ASSR efficacy of the stimulus (3) in a given room and head-orientation condition. The stimulus was convolved with the impulse responses recorded using a HATS and a DIRAC system for every defined room and head-movement condition. This convolved stimulus was then passed through a gammatone filter bank having 24 filters $1/24^{th}$ octave spaced apart representing the auditory filter with respect to the octave bands of interest (0.5 through 4 kHz). Edge effects were removed for the aperiodic speech-modified stimulus by multiplying the sample epochs of each Hilbert envelope by a raised cosine window. Then a discrete Fourier transform was applied on the gated envelopes, and the resulting modulation power was averaged across the epochs and the 24 gammtone filter bands. The modulation power at each octave frequency band was evaluated at the fundamental corresponding repetition rate (ignoring the higher harmonics). The modulation power analysis was used to screen out un-favorable measurement positions.

The ASSR was recorded for all the participants at first in the anechoic chamber and then in the IEC room for the three defined static head-orientation conditions and for both ears. Special care was taken to measure with low EEG noise levels (henceforth referred to as noise level), meeting the rejection ratio of 40 µV. A simple F-detector (6) comparing the power at the repetition rate to the average power across 10 frequency bins on either side of the repetition rate was used to evaluate the detection of the first harmonic at the repetition rate in question. A Bonferroni corrected 1% error rate was used for this test. The measurement was concluded once the F-statistics for all four octave-bands were above the F-critical value, or after a maximum of 20 minutes of recording time. Continuous averaging of response and noise frequency bins improved the signal to noise ratio.

A simulated dynamic head-orientation condition comparable to real head-movement was constructed by combining one-third of each static head-orientation recording for each participant. Initially, the responses were truncated to the length of the recording with the least number of epochs, and these responses were divided into three parts. Then, one of the three parts of each static head-orientation condition was chosen randomly and combined in a random order to simulate the dynamic head-orientation condition. This is illustrated in Figure 2.

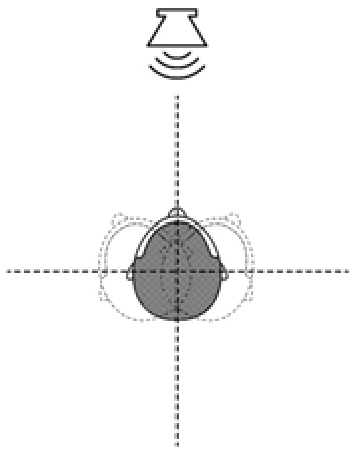

Figure 2: Illustration of simulated dynamic head-orientation condition.

Subsequently, the recorded responses were post-processed along with the simulated dynamic head-movement response. Three primary outcomes: noise-corrected ASSR level, detection time, and noise level were considered. In addition, detection rates were calculated. The noise corrected ASSR level (referred as ASSR level hereafter) was calculated as the difference between the estimated power at the response harmonic and the noise power (6) converted to dB for a better assessment of relative changes across conditions. The detection time was determined as the first time a response was detected with an F-detector using a 5% error rate in the successive weighted average. Any corrections for the repeated measure was thus ignored. A $\log_{10}$ transformation (relative to 1 s) of the determined detection time was performed, and this log-transformed detection time is termed T_{log}. The log transformation was found to yield a more even distribution of residuals in the statistical analysis (3). The noise level was estimated by averaging the noise power in the 10 bands on either side of the response harmonic with respect to a specific repetition rate. The frequency bins close to 50 Hz line-noise, other know interferences, and any other repetition rate harmonics were excluded. The noise level thus determined was later adjusted to the level that would have been found at a testing time of 100 s. This was achieved by adding 10 x $\log_{10}$ (t/100) to the noise level (in dB) of the whole recording, where t is the full recording time. This level is termed L_{100}. This adjustment was necessary as the noise is expected to be lower with longer measurement time. As explained above, some measurements were concluded after reaching the F-critical value, which means that the recording time of each measurement need not be 20 minutes.

The three outcomes of the post-processing: ASSR level, T_{log}, and L_{100} were analyzed using a linear mixed model, whereas the detection rate was analyzed using non-parametric statistical tests. In the mixed effects model, the participants (TP: 1, 2, 3..., 11) were considered a random effect. The fixed effects considered were: test ear (TE: Left and Right), room conditions (RC: Anechoic and IEC), head-orientation condition (HOC: NHM, TS, AS, DHM), and stimulus frequency (FREQ: 0.5, 1, 2, and 4 kHz). Estimated marginal means (7) were determined for the best-fit model, and a post-hoc analysis comparing the means was performed using the Tukey method (8).

3. Results

The mixed model ANOVA results for the three primary outcomes are shown in *Table 1*. For the ASSR level and L_{100} models, the test subject was found to be significant (p<0.001***).

Table 1: Summarized mixed model ANOVA results. Only the significant main effects and interactions are presented. ***p<0.001, **p<0.01, *p<0.05

	ASSR level		Detection Time (T_{log})		Noise Level (L_{100})	
Factor	F statistics	Pr(>F)	F statistics	Pr(>F)	F statistics	Pr(>F)
FREQ	F(3,612)=35	<0.001***	F(3,662)=6	<0.001***		
RC	F(1,612)=83	<0.001***	F(1,662)=4	0.011**	F(1,678)=41	<0.001***
HOC	F(3,612)=11	<0.001***				
HOC:FREQ	F(9,612)=6	<0.001***				
HOC:RC					F(3,678)=9	<0.001***
HOC:TE					F(3,678)=4	0.006**
RC:HOC:TE					F(3,678)=5	0.002**

3.1 ASSR Level

The plot concerning the effect of stimulus frequency, head-orientation, and room conditions is shown in Figure 3. Even though the third order interaction is not significant, it helps to visualize all the significant effects in a single plot, in combination with post-hoc testing (Tukey HSD). Regarding the main effect of FREQ, the post-hoc analysis showed that levels at 0.5 and 1 kHz were significantly smaller than those at 2 and 4 kHz (all p<0.001). The significant main effect of room (RC) indicates lower levels in the IEC room. The overall mean reduction in ASSR level in the IEC room was approximately 2.5dB. For the main effect of head orientation (HOC), the post-hoc analysis shows that only the AS condition is significantly different from the other three (all p<0.05). Finally, regarding the significant HOC:FREQ interaction, the post-hoc results show a significant difference only for the AS condition at 4 kHz (p<0.001).

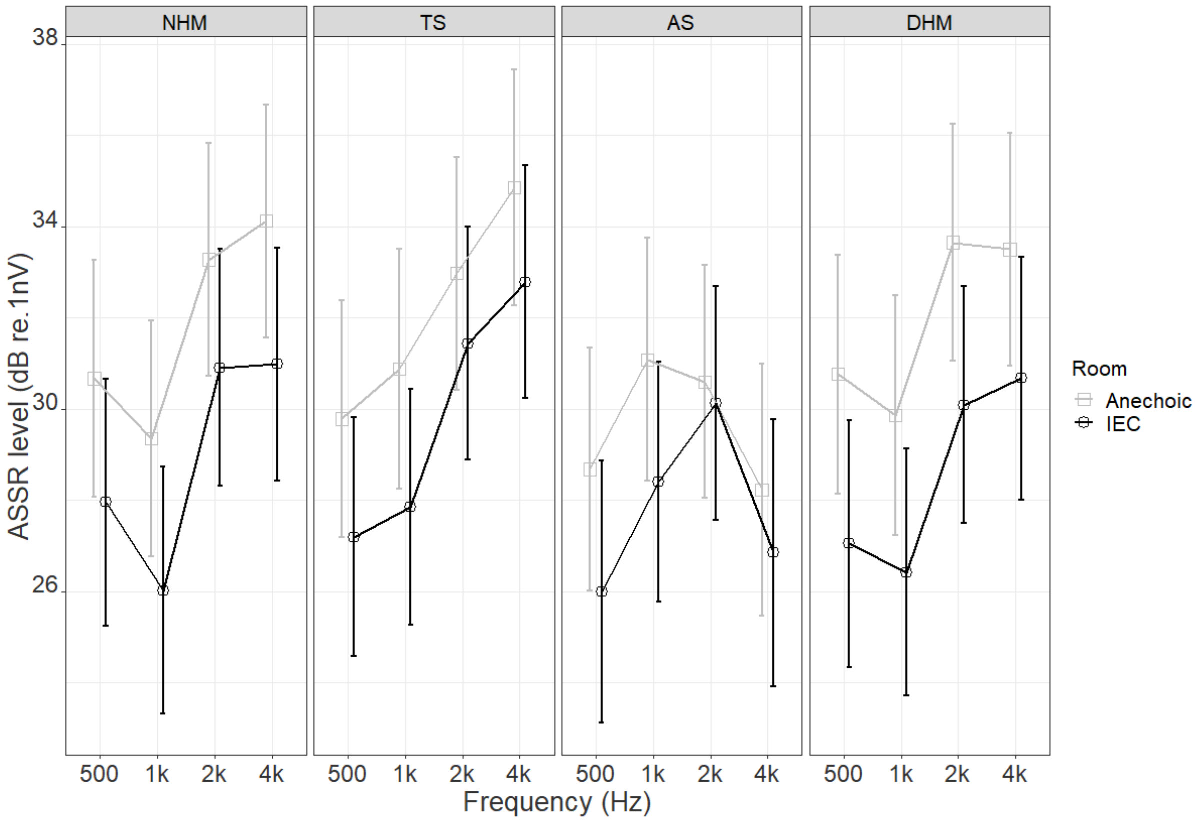

Figure 3: Estimated marginal mean ASSR level plotted across stimulus frequency, room condition, and head-orientation. Error bar indicates 95% confidence interval.

3.2 Detection Time

Figure 4 shows that the higher frequencies (2 and 4 kHz) had lower detection times than the lower frequencies (0.5 and 1 kHz). Also, from Figure 5, it can be seen that detection times in the IEC room were significantly higher than those from the anechoic chamber.

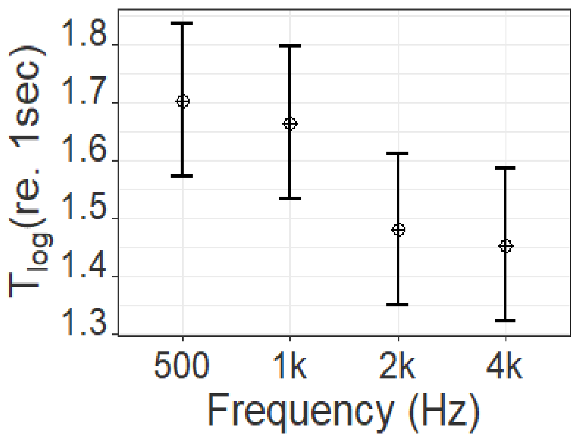

Figure 4: Estimated marginal mean detection time corresponding to stimulus frequency. Error bar indicates 95% confidence interval

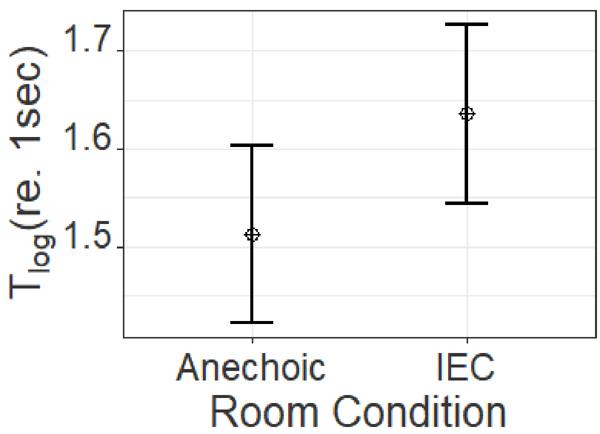

Figure 5: Estimated marginal mean detection time corresponding to room conditions. Error bar indicates 95% confidence interval

3.3 Noise Level

Figure 6 shows the plot concerning the effect of head-orientation, test ear, and room condition on L_{100}. The most interesting result is the significant reduction in noise level in the IEC room. The post-hoc results for the interaction RC:HOC showed that the major contributor to the overall decrease in the noise level in the IEC room was the TS condition. For the significant HOC:TE interaction, the post-hoc result showed a significant difference between the NHM and TS condition for the left ear. The post-hoc analysis on the third order RC:HOC:TE interaction revealed that the difference in noise level at IEC and anechoic chamber were most significant for TS condition for both left and right ears (both $p<0.001$).

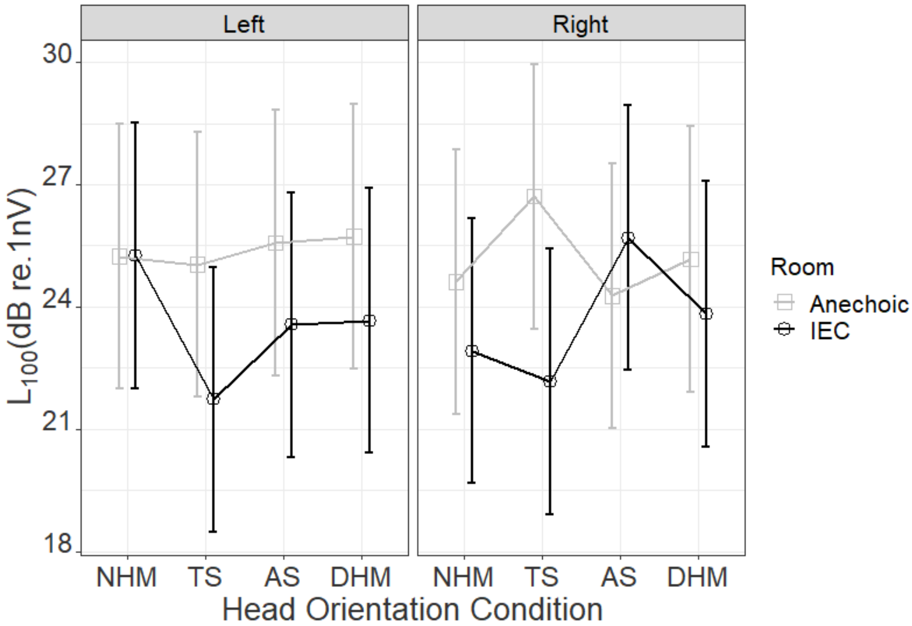

Figure 6: Estimated marginal mean noise level L_{100} (dB re. 1nV) plotted across head-orientation, test ear, and room condition. Error bar indicates 95% confidence interval.

3.4 Detection Rate

An overall detection rate of 91% was obtained (63 non-detections out of 703 data points). The results presented in Table 2 show higher detection at higher frequencies (2 and 4 kHz). The AS condition had the lowest detection rates in both anechoic and IEC room. A Fisher exact test revealed that the reduction in aggregate detection rate at IEC room (89%) compared to the anechoic chamber (93%) was significant ($p=0.017$).

Table 2: Detection rate in percentage across stimulus frequency, head-orientation conditions, and room conditions.

FREQ	Anechoic Chamber				IEC Room				FREQ
	NHM	TS	AS	DHM	NHM	TS	AS	DHM	(Aggregate %)
0.5 kHz	95	95	86	91	82	91	68	82	86
1 kHz	95	91	86	91	82	95	91	82	89
2 kHz	100	100	100	95	95	100	100	95	98
4 kHz	100	95	77	100	100	100	64	86	90
HOC (Aggregate %)	98	95	87	94	90	97	81	86	
RC (Aggregate %)	93				89				

4. DISCUSSION

The general trend in the ASSR levels concerning the stimulus frequency is in good agreement with the previous study (3), with higher ASSR levels towards higher frequencies (except for the AS condition at 4 kHz). It is concluded that the effect of head-movement on ASSR level was limited because the ASSR level for DHM condition corresponding to real head-movement was not significantly different from NHM condition. However, if the head is oriented as in AS condition for the entire time of recording, this could result in a significant reduction of ASSR level at 4 kHz. The observed decrease in ASSR level at 4 kHz for AS condition can be attributed to the head-shadow effect. The mean reduction of ASSR level of 2.5 dB in the IEC room compared to the anechoic chamber is associated with the change in acoustics. The reflections from the surfaces and edges in the IEC room can alter the degree of modulation of the stimulus resulting in a reduced ASSR level.

The detection times generally showed an inverse pattern relative to the ASSR level, in agreement with the previous study (3). It is expected that an increase in ASSR level is accompanied by a reduced detection time, as the criterion signal-to-noise ratio is reached faster with a strong signal. The detection rates also showed close relation to the ASSR level, with the higher detection rates at higher frequencies and a significantly reduced detection rate in the IEC room.

The noise level results were peculiar; the reduction in noise level in the IEC room was unexpected. It could be speculated that the participants were more relaxed and comfortable in the IEC room. During the informal discussion after the measurement, some participant commented that the sound from the speaker in IEC room was more diffused and appealing than the sharp and uncomfortable sound in the anechoic chamber. However, a couple of participants felt the anechoic chamber to be more relaxing. There can also be an order effect as the measurements were first performed in the anechoic chamber. Also, most of the participants did not have prior experience with participating in electrophysiological experiments. All these could have resulted in an increased noise level in the anechoic chamber.

5. CONCLUSIONS

The aim of the study was two-fold: primarily to understand the effect of head-movement on sound-field ASSR and secondarily to understand the influence of the measurement room. The measurements were carried out in an IEC standard listening room and anechoic chamber with three predefined static head-orientation conditions.

The main findings from the study are:

- The comparison of results for NHM and DHM head-orientation condition indicates a minimal effect of head-movement on ASSR. DHM is considered comparable to a real head-movement. However, the AS condition at 4 kHz can influence the overall ASSR level and can have serious implication in a clinical setting.

- The change in acoustics in the IEC room resulted in an overall mean reduction of 2.5 dB in the ASSR level compared to the anechoic chamber. This establishes the influence of the measurement room on ASSR measurements.

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