Provoking and minimising potentially destructive binaural stimulation effects in auditory steady-state response (ASSR) measurements

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An aided sound-field auditory steady state response (ASSR) has the potential to be used to verify the quality of fit of hearing aids on infants. Each aided ear should ideally be tested independently, but it is suspected that binaural testing may be used by clinics to reduce test time. This study simulates 'clinically conceivable' dichotic ASSR sound-field conditions to examine the risk of making false judgements due to unchecked binaural effects. Unaided ASSRs were recorded with a clinical two channel EEG system for 15 normally hearing subjects using a three-band CE-Chirp™ stimulus. It was found that the noise corrected power of a response harmonic can be reduced by up to 10 dB by introducing large ITDs equal to half the time period of the stimulus envelope. This could lead to concluding that a hearing aid fitting is poor, even though the fitting would have passed separate monaural ASSR tests (false referral). No effect was detected for simulated lateralisations of the stimulus, which is beneficial for a proposed aided ASSR approach. Full-scalp ASSR recordings show distinct SNR reductions and topographical changes in response to the large ITDs, and demonstrate the vulnerability of ASSR to montage and inter-subject variation. Findings suggest that multi-harmonic detectors could make binaural measurements robust to artificial reductions of response harmonics cause by large ITDs.

INTRODUCTION

The auditory steady-state response (ASSR) can be used to assess the hearing of non-responsive subjects such as infants, and by extension, when the stimulus is presented as a sound field, assess individually the quality-of-fit of the hearing aid(s) (HA) once adapted to a patient (Rance, 2008). Stimuli presented above the estimated aided ASSR thresholds, monaurally, should provoke a response which is greater than the noise floor by a predetermined F-test ratio to be considered present. The presence of a response then infers that the HA fit is good.

There is, however, the potential that clinics wish to test binaurally, as it has the possibility not only to reduce the testing time by half compared to two independent

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monaural tests but also improves test transparency to parents (Mehta *et al.*, 2019). Despite the apparent benefits binaural testing also has the possibility to introduce interference effects, as a nominally diotic presentation may be disturbed (e.g. by head movement) to produce in reality a dichotic stimulus. In the worst case this may produce artificial test false-negatives, leading to unnecessary additional referrals.

Subsequently, this study considers if it is possible that a single perturbed binaural measurement could lead to a referral whereas the preferred two individual monaural measurements would not.

There are few previous studies investigating plausible clinical dichotic scenarios; Zhang & Boettcher (2008) found that separately increasing interaural time and level differences (ITDs and ILDs) caused positive and negative binaural interaction components (BICs) respectively on 80 Hz click ASSR, while Narayanan (2018) found that a monaural ASSR to a 4 kHz octave band chip carrier can be significantly reduced by a lateralised presentation due to the subject's head shadow. Riedel & Kollmeier (2002) used 15 Hz click auditory brainstem responses (ABR) and found that laterally perceived stimuli produce lower wave V amplitudes than those perceived centrally. Much larger ITDs may also occur in the cases of unilateral digital aid users, where signal processing may delay the arrival of sound ($\approx 5 - 10$ ms Kates, 2008) to the aided ear compared to the unaided. The current study assesses how large ITDs as well as simulated 'realistic' combinations of ITDs and ILDs effect ASSR amplitudes.

METHODS

Two-channel EEG

Fifteen (seven female) normally hearing (symmetric $<$ 20 dB HL 250 Hz - 4 kHz) young (mean 23.2 years, $\pm$ 2.20) listeners participated in the measurements with the two-channel EEG. All participants provided informed consent and all experiments were approved by the Science-Ethics Committee for the Capital Region of Denmark (ref. H-16036391). The stimulus, presented in a soundproof booth, unaided, over Eytmotic ER-1 insert phones, consisted of three modified CE-Chirp^{TM} chirp trains: a double octave width 707 Hz centered (40 Hz rate band), and two single octave width 2 kHz and 4 kHz (90 Hz rate bands). Stimuli were presented at a nominal broadband free-field level of 65 dB SPL with each chirp train scaled to match the equivalent band power of the Internation Speech Test Signal (ISTS) (Holube *et al.*, 2010); except in the case of the lateralised stimuli where frequency banded gains and attenuations were applied derived from Denk *et al.* (2018) behind-the-ear (BTE) head related transfer functions (HRTFs), shown in Figure 2.

The stimulus conditions consisted of a reference diotic condition and seven dichotic conditions. The dichotic stimuli were of three types: (1) rate-specific ITD resulting in envelope anti-phase of either the 40 Hz rate band ('Inv 40', see Figure 1) or the 90 Hz rate band ('Inv 90'), (2) interaural inverse polarities with no effect on the envelopes ('Inv Pol'), (3) lateralised with realistic combinations of ITDs and ILDs to simulate incidence of the stimulus from ±45 degrees (ITD: 354 µs) and ± 90 degrees (ITD: 688 µs) on the azimuthal plane. Data collection for each condition continued until a Bonferroni corrected F-test threshold (corresponding to a p-value of 0.01) was reached for all three response bands in both channels, or until 15 minutes had passed.

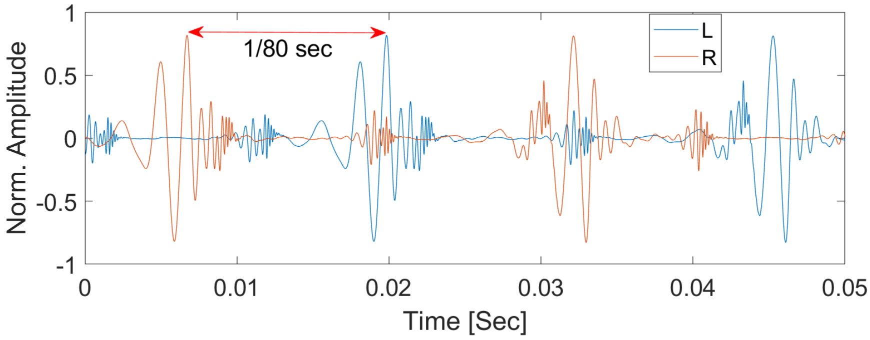

Fig. 1: Stimulus waveforms for left and right channels in the Inv 40 condition. An ITD of $\approx 1/80$ s was introduced to place the envelopes of the 40 Hz rate band into interaural antiphase)

ASSRs were measured using an adapted clinical two-channel EEG system (Interacoustics Eclipse) connected to an RME Fireface UC soundcard, with a vertex - mastoid montage. The data were recorded and processed in custom software using MATLAB. The first two harmonics of the corresponding repetition rate in the averaged frequency domain representation were considered. Reported ASSR levels were noise corrected (NC) by subtracting the mean level of the surrounding 20 frequency bins of each respective response bin, avoiding other response bins or known particularly contaminated bins (e.g., line noise, radio bands).

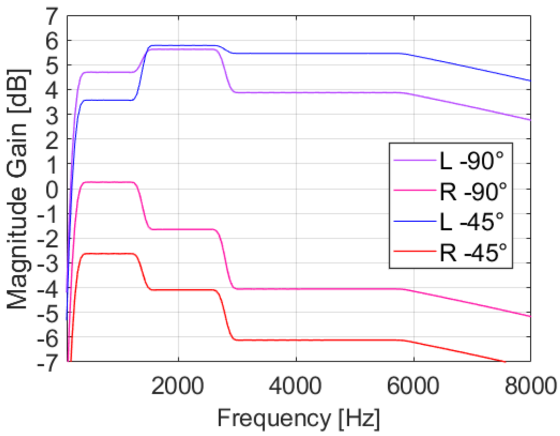

Fig. 2: Frequency band specific gains or attenuations, derived from Denk *et al.* (2018), used to simulate head shadow and baffle effects for stimuli incident from the left; $-45°$ and $-90°$.

The resulting ASSR amplitudes were compared by fitting mixed linear models, implemented in R using the 'lme4' (Bates *et al.*, 2015) package, followed by planned pairwise analysis of variance (ANOVA) comparisons between each condition and the diotic reference with 'lmerTest' (Kuznetsova *et al.*, 2017).

64-channel scalp topography

The Inv 40 condition and the diotic reference were repeated using a 64 channel (BioSemi Active Two) full scalp montage. Four subjects participated in this experiment; two that showed large changes and two that showed small changes between these two conditions in the preceding experiment. The data were low-pass filtered at 1638 Hz, and then stored. Offline, the raw data epochs were high and low pass filtered at 20 Hz and 400 Hz respectively using forward-backward filtering with 2^{nd} order Butterworth filters, in addition to notch filters at 50 Hz, 100 Hz, and 150 Hz. Epochs were automatically and manually screened for muscle activity artifacts and affected epochs were removed. Channels were re-referenced to the grand mean of all EEG channels. The scalp topography was calculated from the signal-to-noise ratios (SNRs), with consistently noisy channels replaced with data interpolated from spatial neighbours using the MATLAB cubic interpolation. Most processing was implemented using the FieldTrip toolbox (Oostenveld *et al.*, 2011) for MATLAB.

RESULTS

Two-channel EEG

Figure 3 shows the noise-corrected ASSR amplitudes for the two-channel recording divided by harmonic and band response. Only the Inv 40 condition produced responses significantly lower than the corresponding Diotic: in the first harmonic of the 707 Hz band, and in the second harmonics of the 2 kHz and 4 kHz bands. First harmonic responses are generally greater than second harmonic, and 707 Hz band responses are generally greater than the other two bands. This is supported by the significant factors Harmonic and Stimulus Frequency in Table 1.

Factor	**ASSR NC Power Level**	
	F statistics	**p**
Subject (random)		<0.0001***
Condition	F(9,1467.4) = 45.6	<0.0001***
Stimulus Freq.	F(2,1467.1) = 123	<0.0001***
Harmonic	F(1,1467.1) = 496	<0.0001***
Channel	F(1,1467.4) = 1.83	0.176
Condition: Stim. Freq.	F(18,1467.0) = 0.565	0.925
Condition: Harmonic	F(9,1467.0) = 1.47	0.154
Stim. Freq.:Harmonic	F(2,1467.1) = 3.95	0.0195*
Stim. Freq.:Channel	F(2,1467.0) = 4.21	0.0151*
Cond.:Stim. Freq.: Harm	F(18,1467.1) = 8.73	<0.0001***

Table 1: ASSR NC level F-test statistics derived from a mixed linear models fit to the processed data from the main 'phase 2' experiment. Type III Analysis of Variance with Satterthwaite's method. Significance codes: 0 - ***, 0.001 - **, 0.01 - *, 0.05 - .

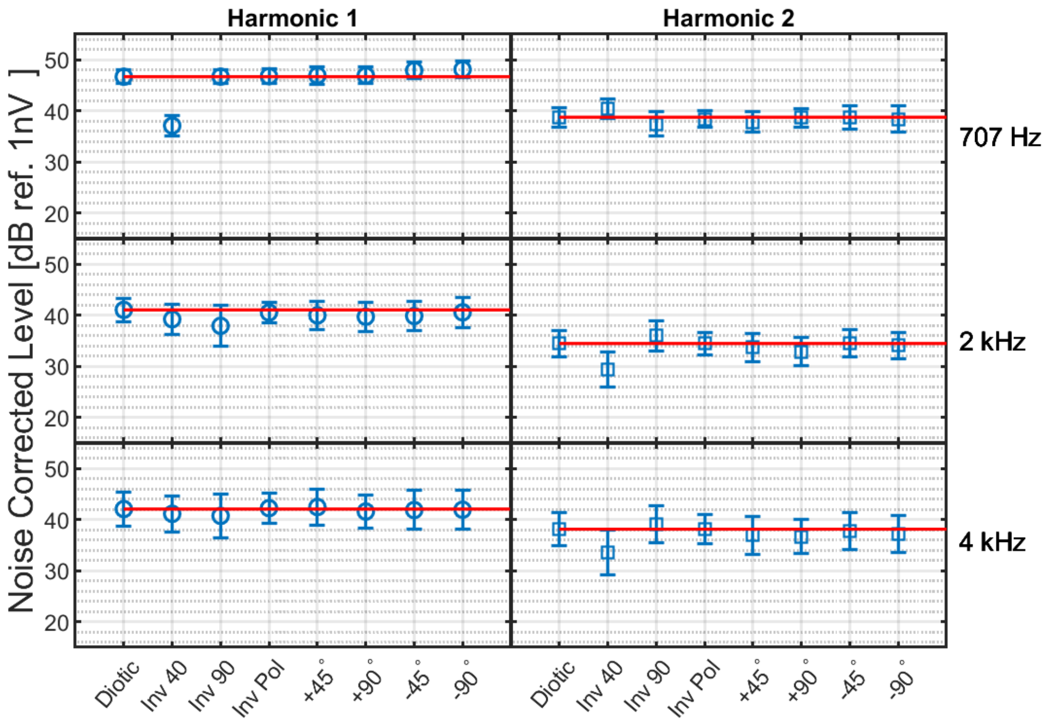

Fig. 3: Noise corrected level of the ASSR for each stimulus condition, shown separately for each stimulus frequency band and response harmonic. Means were taken across subjects and both channels. Error bars represent 95% confidence intervals. The red horizontal lines correspond to the mean level of the relevant reference diotic condition.

Table 1 summarises the F-test statistics from the model fit to the ASSR NC level data. The strong random effect of Subject indicates significant variation among subjects, as expected (Laugesen *et al.*, 2018). The significant factor Condition and three way interaction indicates that the Inv 40 condition has a varied effect depending on the response harmonic and band. The planned pairwise comparisons confirms that the NC ASSR amplitudes were significantly lower in the Inv 40 condition in the first harmonic 707 Hz band (−9.9 dB, $p < 0.0001$) than the corresponding Diotic condition response. Furthermore, amplitudes were also significantly reduced in the Inv 40 Condition in the second harmonic, 2 kHz and 4 kHz bands, (−6.8 dB, $p < 0.0001$ & −5.7 dB, $p = 0.000432$), compared to the corresponding Diotic condition response. No other modifications of the diotic stimulus led to a significant change in the ASSR amplitude.

64-channel scalp topography

Figure 4 shows the 707 Hz band SNR topography for all 64 electrodes for the diotic (left column) and the Inv 40 condition (right column).

In the diotic condition, all listeners had a maximum of the SNR along the vertex-nasion axis with a minimum in often both hemispheres. The location of these minima though were variable. In the Inv 40 condition a reduction of the average SNR was found across all listeners. Inversely now all listeners showed a minimum of the SNR along the vertex-nasion axis, with maxima now occurring reliably lateralised but varying from frontal (subject 8) to occipital (subject 17). It is interesting to note that the vertex electrode in the two-channel EEG montage was for most subjects located in the vicinity of a maximum in the diotic condition and close to a minimum in the Inv 40 condition.

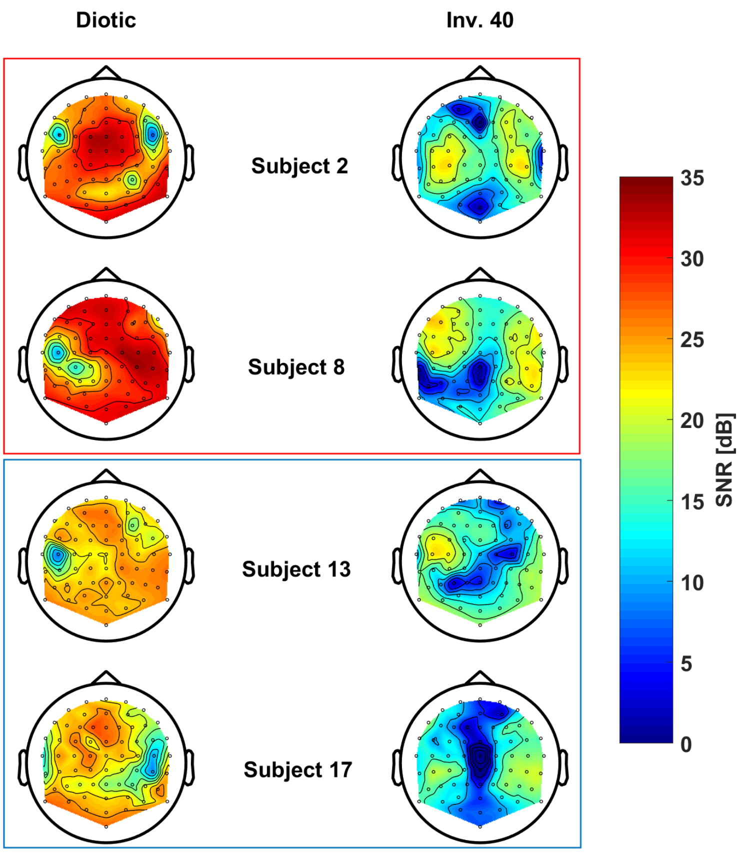

Fig. 4: Mean 707 Hz band SNR topography of the 64 channel scalp montage separately plotted for four subjects during diotic (left column) and Inv 40 (right column) stimulation. The red and blue enclosing boxes indicate the subjects demonstrating large and small reductions in ASSR level from diotic to Inv 40 stimulation respectively.

The SNR patterns in the Inv 40 condition were similar across all four subjects, but during the diotic condition there was a distinction between two groups. Subjects showing a large reduction (red) do so because they start with overall greater SNRs in response to the diotic stimulation than those who show a smaller reduction (blue).

DISCUSSION

No effect of the lateralised stimuli was found. This may be because lateralisation of stimuli has no consequence for ASSR production. Alternatively, as Zhang & Boettcher (2008) found, the BICs in response to ILD and ITD may be opposite or too small to detect, resulting in no observable net effect. This is encouraging for the clinical implementation of sound-field ASSR, as it seems normal frontal incidence of the stimulus does not need to be maintained. This is in opposition to the ABR behaviour reported in Riedel & Kollmeier (2002).

The reduction in response level in the second harmonic compared to the first, and in the 2 kHz and 4 kHz bands compared to the 707 Hz band match the findings of Laugesen *et al.* (2018). The difference between bands is attributed to the varied repetition rates and chirp frequency widths.

The Inv 40 condition had the effect of reducing the 707 Hz band response in the first harmonic, but also resulted in the reduction of the 2 kHz and 4 kHz bands second harmonic responses. Further analysis reveals that the Inv 40 condition also places the envelopes of the second harmonics of the two 90 Hz bands into antiphase, so this response reduction effect seems related to interaural envelope phase. This would suggest that binaural testing on unilateral HA users, which the Inv 40 condition simulates, could artificially suppress some response harmonics and result in good HA fittings being pronounced poor. The chance of this occurring could be minimised or eliminated by using a response detector which always considers multiple harmonics. It is currently unexplained why significant reductions in ASSR are seen under the Inv 40 envelope anti-phasic condition, but none is seen in the similar Inv 90 condition.

The significant factor Subject, along with Figure 4, suggests that during diotic stimulation there is a large inter-subject variation in the response SNR across the head. Furthermore, even in these ideal conditions low SNR areas on the scalp develop, and that their exact location cannot be precisely predicted. This demonstrates the vulnerability of HA validation by ASSR to montage choice as well as diversity in individual's response amplitudes.

In conclusion, if performing binaural tests, it should be avoided for unilateral HA fittings, which may lead to significant artificial response suppression and therefore some false referrals. Naturally however, monaural tests will always give more clarity as to the quality-of-fit of each separate HA, since a single well fitting aid in a binaural test would still produce an ASSR.

ACKNOWLEDGEMENTS

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