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Auditory evoked responses of the complete auditory pathway using structured stimulation sequences.

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Simultaneous recording of transient responses of the complete auditory pathway (including ABR, MLR and ALR) is possible thanks to advanced deconvolution methods. However the simultaneous deconvolution of early and late responses is limited by the small amplitude of ALR components when they are elicited at high stimulation rates and also by statistical constraints related to the properties of the matrix involved in the deconvolution. In this work we propose the use of structured stimulation sequences, involving different time-scale events (i.e. short-term and long-term events) in order to overcome these limitations and to obtain simultaneously good quality early and late transient responses.

Background

Deconvolution provides consistent AEP estimations when the responses are overlapped (i.e. when the response duration is longer than the inter-stimulus interval). This allows the estimation of AEP transient responses at high stimulation rates including the responses of the complete auditory pathway (including the early, middle and late responses in the same experiment).

Even though the mathematical and the numerical problems are solved (with matrix deconvolution performed in the reduced representation space associated by latency dependent filtering), two statistical limitations must be considered for the simultaneous estimation of early and late responses:

- High stimulation rate and long analysis windows cause a large condition number in the matrix to be inverted for the deconvolution, which causes amplification of noise, particularly for late latencies (low frequency components).
- High stimulation rate causes low amplitude of late AEP components (which, together with the amplified noise, makes the late components difficult to be identified).

For these problems, there are obvious solutions, but they cause additional limitations:

- The analysis window can be limited and high-pass filter can be applied to the EEG signal before deconvolution. This reduces the condition number of the matrix to be inverted and avoids amplification of low-frequency noise, but limits the estimation of the transient response to ABR and MLR (the late response is sacrificed).
- The number of events involved in the deconvolution can be increased in order to reduce the effect of the noise. However, this increases the duration of the recording session (an improvement of 3 dB in the signal-to-noise ratio requires doubling the duration of the recording session, under stationary noise).
- The stimulation sequence can be configured for lower stimulation rate (which increases the amplitude of the later responses, and also reduces the condition number of the matrix involved in the deconvolution, reducing the effect of noise amplification). However, again, this increases the duration of the recording session, and additionally, a provides a less natural stimulation.

Methods

In order to improve the quality of AEPs of the complete auditory pathway, we propose the use of structured stimulation sequences, specifically designed for improving the quality of early and late transient responses simultaneously.

The stimulation pattern consists in click-bursts with configurable parameters: the amplitude (a multi-level stimulation can be defined), inter-click interval (with a random distribution in order to allow a well conditioned deconvolution), burst duration, and inter-burst interval (also with random distribution for a well conditioned deconvolution). The responses are estimated separately for the click events (for the early transients) and for the burst events (for the late transients): the clicks are expected to generate clear ABR and MLR responses, while the burst are expected to generate MLR and ALR responses. This stimulation design is expected to provide clear early and late responses simultaneously and to significantly alleviate the statistical limitations mentioned above.

Figure: Reference of AEP responses of the complete auditory pathway using clicks: This figure is extracted from [De la Torre et al. JASA 148(2), 559-613 (2020)], with evoked responses to simple clicks (at different stimulation rates). The figure is included as reference of responses for non-structured stimulation sequences.

Figure: The AEP recording system: The figure represents the elements of the modular and flexible AEP recording system used for these experiments. The recording system includes the electrodes, a microphone preamplifier, an audio interface, the headphones and a computer. The audio interface is used for AD/DA conversion, and for synchronous stimulation (with the headphones) and recording (from the electrodes). The laptop runs a MatLab script where the stimulation is prepared (according to the configuration parameters) and sent to the audio interface, the recorded EEG (captured by the audio interface) is stored and processed, and the AEP responses are estimated.

Figure: The structured stimulation pattern: The figure represents a portion of the signal used for stimulation. Click bursts composed of rarefaction clicks of different levels (27.5, 37.5, 47.5 or 57.5 dB) are randomly presented. All the clicks within a click burst have the same level. The clicks events and the burst events are categorized according to their intensity and deconvolved with the multi-response deconvolution method (including latency dependent filtering and downsampling, see [De la Torre et al., JASA, 155, 3639-3653 (2024)] for details). Independent responses are estimated for the click and the burst events for each stimulation level. For the estimation of the responses to clicks the EEG is band-pass filtered in the band 40-3500 Hz, and the responses are estimated in a latency window of 200 ms. In the case of click-bursts, the band-pass filtering includes the band 1-2000 Hz, and the analysis window extends up to 1000 ms.

Results

The study includes responses from 10 participants. The responses from each participant were estimated from 15 minutes of recording. A total of 4000 bursts (with around 58000 clicks) were presented to each participant (around 1000 bursts and 14500 clicks for each stimulation level).

Figure: Analysis of the responses to click and burst events: The figure represents, in the left panel, the responses to click events (in red), and in the right panel, the responses to the burst events (in blue). The right panel also includes the responses to the clicks (with thin red lines) as reference.

In the responses to clicks, the stimulation artifact can be identified at 0.5 ms (with an amplitude reduction of a factor 3.2 from each level to the next one, corresponding to the steps of 10 dB). The waves III and V of the ABRs are observed at 6 and 8 ms, respectively, and the waves P0, PA and PB/P1 of the MLR components are observed at 15, 25 and 40 ms. Latencies of ABRs are delayed with respect to normal values due to a global delay of 0.5 ms (observed in the stimulation artifact) and because of the stimulation level. The latency of the wave PB/P1 is shorter than expected because of the filter configuration (the 40 Hz cut-off frequency for the high-pass filter). The responses to bursts include clear MLR (P0, PA, PB) and ALR (P1, P2, P3) components with this subject.

Figure: Responses for each participant: On the right side of the poster, the plots with the responses to clicks and to bursts are represented for each participant. All the participants include clear responses to clicks and to bursts, with identifiable ABR and MLR components in the responses to clicks and MLR and ALR components in the responses to bursts. A moderate PAM is observed in participant H, and a large PAM in participant C (at 15 ms). In some participants (A, F and H), the responses to bursts are relatively noisy, particularly in the last portion of the responses (probably due to miogenic noise), but evidence of MLR and ALR waves are observed with all the participants. The deconvolution of burst events provides MLR and ALR responses with larger amplitudes than the click events. The simultaneous deconvolution of both, clicks and bursts, provides more evident responses of the complete auditory pathway. Some dependence of ALR components with the attention of the participant is suggested by the experiments, even though more investigation is necessary (since no controlled experiments were conducted to evaluate the influence of the attention).

Conclusions

The experimental results contribute to a better understanding of the difficulty associated to the simultaneous recording of the early and late responses. The use of structured stimulation sequences allows the independent deconvolution of short-term events (clicks) and long-term events (bursts), providing, in the same experiment more consistent and clear responses from peripheral and central portions of the auditory pathway simultaneously. This contributes to a more accurate evaluation and understanding of the auditory processing at different levels of the auditory pathway.