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Auditory Evoked Responses from Ear-EEG Recordings

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Abstract— **A method for brain monitoring based on measuring electroencephalographic (EEG) signals from electrodes placed in-the-ear (Ear-EEG) was recently proposed. The Ear-EEG recording methodology provides a non-invasive, discreet and unobtrusive way of measuring electrical brain signals and has great potential as an enabling method for brain monitoring in everyday life. This work aims at further establishing the Ear-EEG recording methodology by considering auditory evoked potentials, and by comparing Ear-EEG responses with conventional on-scalp recordings and with well established results from the literature. It is shown that both steady state and transient responses can be obtained from Ear-EEG, and that these responses have similar characteristics and quality compared to EEG obtained from conventional on-scalp recordings.**

I. Introduction

Electroencephalography (EEG) is the recording of brain signals from the scalp and represents aggregated electrical activity from a large number of cortical neurons. Within the clinical domain EEG is a well-established and valuable tool for the diagnosis of neurological disorders, tumors, strokes and brain death. EEG is also extensively applied within neuroscience, cognitive science, cognitive psychology, and in the field of brain-computer interface (BCI).

The character of the EEG signals depends on the location of the electrodes, the state of the brain and the stimulation of the brain through the peripheral nervous system or the optic nerve/retina. An auditory stimulus, for instance, will induce modulated patterns into the EEG signals, and the changes in the EEG from the otherwise spontaneous EEG are called auditory evoked potentials (AEPs) [1].

Recently a novel approach for recording EEG signals from electrodes placed within the ear canal, Ear-EEG, was introduced [2]. In contrast to current EEG recording methods, the Ear-EEG methodology provides at the same time a noninvasive, minimally intrusive, truly wearable, and user friendly method for recording of EEG over long time periods. The Ear-EEG has so far only been explored for the alpha attenuation EEG paradigm; and the performance has been compared to standard on-scalp electrodes by correlation and coherence analysis [2]. In this work the Ear-EEG recordings are evaluated for AEP paradigms; and a rigorous comparative study, focusing on the quality of the recorded AEP, shows that the Ear-EEG provides similar signal-to-noise ratios (SNR) compared to conventional on-scalp recordings. This establishes the foundation for the use of Ear-EEG in practical applications - from biomedical devices to BCI.

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II. Ear-EEG/AEP Recording Setup

The Ear-EEG signals are recorded by means of electrodes placed in the outer ear, where the ear-electrodes made of silver (Ag) are embedded on customized earpieces. The earpieces are produced using the same manufacturing processes (wax-impression, 3D scanning, CAD modeling, additive manufacturing technology (SLA)) as is standard in customized hearing aid ear-plugs. The earpieces are hollow, with an $\varnothing 3$ mm hole at the end, so that sound can pass unimpeded to the eardrum. On each ear-piece are placed 4 electrodes, and for all the recordings reported in this paper the electrode positions were ExA, ExB, ExE and ExH (see the naming convention in the Appendix). The electrode areas are approximately 20 mm^2; an example of an earpiece with electrodes is shown in Fig.1(a) and Fig.1(b). In the sequel, electrode ExH is used as reference electrode, ExA is used as ground (common mode feedback), and the EEG signals are recorded from the ExB and ExE relative to ExH. It is emphasized that all the Ear-EEG recordings reported in this paper are truly in-the-ear measurements; that is, all the electrodes, including the reference and the ground electrodes, are placed within the ear, and these electrodes are galvanically isolated from other electrodes placed on the test-subject (e.g. scalp electrodes and electrodes in the opposite ear). The recording amplifier was the g.USBamp by g.tec; this recording amplifier is well suited because it has 4×4 independent, synchronous sampled, recording channels.

Before recording the concha and the ear canals are cleaned with ethanol. Conductive gel is applied to the electrodes, the earpieces are put in place, and electrode impedances are tested to ensure that impedances are below 10 kOhm. An earpiece placed in an ear is shown in Fig. 1(c) and Fig.1(d).

The sound stimulus was presented binaurally using headphones, the setup was gain calibrated at 1 kHz, and all audio stimuli are presented with a maximum amplitude corresponding to a sound pressure level (SPL) of 80 dB relative to 20 μPa. The headphones were Beyerdynamic DT 770 PRO (250 Ohm) driven by a ESI Dua Fire soundcard; the audio setup was calibrated using a Brüel&Kjær Head and Torso Simulator, Type 4128C, equipped with IEC 711 Ear couplers. All sound stimuli were generated digitally with 24 bits resolution and 44.1 kHz sampling rate.

III. Steady State Responses

The auditory steady state responses (ASSR) were first reported in [3], and have since been extensively studied primarily as an objective assessment of the hearing threshold level. ASSRs can be evoked by many different types of stimuli; most typically amplitude modulated narrow- or broad-band

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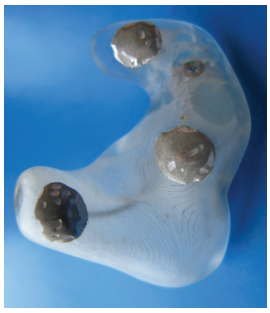
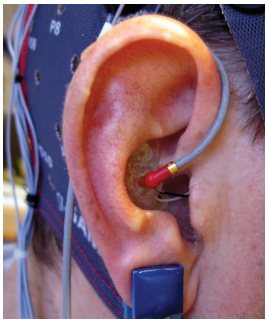
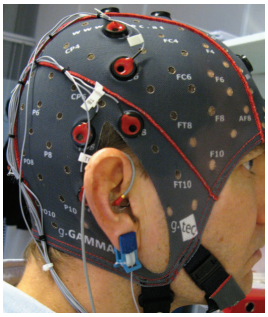


(a) An earplug with electrodes ERA, ERB and ERH visible.

(b) An earplug with electrodes and connector (opposite view of Figure 1(a)). Electrode ERE is visible.



(c) Right ear with earplug.



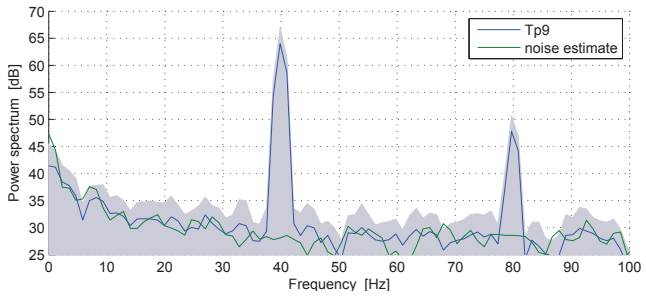
(d) Side view of test subject showing the recording setup.

Fig. 1. View of a right ear earplug and the Ear-EEG recording setup.

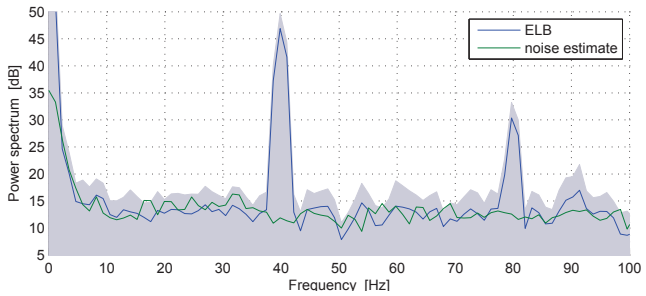
signals. The neural generators of the ASSR varies with the modulation frequency: ASSRs with modulation frequency below 20 Hz are dominated by late cortical responses, in particular the auditory cortex and related areas; for modulation frequencies between 20 and 60 Hz the responses are similar to the middle latency responses; modulation frequencies above 60 Hz are related to the cochlea, auditory nerve and brainstem [4]. In the context of hearing threshold assessment, ASSRs are typically assessed with multiple simultaneous modulation frequencies, typically at frequencies above 80 Hz [5].

Although the physiological assessment of hearing threshold is by itself an interesting and relevant field of investigation, and Ear-EEG is likely to play a future role within audiology and hearing aid technology [6], this is not the focus of the manuscript. We instead aim to demonstrate that established EEG responses can be recorded from ear electrodes, and to show that the signal quality is similar to conventional recording techniques.

The sound stimulus used to induce the ASSR was white Gaussian noise amplitude-modulated with a 40 Hz sinusoid (SPL 69.4 dB RMS rel. 20 μPa). The EEG was recorded simultaneously from 8 scalp electrodes and 4 Ear-EEG electrodes; only results from electrodes TP9 and ELB are presented here as they are representative for all the scalp and Ear-EEG electrodes respectively. The ear electrodes were instrumented as described in Section II, and in the case of the on-scalp electrodes, the right ear lobe was used as reference and the Cz electrode as ground (common mode feedback). The evoked response was estimated by averaging 256 time-domain waveforms resulting in an increase in the SNR of 24 dB. Along with the evoked response, the noise signal was estimated by changing the sign of the recorded waveform in every second segment of the averaging, whereby the deterministic (evoked) part of the signal is eliminated. The power spectra of the estimated responses are shown in Fig. 2; the top panel shows the results for the scalp electrode (TP9), and the bottom panel for the ear electrode (ELB); the blue line shows the ASSR, the green line the estimated noise, and the shaded area the estimated standard deviation for the ASSR. The modulation frequency and the second



(a) ASSR for the left temporal lobe, electrode TP9.



(b) ASSR for the left ear, electrode ELB.

Fig. 2. Power spectrum of the auditory steady-state response evoked by white Gaussian noise amplitude-modulated with a 40 Hz sinusoid.

harmonic component are clearly observed from both the on-scalp and the ear electrode spectra. The averaged ASSRs are in both cases approximately 30 dB above the noise estimate, corresponding to an SNR of 6 dB in the raw EEG signals. The second harmonic component is in both cases approximately 15 dB above the noise estimate, corresponding to an SNR of -9 dB in the raw EEG signals. It is observed that the overall signal level is approximately 20 dB lower in the ear recording compared to the scalp recording, however as the SNR is effectively the same the lower signal amplitudes of the ear electrodes do not compromise the signal quality. The lower signal amplitudes are likely due to significantly shorter distances between sensing and reference electrodes compared to conventional on-scalp recordings, and also due to the fact that the bone structures separating the brain and the surface of the ear canal are thicker than the bone structure in the parts of the skull where conventional scalp-electrodes are placed.

An equally clear and unambiguous result was obtained at

80 Hz amplitude-modulation, demonstrating that Ear-EEG makes it possible to record AEPs from both the auditory pathway and from the cerebral cortex.

IV. Transient Responses

This section considers the P_1–N_1–P_2 complex and the mismatch negativity (MMN) which are auditory event-related potentials (ERP's) that are observed 50–300 ms after stimulus onset. These AEPs are brain responses that are evoked by sound stimulus and processed in or near the auditory cortex [1]. The presence of auditory ERPs indicates that the stimulus has been detected at the level of the auditory cortex, but does not in general provide information regarding cognitive discrimination.

The sound cue (event) used for the P_1–N_1–P_2 complex recordings was a 1 kHz sinusoid of duration 200 ms, with an attack and release time of 10 ms. The inter-stimulus-interval (ISI) was randomly chosen in the interval between 1.7 and 2.3 s. The presentation of the sound stimulus and the EEG recording setup was the same as described in the previous sections. The resulting AEP waveform is shown in Fig. 3, where the dashed lines show the waveforms estimated by averaging 4×64 segments, the solid line the averaged waveform of all 256 segments, and the shaded area the standard deviation of the 256 segments around the mean. It

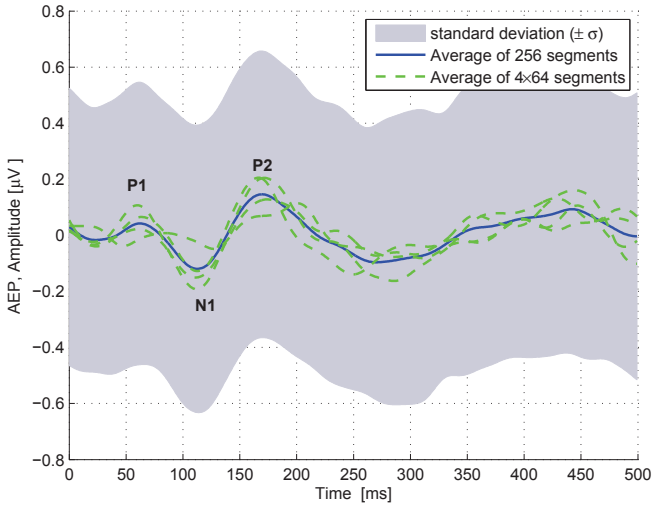


Fig. 3. The Ear-EEG P_1–N_1–P_2 complex evoked by a 1 kHz sinusoid. The dashed lines denote the waveforms estimated by averaging 4×64 segments, the solid line the averaged waveform of 256 segments, and the shaded area the standard deviation of the 256 segments around the mean. The signal was recorded from electrode ELE.

is observed that the AEPs for the 4×64 segments have very similar waveforms as the waveform obtained by averaging all 256 segments, indicating that the result is consistent over all the ERPs. The well-known P_1–N_1–P_2 complex is readily recognized from the averaged waveform, see e.g. [1] (Fig. 23.1) for comparison. The peak-to-peak amplitude of the P_1–N_1–P_2 complex is approximately 0.4 μV, that is, 10 to 20 dB lower than that observed from conventional recordings. This weaker response is consistent with the ASSR results described in Section III and is likely caused by the same reasons.

The MMN response is elicited with an oddball paradigm in which infrequently occurring deviant cues are embedded in a series of frequently occurring standards cues; for example let "…/s/, /s/, /s/, /s/, /s/, /d/, /s/, /s/, /s/, …" represent a part of the stimuli where /s/ represent a *standard* cue, /d/ represent a *deviant* cue, and the punctuation mark represent a random time separating the cues. The stimuli employed in this study used a 440 Hz tone as the standard cue, and an 880 Hz tone as the deviant cue. Both cues had duration of 100 ms and an attack and release time of 10 ms. The standard and deviant cues were presented with probabilities of 0.9 and 0.1 respectively. The time between the cues was random between 0.6 and 1.2 s, this random time was inserted in order not to evoke a steady state response. The stimuli were presented at the same level and simultaneously in the left and right ear.

Typically, the MMN manifests itself as an enhanced negativity in response to the deviant cue relative to the observed response for the standard cue. The observed evoked responses from the electrode position ELE, with all other conditions as described previously, are shown in Fig.4. Observe that the response to the deviant cue has a clear enhanced negative response around 125 ms after the cue onset. The MMN is best observed by subtracting the deviant-cue evoked response from the standard-cue evoked response. This difference-waveform is shown as the solid line in Fig. 4, and the so obtained MMN waveform is similar to MMN

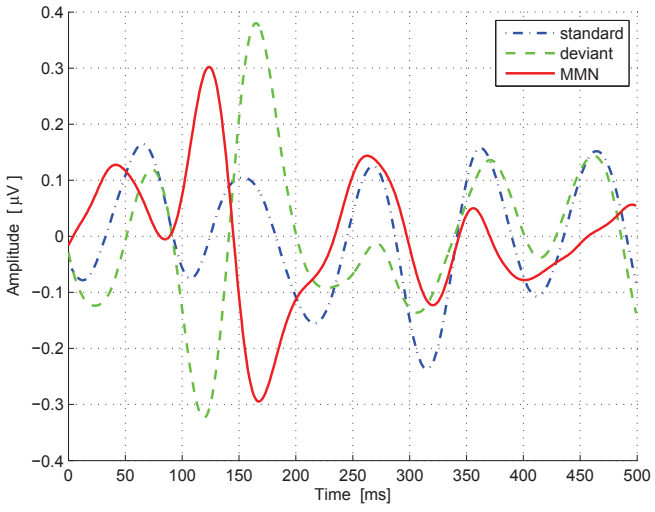


Fig. 4. Mismatch Negativity waveform from Ear-EEG, electrode ELE. Response to standard cues (dash-dot line), deviant cues (dashed line) and the difference between the standard and deviant response (solid line).

waveforms reported in the literature, see e.g. [1] (Fig. 23.2). As for the ASSR and the P_1–N_1–P_2 complex, the MNN waveform was approximately 10 to 20 dB weaker than that observed from conventional recordings. However, the evoked responses were obtained from a similar number of averages

as reported in the literature, re-confirming that the Ear-EEG signals have a similar SNR compared to conventional on-scalp recordings.

V. Conclusion

This study has investigated auditory evoked responses (AEP) obtained via Ear-EEG, a novel EEG recording methodology in which the electrodes are placed within the ear. It has been demonstrated that three of the most well established AEPs, namely the ASSR, the P_1–N_1–P_2 complex and the MMN, spanning activity from the auditory nerve to the cerebral cortex, can be observed from the Ear-EEG. A rigorous comparison with on-scalp electrodes has shown that the evoked responses from the Ear-EEG are typically 10 to 20 dB lower in amplitude than those of conventional on-scalp recordings, while maintaining a similar SNR. These results, together with the user-friendly aspects of the Ear-EEG, establish the basis for the use of Ear-EEG for real applications requiring long term EEG monitoring.

Appendix
Ear Electrode Naming Convention

This section establishes a naming convention for ear electrodes. The ear electrodes are denoted ELx and ERx for the electrodes in the left and right ears respectively, with x denoting the location. In each ear there are defined 12 electrode positions which are denoted by letters from A to L. The letters A, B and C denote electrode positions in the concha part of the ear; the letter D denotes the ear lobe electrode, and the letters E through L denote electrode positions in the ear canal. For instance, according to this naming convention the electrode ERB is an electrode placed in the concha region of the right ear. These electrode positions are illustrated in Fig. 5 for the left ear; the same naming convention applies to the right ear. The electrodes in the ear canal are placed before the bony part of the ear canal, and the electrode position is defined by the direction (angle) of the electrode relative to the vertical axis. The vertical axis is defined as perpendicular to the plane defined by the Oz, FPz, T7/T8 electrode positions (as defined by the 10-20 electrode position system).

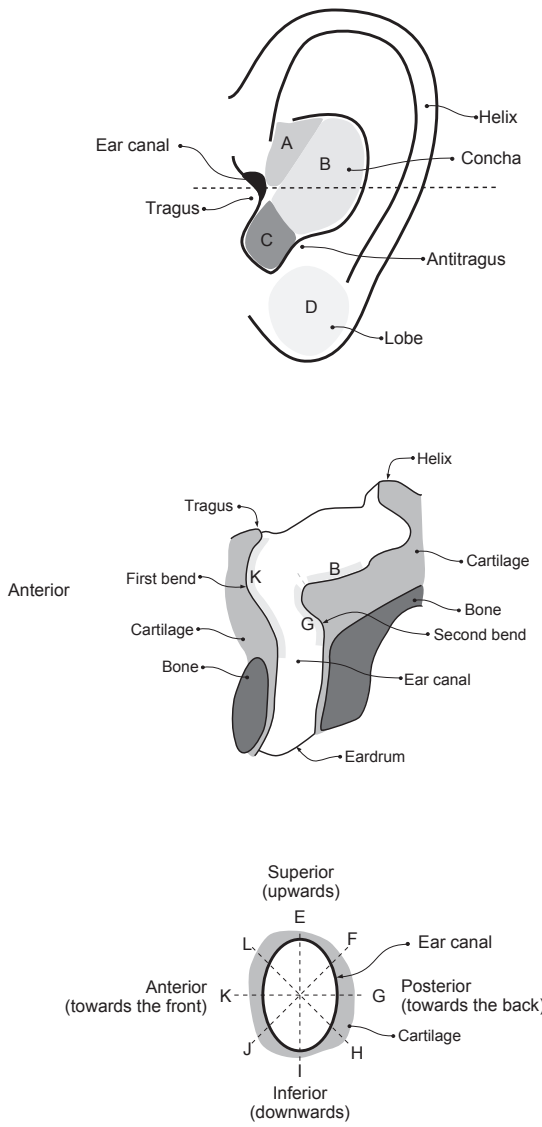


Fig. 5. Ear electrode naming convention for the left ear. Top panel: Sketch of the exterior part of the ear, showing the four regions corresponding to the electrode labels A through D. Middle panel: Cross sectional sketch of the outer ear in the axial plane, the sectional view is indicated by a dashed line in the upper figure. Electrode position B, G and K are indicated on the figure. Bottom panel: Cross sectional view of the ear canal (sagital plane) showing the electrode labels in the ear canal. The electrodes are named only based on the direction relative to the vertical axis, and not based on the depth in the ear canal.

Acknowledgment

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