Real-Life Dry-Contact Ear-EEG

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Abstract— **Our brain state is affected by and adapted to our surroundings. Therefore, to study natural states of the brain, it is desirable to measure brain responses in natural environments outside the lab. Among functional brain scanning methods, electroencephalography (EEG) is the most promising method for non-invasive brain monitoring in real-life environments. To enable long-term recordings in real-life, EEG devices must be wearable, user-friendly, and discreet. Ear-EEG is a method where EEG signals are recorded from electrodes placed on an earpiece inserted into the ear. The compact and discreet nature of an ear-EEG device makes it suitable for long-term real-life recordings. In this study, 6 subjects were recorded with conventional scalp EEG and ear-EEG. All recordings were performed with the same instrumentation and paradigms in both a lab setting and a real-life setting. The ear-EEG recordings were performed with a previously developed dry-contact ear-EEG platform. Signals from the scalp electrodes and ear-electrodes were recorded by the same biosignal recorder, enabling re-referencing in the post-processing and analysis. The study comprised four paradigms: auditory steady-state response (ASSR), steady-state visual evoked potential (SSVEP), auditory onset response, and alpha band modulation. When the data were analyzed with a scalp reference (Cz), all the investigated responses were statistically significant in recordings from both settings. Statistically significant ASSR and SSVEP were measured in the lab by ear-electrodes referenced to an electrode within the same ear. In real-life, only the ASSR was statistically significant for a reference within the same ear. The results demonstrates that electrical brain activity can be recorded from dry-contact electrode ear-EEG in real-life.**

I. Introduction

Investigation of human brain function with electrophysiological and hemodynamical modalities, such as EEG and fMRI, have in the past largely been limited to laboratory studies. However, the state of our brain is influenced by our surroundings, and the response from the brain is influenced by the state of our brain. Therefore, the restriction to laboratory recordings represents a fundamental limitation. Recording of EEG in real-life overcome this limitation, enabling research of evoked responses and spontaneous responses related to everyday life situations, and could potentially open up new fields of applications [1].

Previous studies of evoked potentials in the mouse brain have shown that visual and auditory evoked potentials are significantly different when the mouse is moving as compared to not moving [2] [3]. It seems reasonable to expect that similar phenomena applies to humans; i.e. measurements of brain responses performed in real-life settings are different from responses measured under restrained laboratory settings. Devices for recording of EEG in the user's everyday life must enable long-term recordings without obtruding daily life activities. To obtain this, the EEG device must be wearable, user-friendly, and discreet [4]. Commercial wearable devices are typically based on standard scalp montages, causing the device to be clearly visible and often uncomfortable to wear for long-term recordings. Some research projects have focused on designing devices for long-term monitoring, which do not attract attention during everyday life activities. This include devices for measuring EEG around the ear [5], on the ear [6], and in the ear [7].

Ear-EEG is a method where EEG is recorded from electrodes placed on an earpiece inserted into the ear [7] [8] [9]. The compact and discreet nature of an ear-EEG device makes it suitable for real-life recordings. However, devices for real-life monitoring must also be user-friendly and comfortable to wear. To address these aspects, we recently developed a dry-contact ear-EEG platform, comprising dry-contact electrodes and a soft-earpiece [10]. To better understand real-life artifact, we conducted a study of physiological artifacts for ear-EEG and scalp EEG [11]. The study confirmed that ear-EEG was suitable for real-life monitoring, and showed that artifacts related to jaw muscle contractions were higher in the ear compared to the scalp. Eye-blinking did not influence ear-EEG, but was present in the scalp EEG. Eye movement artifacts were present in both ear and scalp recordings.

The current study presents recordings of ear-EEG, performed with the dry-contact ear-EEG platform in both a lab setting and a real-life setting. The ear-EEG recordings were compared to conventional wet-electrode scalp recordings.

II. Methods

Recordings were performed in a controlled laboratory setting, and uncontrolled environments in real-life. The same paradigms and instrumentation were used for the recordings in the lab setting and the real-life setting, enabling comparison of the EEG measurements from the two settings.

A. Experimental setup

The ear-EEG were recorded from actively shielded dry-contact IrO_2 electrodes mounted in soft-earpieces as described in [10]. Four electrodes were mounted in each earpiece as shown in Fig. 1. The electrode positions were ExA and ExB in the concha part of the ear, and ExE and ExI in the ear-canal, where x denotes the left (L) or right (R) ear [7]. A headcap (TMSi B.V., The Nederlands), containing 24 wet Ag/AgCl electrodes, was used for the scalp recordings.

The EEG recordings were acquired with a sampling rate of 2000 Hz by a 32 channel portable MOBITA EEG amplifier (TMSi B.V., The Nederlands). An Ambu WhiteSensor

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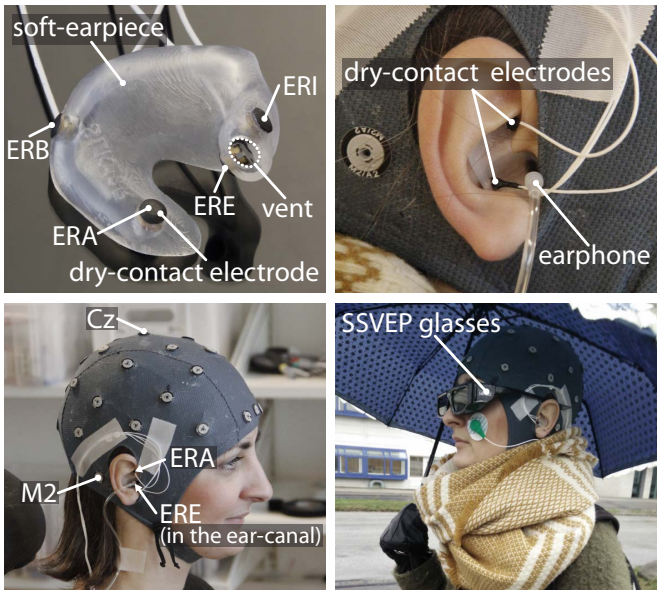


Fig. 1. Top left: Soft-earpiece for the right ear, with electrodes mounted in positions A, B, E, and I. Top right: The earpiece and an earphone inserted into the ear. Bottom left: The full setup with scalp EEG and ear-EEG. Bottom right: The SSVEP stimulation was performed by modulating the ambient light with the SSVEP glasses.

electrode (Ambu A/S, Denmark), located at the left cheek, was connected to the GND of the amplifier. Prior to insertion of the earpieces, the ears were cleaned with alcohol.

6 subjects (4 males) with normal hearing and vision, and an average age of 32 (s.d. 6) years, participated in the study. In the lab setting, the subjects were seated in a comfortable chair and instructed to relax. In the real-life setting, the subjects walked on the sidewalk of roads close to Aarhus University, Denmark. No restrictions were given for head and eye movements. Recordings were made on six different days; as the experiment protocol did not take weather conditions into account, there were quite large differences in weather conditions over the six recording days. Thus, four of the recordings were performed during moderate wind and two were performed during mild rain.

Auditory stimuli were presented to the subjects with the same intensity and phase in both ears by insert earphones (3M E-A-RTONE™ GOLD). The tubes from the earphones were inserted into the vents of the earpieces, as shown in Fig. 1, and the individual auditory sensation level (SL) was determined for a 1000 Hz tone. An auditory steady-state stimulus was presented at a sound level of 52 dB_{SL}, and a stimulus for auditory onset response was presented at a sound level of 60 dB_{SL}.

All recordings were bandpass filtered with the EEGLAB FIR filter function "pop_eegfiltnew()" [12]. The cutoff frequencies are given below for each paradigm.

B. Electrode configurations

The EEG data were analyzed with the electrode configurations sketched in Fig. 2. Within-ear: The measuring electrode and the reference electrode were located within the same ear. Ear-scalp: The measuring electrode was an ear-electrode and the reference was the Cz scalp electrode. Scalp-scalp: The measuring electrode was the M1 or M2 electrode and the reference was the Cz electrode.

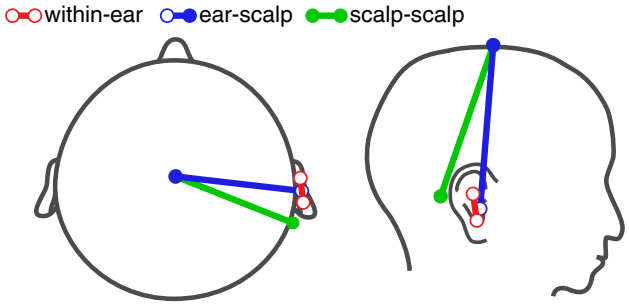


Fig. 2. Illustration of the electrode configurations used in the data analysis. Filled circles indicate wet scalp electrodes and open circles indicate dry-contact ear-electrodes.

C. Steady-state responses

Two steady-state stimuli were studied. Each of the stimuli was presented to the subjects for 5 minutes.

The stimulus for the steady-state visual evoked potential (SSVEP) was presented to the subjects by modulating the ambient light with 9 Hz, using the SSVEP glasses shown in Fig. 1 and detailed in [10]. In the lab setting, the subjects were looking at a monitor displaying a white screen, and in real-life, the natural daylight was the primary light source. The stimulus for the auditory steady-state response (ASSR) was Gaussian distributed white noise amplitude modulated with 40 Hz. In the lab setting, the subjects had closed eyes, and in real-life, the subjects were walking with eyes open.

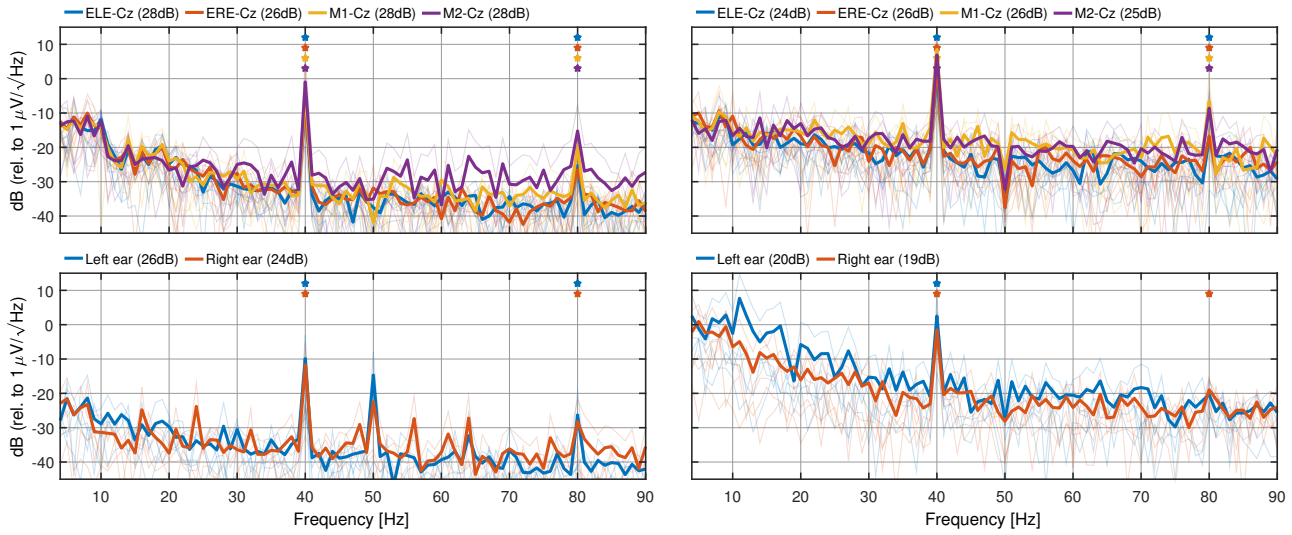
The steady-state response (SSR) recordings were bandpass filtered from 2 to 100 Hz, and a second order 50 Hz notch filter was applied to reduce power line noise. Then, the data were segmented in 1 s segments, aligned to triggers of 8 Hz for ASSR and 9 Hz for SSVEP. The 256 segments with the lowest mean power from 55 to 75 Hz were selected for the data analysis. The SSR for ear-scalp and scalp-scalp electrode configurations were calculated by time domain averaging (TDA) of the selected segments.

Within-ear electrode configurations generally result in a lower SSR, compared to ear-scalp electrode configurations [7] [10]. To obtain a reliable SSR for all subjects, the within-ear electrode configurations were optimized for each subject [13]. To avoid overfitting, each electrode configuration was trained on half of the selected segments, and tested on the other half. This cross-validation was performed for 100 different training and test configurations, and the TDA of all the test data were calculated. The method is detailed in [10].

The SNR was calculated, at each harmonic of the ASSR and SSVEP, as the ratio between the power at the harmonic and the mean power of the noise in a frequency band ± 5 Hz relative to the harmonic. The power at the harmonic was excluded from the noise power estimate.

D. Auditory onset response

An auditory evoked onset response was also included in the study. The stimulus was a 1 kHz sinusoid of duration



(a) Lab

(b) Real-life

Fig. 3. Lab (left) and real-life (right) grand average power spectra of the ASSR for ear-scalp and scalp-scalp electrode configurations (top row) and within-ear electrode configurations (bottom row). The faded lines are the response for each subject. The SNR of the first harmonic ASSR is given in the legends, and a star marker indicates a statistically significant ASSR ($p<0.05$, F-test).

200 ms (including 10 ms rise and fall times). The stimulus-onset asynchrony (SOA) was randomly chosen between 1.7 and 2.3 s. The stimulus was presented to the subjects for 5 minutes. In the lab setting, the subjects had closed eyes, and in real-life, the subjects walked with their eyes open.

The recorded EEG data were bandpass filtered from 1 to 25 Hz and segmented with limits of -100 to 500 ms relative to the onset of the stimulus. The noise level of each epoch was estimated as the mean power from 55 to 75 Hz, based on the unfiltered EEG data. The event related potential (ERP) was extracted by TDA of the 128 segments with the lowest noise level. The mean amplitude from -100 to 0 ms was used for baseline correction.

E. Alpha band modulation

Recordings of spontaneous EEG were also included in the study, to complement the recordings of the SSRs and auditory onset response. The focus was on occipital alpha band activity, which is modulated by visual attention [14].

The subjects were instructed for two conditions; 1) Eyes open. 2) Relaxing with closed eyes. The first condition was condition 1, and an auditory cue indicated a change in condition every 60 second. The measurements had a duration of 4 minutes. The subjects were walking during the real-life recordings, and for the closed eyes periods the subjects were instructed to hold their hand on a handrail while walking.

The EEG recordings were bandpass filtered from 2 to 45 Hz and segmented in 4 s segments, with 2 s overlap. The mean alpha band power in the interval 8-12 Hz was calculated for each segment, and segments with a mean alpha band power above 100 $\mu V^2/Hz$ were left out of the analysis.

III. Results and Discussion

In the following we present EEG recordings from the lab setting and the real-life setting. Recordings from a few ear-electrodes were discarded in the data analysis as specified in Table I. An ear-electrode was discarded if none of the possible within-ear electrode configurations involving the electrode, resulted in a statistically significant first harmonic ASSR ($p<0.05$, F-test).

Left ear - Lab				**Right ear - Lab**			
ELA	ELB	ELE	ELI	ERA	ERB	ERE	ERI
0.2	0.3	0.2	0.2	0.5	0.5	0.2	0.3
Left ear - Real-life				**Right ear - Real-life**			
ELA	ELB	ELE	ELI	ERA	ERB	ERE	ERI
0.5	0.7	0.2	0.2	0.3	0.7	0.0	0.2

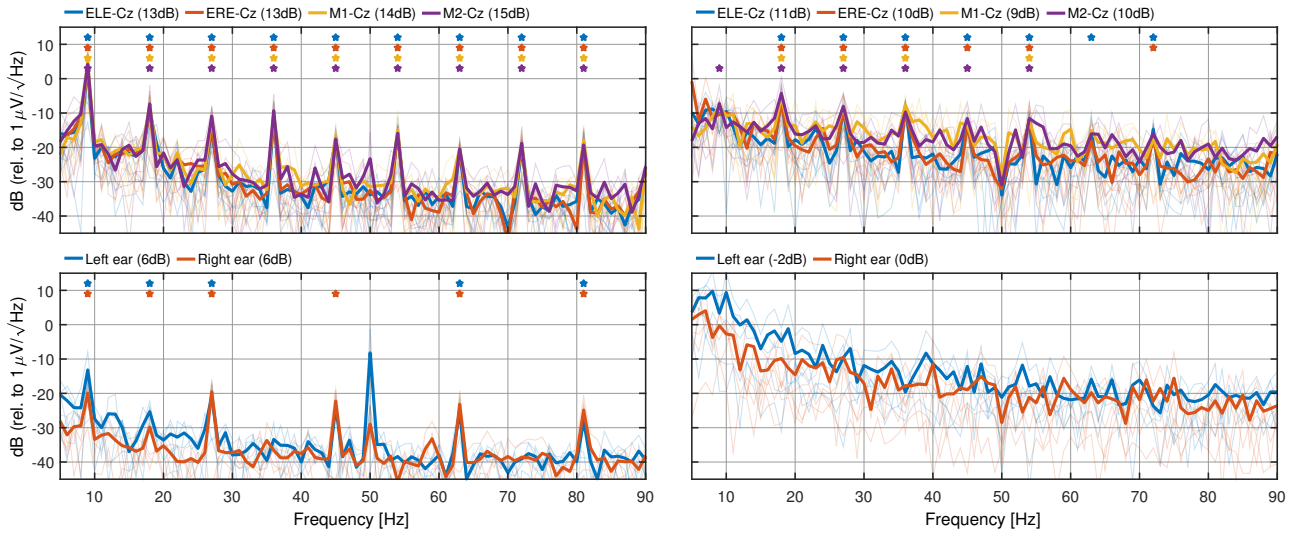
TABLE I

Discard ratios given for each ear-electrode location. Concha electrodes marked with gray.

A. Steady-state responses

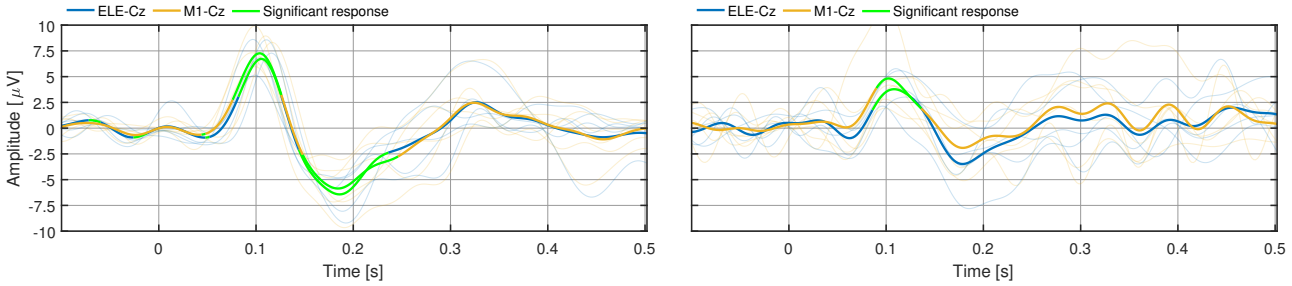
Fig. 3 shows a clear and statistically significant first harmonic ASSR for all electrode configurations in measurements from both settings. This is promising for the future application of ear-EEG to estimate the objective hearing threshold in the everyday life, where it could be used to improve the performance of hearing aids [15]. Comparing the power spectra for the lab setting and the real-life setting, the noise floor of the real-life recordings was approximately 20 dB higher. However, the power of the first harmonic ASSR was also higher in real-life, causing the SNR for the ear-scalp electrode configurations to be similar for the two settings. For the within-ear electrode configurations, the SNR was slightly lower in real-life. The higher noise floor of the real-life recordings was likely related to both motion artifacts and physiological artifacts [11].

Fig. 4 shows the SSVEP measured in the two settings. For ear-scalp and scalp-scalp electrode configurations, the second to fourth harmonics of the SSVEP were statistically significant in both settings. In real-life, the first harmonic SSVEP was not statistically significant for most of the



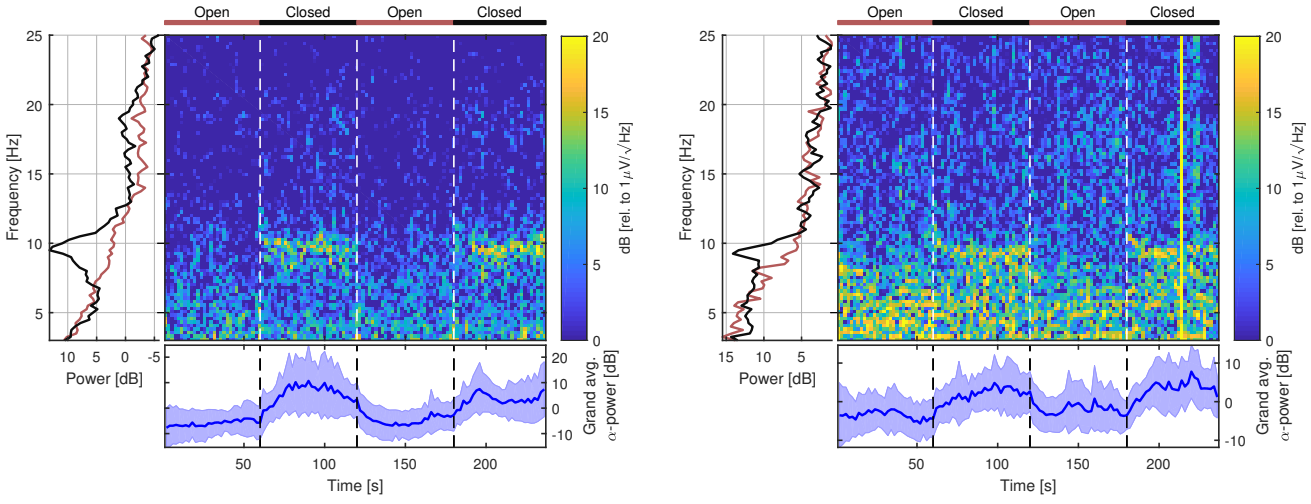
(a) Lab (b) Real-life

Fig. 4. Lab (left) and real-life (right) grand average power spectra of the SSVEP for ear-scalp and scalp-scalp electrode configurations (top row) and within-ear electrode configurations (bottom row). The faded lines are the response for each subject. The SNR of the second harmonic SSVEP is given in the legends, and a star marker indicate a statistically significant SSVEP ($p<0.05$, F-test).



(a) Lab (b) Real-life

Fig. 5. Grand averaged auditory onset responses for ear-scalp and scalp-scalp electrode configurations. The faded lines are the auditory onset response for each subject. The overlaid green line indicate intervals where the grand averaged auditory onset response were significantly ($p<0.05$) different from zero, measured by a one sample t-test.



(a) Lab, ear-scalp electrode configuration ELE-Cz (b) Real-life, ear-scalp electrode configuration ELE-Cz

Fig. 6. Top: Spectrograms and power spectra for a single subject, measured in the lab and real-life settings. The open and closed eyes intervals are indicated above the spectrograms. Bottom: Grand average of the mean alpha band power (8-12 Hz). The shaded area indicate ± 1 standard deviation of the grand average. The grand average plots have been smoothed with a 3 tap mean filter. All dB values are relative to $1\mu V/\sqrt{Hz}$.

electrode configurations. From the current study it cannot be determined, if the missing first harmonic SSVEP in the real-life recordings, should be attributed to changes in the stimulation, changes in the brain response, or other circumstances. For the within-ear electrode configurations, the first three harmonics of the SSVEP were statistically significant in the lab setting, whereas no statistically significant SSVEP was measured in real-life. The missing response is likely related to the increased noise floor of the real-life recordings.

Fig. 7 was used to determine the optimal number of segments in the TDA. Fig. 7(a) shows the noise level of the segments from the real-life ASSR recordings, sorted in ascending order and for a within-ear electrode configuration. The noise level was calculated as the mean power from 55 to 75 Hz. Fig. 7(b) shows the noise level after TDA versus the number of segments in the TDA. Fig. 7(a) illustrate that it is not beneficial to include all segments in the TDA. For the current study, the analysis of the ASSR and SSVEP recordings was performed using the 256 segments with the lowest noise level. Fig. 7 supports that this is a reasonable tradeoff between noise level and number of segments.

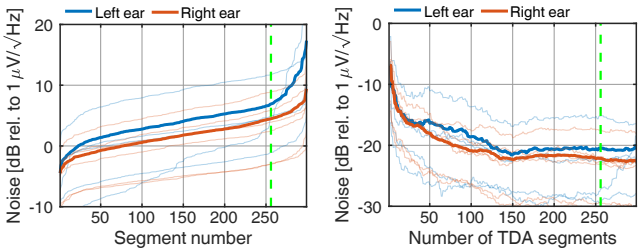


Fig. 7. (a) The noise level of segments from the segmented real-life ASSR recordings, for a within-ear electrode configuration. The segments were sorted according to the noise level, which was calculated as the mean power from 55 to 75 Hz. (b) The noise level after TDA versus the number of segments in the TDA. TDA was always performed using the segments with the lowest noise level. Faded lines show the noise level for each subject.

B. Auditory Onset response

Fig. 5 shows the auditory onset responses for ear-scalp and scalp-scalp electrode configurations. The timing of the onset response for both settings has the well known P_1-N_1-P_2 structure, with continuous intervals of statistical significance at the time of the most prominent peaks [8]. The response was not statistically significant for within-ear electrode configurations.

C. Alpha band modulation

Fig. 6 shows spectrograms and power spectra for a single subject and the grand average alpha band power, for the ear-scalp electrode configuration ELE-Cz. The alpha modulation was clearly visible on both the single subject spectrograms and in the modulation of the grand average alpha band power. The grand average alpha band modulation ratio was 2.7 ($p<0.001$) and 1.6 ($p<0.001$) for the lab setting and the real-life setting, respectively. The alpha band modulation was not statistically significant for within-ear electrode configurations.

IV. Conclusion

Recordings of ear-EEG and scalp EEG were performed with the same instrumentation and paradigms in both a laboratory setting and a real-life setting. 6 subjects participated in a study of auditory steady-state response (ASSR), steady-state visual evoked potential (SSVEP), auditory onset response, and alpha band modulation. The analysis of scalp (Cz) referenced EEG data showed high similarity between recordings from wet scalp and dry-contact ear-electrodes for both settings. All the investigated responses were statistically significant in both settings with the scalp reference. For within-ear referenced ear-electrodes, statistically significant ASSR and SSVEP were measured in the lab, whereas in real-life only the ASSR was statistically significant. Auditory onset response and alpha band modulation was not statistically significant for within-ear referenced ear-electrodes. Generally, the noise level was approximately 20 dB higher for the real-life recordings compared to the lab recordings. The results show that electrical brain activity can be recorded from dry-contact electrode ear-EEG in real-life. With further development of the dry-contact electrodes and earpieces it appears to be realistic to implement ear-EEG into unobtrusive and user-friendly devices for brain-monitoring in real-life.

Acknowledgment

This research was supported by Innovation Fund Denmark (j.nr. 110-2013-1 and j.nr. 7050-00007A).

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