A Method for Quantitative Assessment of Artifacts in EEG, and an Empirical Study of Artifacts

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Abstract— **Wearable EEG systems for continuous brain monitoring is an emergent technology that involves significant technical challenges. Some of these are related to the fact that these systems operate in conditions that are far less controllable with respect to interference and artifacts than is the case for conventional systems. Quantitative assessment of artifacts provides a mean for optimization with respect to electrode technology, electrode location, electronic instrumentation and system design. To this end, we propose an artifact assessment method and evaluate it over an empirical study of 3 subjects and 5 different types of artifacts. The study showed consistent results across subjects and artifacts.**

I. Introduction

Electroencephalography (EEG) is a non-invasive method for recording signals, that represents aggregated electrical activity from populations of temporally synchronized and spatially aligned neurons, in the brain. EEG recording systems have found widespread use within both clinical practice and in neuroscience. Over the past decades conventional high quality and high density EEG recording systems have translated into ambulatory and wearable systems [1]. These are not substitutes for the conventional systems, but open new opportunities for monitoring brain activity under less restrictive conditions. Ambulatory systems typically aim at providing long-term EEG recordings for clinical assessment of neurological diseases, usually at the expense of reduced spatial resolution (i.e. fewer electrodes) and less control of interference and artifacts. Wearable systems take this trend a step further, to provide less obtrusive and more user-friendly systems, and enable brain monitoring in the user's everyday environment.

The emergence of wearable EEG technology opens completely new fields of applications and research. Applications include both medical and assistive devices, e.g. devices for impending hypoglycemic seizure warnings in insulin-treated diabetics [2] or for the monitoring of frequency and length of seizures in childhood absence epilepsy [3]. Wearable systems also expand opportunities within existing research areas, e.g. in neuroscience in the study of social interactions [4]. A recent innovation in wearable EEG is the so-called EarEEG in which the EEG is recorded from devices placed in the ear-canals [5][6].

Recording of EEG signals, which are in the microvolt range, is challenged by interference in terms of noise and artifacts. These challenges are significantly larger as we move from conventional recordings to ambulatory and wearable recordings. Whereas, to a large extent, artifacts and interference can be avoided or controlled in the clinical environment, this is not the case for scenarios in which the wearable systems are intended to operate.

Artifacts are a fundamental and inherent problem in EEG recordings. There is a variety of root causes for artifacts including eye blinks, eye movements, muscle activity and motion artifacts [7]. Previous work on EEG artifacts has focused on the characterization of the artifacts [8][9], algorithms for automatic detection and removal of artifacts [10][11], and empirical studies of performance degradation of e.g. brain-computer-interface due to artifacts [12].

In this paper a method for quantitative assessment of artifacts is proposed, with the aim to provide a tool for rigorously assessing the problem, and thereby leveraging the engineering of technology for reducing artifacts. The method is based on measuring an evoked potential (EP) in a controlled environment with low levels of noise and artifacts. The ratio between the EP and the *background noise floor* is referred to as the signal-to-noise ratio (SNR). The same evoked potential is then measured under artifact conditions, and the artifact can then be quantified in terms of an SNR deterioration.

To demonstrate the feasibility of the method, and to provide some initial quantitative results for some of the most common types of artifacts, the results from an empirical study over three subjects are presented. The study comprises EEG recordings from electrodes distributed over the scalp, and from electrodes placed in the ear (EarEEG). The paper is organized as follows: Section II describes the proposed method, Section III presents the results obtained from the empirical study of artifacts and Section IV concludes the paper.

II. Methods

A. Quantitative Assessment of Artifacts

We propose a method for quantitative assessment of artifacts. The method is based on measuring an evoked potential (EP) in a controlled environment with low levels of noise and artifacts – this will be denoted as the *artifact free* condition. The same evoked potential is then measured under artifact conditions, and the artifact can then be quantified in terms of a SNR deterioration. The type of EP should be one that is "stable" and which does not interfere or interact with the artifact under study. In this regard a "stable" EP is one

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that is not influenced by e.g. attention, cognitive processes, habituation or fatigue.

The amplitudes of EPs are in general lower than the amplitude of the spontaneous EEG, making it necessary to average over multiple trials in order to reveal the event-related potentials (ERP). When performing the averaging, the type of EP must be carefully considered as described in [13]. A steady-state response is evoked by a periodic stimulus which consequently has a discrete frequency spectrum with ERP components at the harmonic frequencies of the stimulation. By comparison, a transient response has an ERP with a continuous frequency spectrum, therefore making it harder to distinguish the ERP and the noise.

In the case of the steady-state type of EP, the ERP is estimated by time-averaging segments having a length corresponding to an integer number of periods of the stimulus. The noise is estimated using the same segments and applying the plus-minus method as described by Schimmel [14]. The power spectra is calculated as the square of the amplitude of the discrete Fourier transform (DFT) of the time-averaged signals.

The SNR is now defined as the ratio between the power spectrum of the signal and the noise

$$\mathrm{SNR} = 10 \cdot \log_{10}\left(\frac{P_s(f_{EP})}{\frac{1}{N}\sum_{f_{low}}^{f_{high}} P_n(f)}\right) \quad [\mathrm{dB}] \qquad (1)$$

where $P_s(f)$ and $P_n(f)$ is the power spectrum of the signal and noise respectively, f_{EP} is the frequency of the steady-state stimulus, f_{low} and f_{high} defines the frequency range on which to base the noise estimate, and N is the number of frequency bins from f_{low} to f_{high}. f_{low} and f_{high} can be defined in an arbitrary frequency range of the noise power spectrum, making it possible to calculate the SNR for frequency ranges that do not include f_{EP}.

The SNR can now be estimated both in the artifact free condition, $\mathrm{SNR}_{\mathrm{AFC}}$, and in the artifact condition, $\mathrm{SNR}_{\mathrm{AC}}$. The method is illustrated in Fig. 1, and formally the SNR deterioration (SNRD) is defined as the SNR difference in dB

$$\mathrm{SNRD} = \mathrm{SNR}_{\mathrm{AFC}} - \mathrm{SNR}_{\mathrm{AC}} \qquad (2)$$

Ideally the power of the ERP is constant, and thus in principle the SNRD is just the ratio between the power of the noise in the artifact condition and the artifact free condition. However, in practical measurement setups the EEG signal amplitude will vary over time and through the course of the experiment because of changes in e.g. the electrode-skin interface. Under the assumption that the physiological ERP is constant within a subject the proposed method eliminates these variations.

B. EP Stimulus

The empirical study presented in this paper utilized an auditory steady-state response (ASSR) [15]; this paradigm is simultaneously “stable”, does not interact with the artifacts

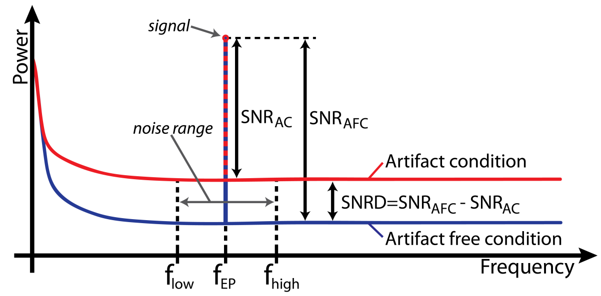

Fig. 1. The SNR was calculated as the ratio between the signal and the noise in dB. The signal was described by the power of the signal estimate at f_{EP} and the noise was the mean power of the noise estimate in the area from f_{low} to f_{high}. The SNRD was the difference between the SNR in the artifact free condition and the artifact condition in dB.

under study and is of the steady-state type. Furthermore, as temporal lobe and ear-canal electrodes have our special interest, it was natural to chose a stimulus having a primary sensory cortex located in the vicinity of these electrodes, which is indeed the case for the auditory cortex. The auditory stimulus signal was white noise amplitude modulated (AM) with 40 Hz; the audio signal was monotically presented to the subject in headphones.

C. EEG Setting

The EEG signal was recorded using two synchronized 16 channel g.tec g.USBamp EEG recorders. One amplifier was used to record scalp EEG from active g.tec g.LADYbird electrodes and the other amplifier was used to record EarEEG from passive silver electrodes embedded on the surface of custom made ear-pieces as described by Looney et al. [16]. The scalp electrodes were all referenced to the FCz electrode and the Cz electrode was used as ground. The EarEEG electrodes were labeled according to the scheme described by Kidmose et al. [13]. ELB and ERB electrodes were used as reference and the ELA and ERA electrodes were used as ground. The left and right ear-piece were connected to two different and galvanically decoupled channel groups in the EEG amplifier. The subject was seated comfortably on a chair during all the recordings and was asked to relax as much as possible.
All recordings were conditioned with a fourth-order notch filter to remove 50 Hz AC interference. A subsequent fourth-order Butterworth highpass filter was applied to retain frequencies over 0.5 Hz.

D. Artifact Conditions

Three types of artifact were chosen to illustrate how a quantitative, systematic and reproducible analysis of artifacts in EEG recordings can be performed. Three subjects (two males and one female) with no history of neurological disorders and normal audiological status aged between 24 and 42, participated in this study.

1) Jaw artifacts: The characterization of jaw artifacts was divided into three artifact conditions; a) Controlled jaw movement, b) Jaw clenching, c) Measured bite-force.
a) The custom-made device shown in Fig. 2 was used to

ensure a continuous and repeatable movement of the jaw. The subjects bit around the tip of the device, and an oval ball mounted on a shaft driven by a motor controlled the movement of the tip of the device. The distance between the tip of the lower and upper part of the clamp changed from 3 mm to 12 mm in 3 seconds.

b) During the jaw clenching measurement the subjects clenched their teeths as hard as possible for intervals of 30 seconds.

c) A strain gauge was attached to the lower part of the clamp to measure the bite-force. The measurement helped to ensure that the subjects had a steady bite-force during the bite periods of the recording. The subjects bit around the tip of the clamps with the maximal force that they could hold for intervals of 30 seconds.

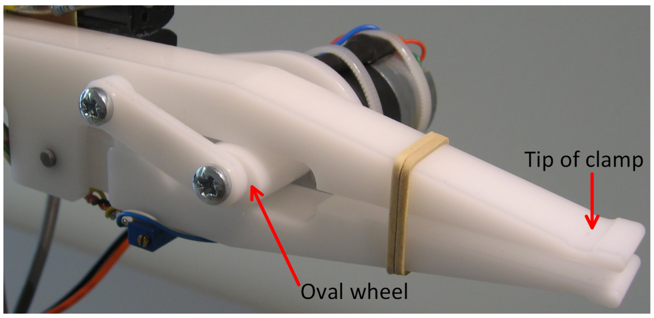

Fig. 2. A custom made device to ensure a continous and repeatable movement of the jaw and to measure the bite-force.

2) Eye movement: In the eye-movement paradigm the subjects moved their eyes to follow a ball on a monitor. The ball had two conditions: in motion and steady. In motion the ball position followed a sinusoidal function whereby the position, velocity and acceleration of the eyes became continuous, and in the steady conditions the ball was in the center of the display. The monitor was a 32" LCD display (569x343 mm^2) placed in front of the subject at a distance of 600 mm from the subject's forehead, a chin-rest was used to keep the head steady during the recordings, and the ball (diameter of 7 mm) moved horizontally from edge to edge on the display corresponding to a ± 25 degrees movement of the eyes. The paradigm toggled between the conditions in intervals of 30 seconds enabling calculation of the SNRD between the motion and the steady periods.

3) Head movement: In the head movement paradigm the subjects moved their head with their gaze fixed on a ball displayed on a monitor as described for the eye movement paradigm. To ensure that subjects only moved their head and not their eyes, they looked at the monitor through pair of goggles with a narrow field of view (the goggles glass was covered with a frosted window foil and a single hole drilled in the center restricted the field of view).

III. Results

The recordings from the three subjects were combined and an interperson time averaging for each electrode and artifact condition was calculated. Fig. 3 shows the power spectra of

	1. Artifact free condition		**2. Forced jaw move**		**3. Jaw clenching**		**4. Meas. bite-force**		**5. Horz. eye move**		**6. Horz. head move**		**←Subject**
ERK	25.7	21.3 33.9 22.0	-0.1	0.7 -1.0 0.1	5.5	7.5 4.6 4.4	1.8	-2.1 5.9 1.5	-1.3	-0.9 -1.3 -1.8	3.8	1.3 7.3 2.8	← 1 ← 2 ← 3
ERG	25.6	21.5 33.1 22.4	1.0	3.4 -0.1 -0.3	4.2	NA 3.7 4.7	1.7	0.1 3.2 1.7	-1.1	NA -0.9 -1.3	3.3	1.4 5.2 3.4	
ERI	24.9	18.7 33.7 22.2	0.3	1.3 -0.7 0.3	4.0	3.7 4.4 3.7	1.5	-3.9 6.5 1.9	-2.5	-3.0 -1.7 -2.7	2.8	0.5 4.7 3.2	
ERE	25.4	21.0 33.6 21.6	0.5	1.3 0.9 -0.8	8.2	11.3 8.6 4.6	0.6	-2.7 4.4 0.2	-2.8	NA -2.2 -3.5	2.5	1.9 1.3 4.3	
ELK	27.5	25.8 33.9 22.9	2.6	0.2 4.2 3.4	9.9	11.1 14.6 3.9	3.4	2.0 5.8 2.4	-1.2	1.5 -2.4 -2.6	1.2	-5.0 6.4 2.3	
ELG	24.0	18.1 31.7 22.3	3.1	0.4 4.5 4.3	8.1	12.1 9.1 3.1	3.3	1.5 5.2 3.2	-1.9	NA -3.1 -0.7	1.7	-2.3 5.6 1.6	
ELI	26.9	24.9 33.4 22.3	2.7	0.8 3.0 4.2	8.1	13.6 7.0 3.7	2.7	2.7 3.2 2.2	-2.1	-3.8 -0.8 -1.6	1.9	-1.7 6.9 0.7	
ELE	26.1	23.3 33.3 21.6	2.0	0.7 3.3 2.0	14.0	15.4 23.0 3.7	3.4	2.5 7.3 0.3	-2.3	NA -3.8 -0.8	0.4	-3.5 3.7 0.9	
TP8	22.0	21.9 24.2 20.1	0.8	1.0 -0.1 1.4	5.8	5.8 4.2 7.5	-0.6	1.3 -2.6 -0.6	0.5	1.0 1.8 -1.3	1.3	-1.2 7.5 -2.4	
T8	17.5	16.3 24.5 11.7	1.2	6.4 -2.3 -0.5	-0.2	-1.3 1.0 NA	-1.0	1.0 -3.0 NA	-0.7	1.4 2.5 -6.0	1.8	1.0 5.2 -0.9	
CP6	21.8	22.9 22.7 19.7	2.1	3.5 0.3 2.4	7.2	7.6 6.9 NA	1.5	-0.0 3.1 1.5	0.6	1.0 0.9 -0.0	-0.0	-1.3 3.2 -2.1	
C4	17.4	19.5 19.4 13.3	1.3	2.2 -1.9 3.6	-0.0	1.5 -1.5 NA	4.9	4.4 NA 5.4	0.9	2.1 2.1 -1.4	-0.9	0.4 NA -2.1	
Po8	20.3	23.8 19.6 17.5	1.9	4.1 0.3 1.3	3.0	NA 0.7 5.2	-1.5	0.6 -2.7 -2.3	-2.6	-1.6 -3.2 -3.1	1.5	4.7 1.1 -1.4	
P2	21.9	22.7 21.6 21.4	-0.1	-0.4 -1.4 1.4	5.1	2.6 7.4 5.4	0.3	1.4 -2.9 2.3	-0.8	-0.6 0.5 -2.4	0.7	1.9 0.4 -0.1	
F2	12.7	11.3 14.0 NA	-2.2	-2.2 -2.6 -1.9	3.3	NA 0.9 5.6	4.9	6.2 3.6 NA	-0.3	-2.3 1.7 NA	0.1	NA NA 0.1	
F8	13.0	6.0 19.9 NA	-2.3	-1.8 -2.9 NA	1.3	NA 1.3 NA	NA	NA NA NA	-0.7	0.4 0.7 -3.3	-1.6	NA NA -1.6	
TP7	17.9	20.0 12.8 20.9	0.1	2.0 -1.5 -0.3	3.2	1.6 NA 4.9	0.2	0.1 NA 0.4	-1.7	-1.5 NA -1.9	0.3	0.5 NA 0.0	
T7	13.8	14.9 15.7 10.8	1.2	3.3 0.0 0.4	-1.0	NA -1.0 NA	-3.6	-7.0 NA -0.3	-1.0	-5.3 4.0 -1.7	0.5	-0.2 0.1 1.5	
CP5	19.6	23.1 17.3 18.5	0.6	2.6 -0.6 -0.0	5.2	6.6 3.8 NA	1.0	2.0 NA 0.0	0.8	-2.0 5.5 -1.1	-0.4	-0.2 -0.2 -0.8	
C3	16.6	16.8 16.4 NA	1.6	0.8 2.3 NA	NA	NA NA NA	-2.1	-2.1 NA NA	-2.9	-4.4 0.5 -4.8	-3.2	-2.6 NA -3.7	
Po7	21.5	26.1 18.1 20.4	1.5	2.3 0.3 2.0	2.1	1.5 0.3 4.4	-2.0	0.2 -7.0 0.8	-1.9	-4.5 -1.4 0.1	-0.1	0.6 0.6 -1.6	
P1	21.6	23.5 19.8 21.4	0.3	0.2 -0.4 1.1	4.9	5.6 4.2 4.8	1.2	2.3 -0.9 2.3	-1.0	-2.5 1.1 -1.6	0.2	1.2 -1.0 0.5	
F1	13.4	16.0 13.6 10.5	0.3	-0.4 -3.4 4.5	3.1	3.1 NA NA	1.8	2.8 NA 0.8	-1.3	0.7 -1.5 -2.9	-0.3	1.0 NA -1.5	
F7	13.9	9.2 20.6 11.9	1.0	3.5 -2.1 1.7	-2.1	NA -2.1 NA	1.3	NA -4.6 7.1	-2.7	-6.6 1.6 -3.3	0.0	1.8 -1.6 -0.1	
Scalp EEG	17.2	18.4 18.8 14.6	0.5	1.7 -1.0 0.7	2.4	0.9 0.5 5.8	-0.0	3.1 -4.1 0.8	-0.5	-1.6 2.3 -2.3	-0.5	0.3 -0.8 -1.0	
EarEEG	25.8	21.8 33.3 22.1	1.5	1.1 1.8 1.7	8.3	11.7 9.4 4.0	2.3	0.0 5.2 1.7	-2.5	-3.6 -2.0 -1.9	2.2	-0.9 5.1 2.4	

TABLE I

SNR [dB] for the artifact free condition and the SNRDs [dB] for the artifacts conditions 2-6 in the frequency range from 35-45 Hz. The 3 numbers to the right in each cell are the values for each subject and the value to the left is the mean value. The lower part of the table summarizes the results in terms of an average over all SNR and SNRDs for all scalp electrodes and EarEEG electrodes respectively. "NA" denotes discarded recordings.

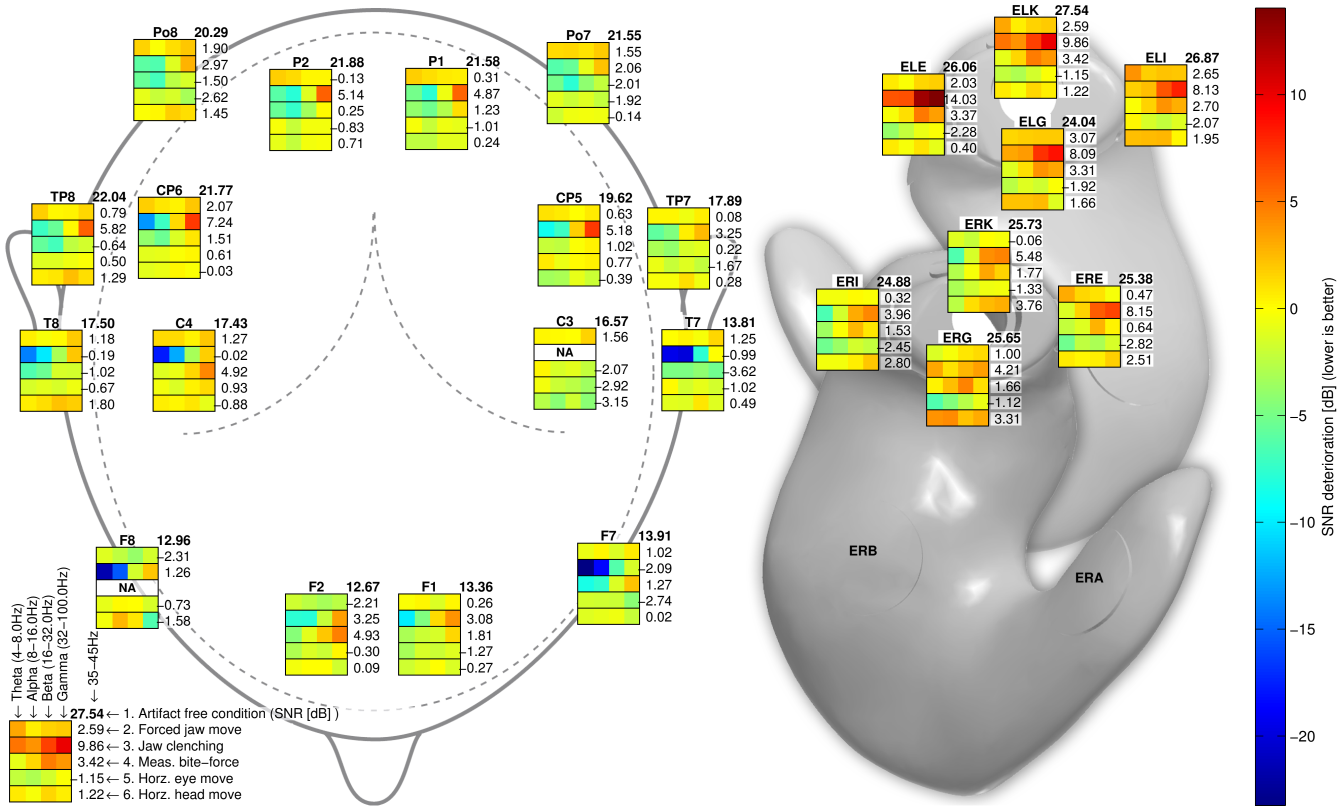

Fig. 4. The SNRD for electrode positions on the scalp and electrodes on the left and right ear-piece. The SNRD was calculated for each subject. The average SNRD was then calculated by performing interperson averaging of the decibel SNRD values for each artifact condition, frequency band and electrode. The SNRD was calculated in the clinical bands: Theta (4-8 Hz), Alpha (8-16 Hz), Beta (16-32 Hz) and Gamma (32-100 Hz) and expressed as a color-code. The SNRD was also calculated in the range from 35-45 Hz to express the SNR in the area of the ASSR response.

the combined data from a typical EarEEG electrode, ELI. The noise-floor of the different artifact conditions had a similar flat shape, and the power of the 40 Hz ASSR response was comparable between artifact conditions. The SNR was calculated as described in section II-A with f_{low} and f_{high} defined as 35 Hz and 45 Hz respectively. The SNR values in Fig. 3 is an interperson averaging of the decibel SNR values for each artifact condition. The variation in the SNR between artifact conditions was noticeable, with jaw clenching and head movement artifact conditions having the lowest SNR values. On average the artifact free condition was 6.3 dB higher than the SNR of the artifact conditions.

Fig. 4 and Table I provide an overview of the SNR deterioration (SNRD) during the artifact conditions for the different electrode positions and frequency bands. All the SNRD values are based on time averaged data with a segment size of 4 seconds. A few recordings were discarded because no ASSR response was observed. The discarded recordings are denoted "NA" in Table I. In a few experiments the table shows negative SNRDs, reflecting the fact that the measured ERPs in between experiments are still subject to certain variations.

The SNR of the artifact free condition in Fig. 4 and Table I give a picture of a higher SNR for the EarEEG when

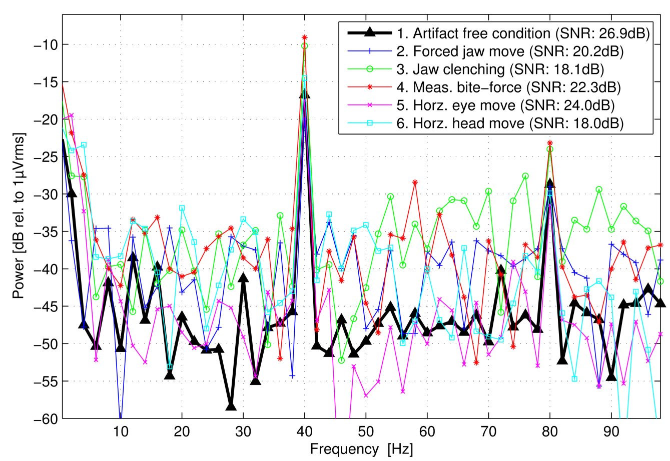

Fig. 3. Power spectra of the data recorded from electrode ELI for the different artifact conditions. The SNR value was calculated as described in section II-A with f_{low} and f_{high} defined as 35 Hz and 45 Hz respectively. The plot is based on time averaging of the recordings using a segment size of 0.5 seconds.

compared to the scalp EEG, however the artifact conditions seem to cause a larger SNRD on the EarEEG recordings. Jaw clenching is well known to induce severe artifacts on scalp EEG recordings [9], and this was also the case in the current study. SNRD related to the jaw clenching artifact condition was especially visible on the EarEEG recordings, and the average SNRD was 8.3 dB as given in Table I. A SNRD was also visible on the scalp EEG, but was not as noticeable. The SNRD during horizontal head movements were relatively high for the EarEEG when compared to scalp EEG. During the recordings the subjects noticed that head movements caused a drag on the cables connected to the EarEEG electrodes. This drag may have resulted in a movement of the ear-piece, and thereby causing motion artifacts. These motions might have been the reason for the SNRDs related to head movements, and it will consequently be possible to reduce these artifacts by improving the wiring to the EarEEG. Furthermore it should be noted that the scalp electrodes were active and the ear electrodes were passive, therefore the ear electrodes were more prone to interference induced by cable motions. This is most likely a secondary aspect.

When comparing the scalp EEG and EarEEG for the other artifact conditions no noticeable differences were observed. Another interesting aspect was that the SNRD was at approximately the same level for all the clinical frequency bands, which is supported by Fig. 3 where the noise-floor has a flat shape.

IV. Conclusion

A method for the quantitative assessment of artifacts in EEG was established and evaluated. The method was used to calculate SNR deteriorations for five different artifact conditions on recordings from both scalp EEG and EarEEG electrodes. Evaluation of EEG recordings in a condition with low levels of noise and artifacts indicated that the SNR of the EarEEG electrodes was higher than the SNR of the scalp EEG electrodes, however the SNR deterioration for EarEEG was higher when compared to scalp EEG. The largest SNR deteriorations were observed during jaw clenching and head movement. Jaw clenching is well known to cause severe artifacts in EEG, and head movement was only noticeable on EarEEG where the SNR deterioration might have been caused by drag in cables to the ear-pieces. The artifacts investigated have been generated in a systematic and reproducible manner, and custom-made devices and procedures have been developed to obtain this. The methodology introduced is suitable for a more extensive study of artifacts in EEG.

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