Ear-EEG: User-Centered, Wearable & 24/7 BCI

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Project description | We present a radically new solution for EEG-based brain computer interface (BCI) where electrodes are embedded on a customized earpiece, as typically used in hearing aids (Ear-EEG). This provides a noninvasive, minimally intrusive and user friendly way of recording EEG over long time periods (days) and in natural environments. The operation of Ear-EEG is illustrated for alpha-attenuation and responses to auditory stimuli, and its potential in BCI is evaluated on an SSVEP study. We show that Ear-EEG bitrate performances are comparable with those of on-scalp electrodes, thus promising a quantum step forward for wearable BCI.

User-Centered BCI

Electroencephalogram (EEG) technology is widely used as a low cost means of detecting brain activity for brain computer interface (BCI), it also permits a wider scope of use than, say functional magnetic resonance imaging. Opportunities for EEG-based BCI are rapidly expanding beyond medical uses, such as neuroprosthetics, to non-medical uses for healthy subjects including fatigue monitoring, gaming, and equipment control. Yet, more ***widespread use of BCI is limited by conventional recording systems which are bulky and cumbersome*** and which primarily operate in the laboratory setting.

This highlights the ***need for wearable systems which allow long-term recordings in natural environments*** [1]. Such systems are particularly useful in applications for which a trade-off in performance is acceptable in order to enhance user comfort. Improvements in battery size and dry electrode technologies[1] are advances, but on-scalp electrodes still require a means for stable attachment (cap and/or adhesive), making the recording process uncomfortable and stigmatising. In order for EEG-based BCI to be adopted more widely and in natural environments, the recording technology should be [2, 3]:

- **Discreet** - not clearly visible or stigmatising,
- **Unobtrusive** - comfortable to wear and impeding the user as little as possible,
- **User-friendly** - users should be able to attach and operate the devices themselves.

Figure 1: [**Left**] The left Ear-EEG earplug with electrode positions visible (grey dots) and an arrow indicating the direction in which it enters the ear canal. [**Right**] Recording setup: joint recording of Ear-EEG and on-scalp EEG for comparative analysis.

[1] Conventional electrodes require the use of conductive gel to enable an electrical connection between the electrodes and the scalp.

Ear-EEG

To further expand the use of BCI we have recently introduced Ear-EEG [2, 3, 4], a technology which satisfies core user requirements (**unobtrusive**, **discreet** and **user-friendly**). This represents a quantum step forward in wearable EEG whereby, benefiting from the underlying hearing aid platform, all electrodes (including reference and ground) are embedded on a customized earpiece placed within the ear canal and the outer ear (see Figure 1). The tight fit between the earpiece and ear canal ensures that the electrodes are held firmly in place, thus overcoming some critical obstacles in scalp EEG – such as motion artifacts and experiment repeatability.

The Ear-EEG approach has recently been rigorously validated [2, 3, 4] in terms of time, frequency and time-frequency signal characteristics for a range of EEG responses (see Figure 2); its robustness to common sources of artifacts has also been demonstrated (see Figure 2, upper). Comparative analysis of the alpha attenuation response (see Figure 2, centre) shows that Ear-EEG responses match those of neighbouring scalp electrodes located in the temporal region [2]. In general, while signal amplitudes measured from within the ear are weaker, so too is the noise, and for certain auditory responses the ***signal-to-noise ratios (SNR) are similar*** (see Figure 2, lower) [4]. All in all, Ear-EEG offers a unique balance between key user needs and recording quality to enable long-term EEG monitoring in natural environments.

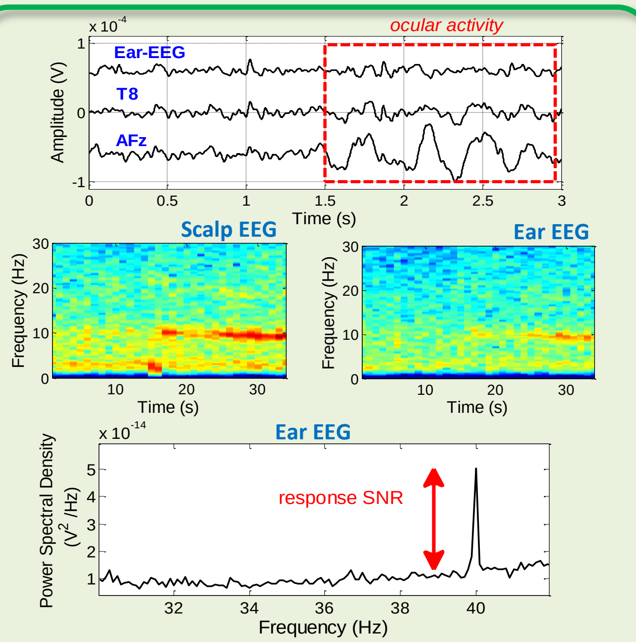

Figure 2: [**Upper**] Time waveforms for scalp and Ear-EEG over 3s with consecutive eye blinking starting at 1.5s, Ear-EEG exhibits a suppression of ocular artifacts. [**Centre**] Time-frequency plots as subject closes eyes from 15-35s, with increased activity visible for scalp [**Centre, left**] and Ear-EEG [**Centre, right**] in the alpha range (8-12 Hz). [**Lower**] The auditory steady state response for Ear EEG (40 Hz stimulus). The SNR (ratio of the response peak to background EEG) matches that of temporal scalp electrodes [4].

Table 1: SSVEP-BCI capacity ratios for scalp and Ear-EEG. C_{EL} and C_{ER} denote respectively the capacities of left and right Ear-EEG electrodes, and C_{Oz}, C_{TP7} and C_{TP8} the capacities of electrodes Oz, TP7 and TP8. Subjects $\mathbf{S_1}$ to $\mathbf{S_4}$ attended stimuli of 15 Hz and 20 Hz.

	S_1 [15Hz]	S_1 [20 Hz]	S_2 [15Hz]	S_2 [20Hz]	S_3 [15Hz]	S_3 [20Hz]	S_4 [15Hz]	S_4 [20Hz]	Mean
C_{EL}/C_{TP7}	0.44	0.51	0.24	0.32	0.46	0.78	0.85	0.71	0.54
C_{EL}/C_{Oz}	0.39	0.31	0.24	0.21	0.39	0.78	0.80	0.44	0.45
C_{ER}/C_{TP8}	0.38	0.42	0.93	0.89	0.51	0.54	0.48	0.51	0.58
C_{ER}/C_{Oz}	0.23	0.38	0.95	0.44	0.31	0.52	0.62	0.40	0.48

Ear-EEG: SSVEP-Based BCI

The potential of Ear-EEG in BCI applications is illuminated for a core paradigm – the steady state visual evoked potential (SSVEP) – the basis for the best performance in EEG-BCI to date [5]. We employed a grid of LEDs flashing at different frequencies: 13, 14, 15 and 16 Hz. The setup enables a user to communicate an instruction as attending a given LED induces the SSVEP – increased activity at the stimulus frequency in the EEG. Figure 3 illustrates the BCI mode-of-operation of Ear-EEG; observe peaks in the spectrum at the location of the attended frequencies.

BCI Performance Evaluation

For rigor, ***we have evaluated the BCI performance of Ear-EEG using a metric that is independent of the stimulus presentation***.[2] This was achieved by assessing the SNR, that is the ratio between the power spectral density (PSD) of the SSVEP response peak[3] and the background EEG estimate, for both the scalp and Ear-electrodes (similar to the analysis illustrated in Figure 2, lower), for different subjects and stimulus frequencies[4] (trials of length 256s). The Shannon-Hartley theorem, $C = B\log_2(1+SNR)$, where B is the bandwidth of the channel and the SNR is expressed as a linear power ratio, was used to evaluate the bitrate performances (bits/sec) for each electrode. Table 1 shows the capacity ratios for Ear-EEG relative to 1) neighbouring TP7 and TP8 on-scalp electrodes (located in temporal region); and 2) the Oz on-scalp electrode, a natural choice for visual potential detection (located in occipital region).[5]

Table 1 shows that Ear-EEG electrodes attain an average BCI bitrate capacity[6] of 55% that of neighbouring scalp electrodes (mean ratio is 0.56). Compared to the Oz electrode, optimal for SSVEP-based BCI [5], observe that ***Ear-EEG exhibited a performance reduction (bits/min) of only approximately 50%.*** The best results for each subject are marked in red, with the bitrate capacity ratios exceeding 0.70 for three of the four subjects, and even reaching 0.95 (see Table 1: Subject 2).

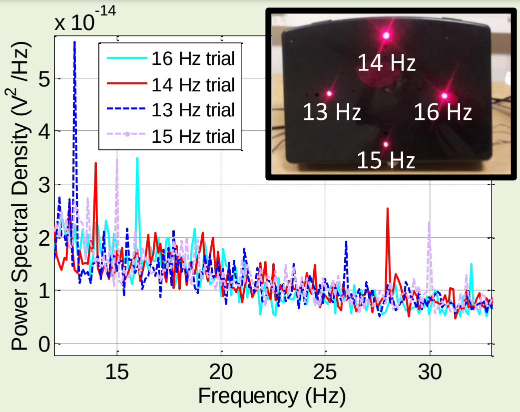

Figure 3: The average Ear-EEG power spectral density (PSD) for four 120s trials as the user attended 13, 14, 15 and 16 Hz stimuli. [**Insert: upper right**] The SSVEP stimulus interface with four LEDs.

Summary

We have illuminated the usefulness of the Ear-EEG methodology for BCI, where all the electrodes (including reference and ground) are embedded on an earpiece. For a fair comparison, scalp and Ear-EEG electrodes have been evaluated via the same recording amplifier. Future commercial Ear-EEG earplugs will incorporate the recording and signal processing electronics, as is a standard in hearing aids. This will enable the freedom to perform wearable BCI in any environment and in real-time over long time periods (days) and to meet core user needs (***robust***, ***discreet*** and ***comfortable***). The rigorous analysis against standard on-scalp electrodes has illustrated the potential of Ear-EEG in expanding the horizons of real-world BCI, while keeping the same order of magnitude of the channel capacity.

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[2] Stimulus presentation design can greatly affect the performance of a BCI system and is itself a focus of research, we therefore evaluated Ear-EEG based on the SNR of the SSVEP response.

[3] The SNR was estimated at the fundamental frequency of the stimulus.

[4] To ensure a fair comparison between scalp and Ear-electrodes, EEG was recorded for both approaches using the same amplifier (g.USBamp by g.tec) which has several independent blocks of inputs.

[5] All scalp electrodes were referenced to the earlobe and the ground electrode was placed at Cz (10-20 system). All Ear-electrodes were inside the ear, including reference and ground (see [4] for more details).

[6] C_{EL} and C_{ER} denote the capacities for the left and right earpieces respectively.