Ear-EEG: Continuous Brain Monitoring

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Abstract We present a radically new way of recording EEG comfortably and unobtrusively over long time-periods in natural environments. This break-through has been achieved using electrodes embedded on a customized earpiece as typically used in hearing aids (Ear-EEG). We illustrate the potential of Ear-EEG as an enabling technology for a number of uses beyond traditional BCI, which are currently limited by the inconvenience of standard EEG recording methods. We show that Ear-EEG enables both conventional BCI and next-generation applications such as the evaluation of hearing capability and the monitoring of fatigue and drowsiness.

Keywords Ear-EEG · Brain computer interface (BCI) · Non-medical BCI · Wearable EEG · Hearing threshold estimation · Fatigue estimation

1 Introduction

Opportunities for EEG-based BCI are rapidly expanding beyond medical uses, where the primary aim is a high-performance *communication* pathway for paralyzed patients, to numerous non-medical uses wherein the goal is a continuous

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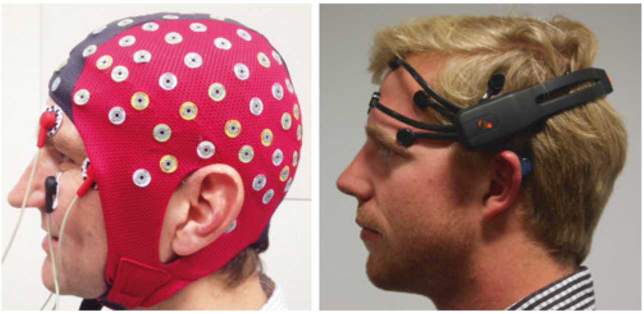

Fig. 1 *Left* A 128-channel ‘stationary’ EEG system (asalab, by ANT neuro) and *right* a wearable system (Emotiv EPOC headset)

measurement of brain state (Blankertz et al. 2010; Allison et al. 2013). Typical applications could include monitoring fatigue or stress to optimize performance at work, or diagnosing sleep disorders (Ward et al. 2012). This all requires overcoming several multi-disciplinary challenges in e.g. machine learning and signal processing, but most crucial of all is the realisation of a robust and portable technology for continuous recording of EEG. The first ambulatory EEG (AEEG) systems appeared in the 1970s (Waterhouse 2003), aided by developments in miniature preamplifiers and continuous analog-recording technology. Digitization of recording platforms, coupled with the integration of computer technology, has provided even greater portability, and current recording systems can operate for 24 h with up to 32 channels. However, conventional recording systems remain bulky and cumbersome, and primarily operate in the laboratory setting (see Fig. 1, left), highlighting the need for so-called wearable systems that allow long-term recordings in natural environments (Casson et al. 2010).

1.1 Towards Wearable EEG

The concept of wearable EEG is of particular value in non-medical BCI applications where a trade-off in performance is acceptable in order to satisfy needs of the user. One of the ways such a trade-off can be achieved is in the design of systems which can accommodate smaller batteries, thereby reducing the system size and increasing its wearability (see Fig. 1, right), either by reducing the number of electrodes or through advanced data compression algorithms which reduce data logging or transmission costs [50 % raw data reduction using lossless compression techniques (Casson et al. 2010)].

Another key advance in wearable EEG is dry electrode technology; standard systems require the use of conductive gel to enable an electrical connection between the electrodes and the scalp, which is time consuming, can cause discomfort and limits the time that the recording system can remain functional as the gel dries out. Dry electrode technologies have been in development since the late 1960s (Richardson et al. 1968; Bergey et al. 1971) and recent research illustrates that, for motor imagery BCI, dry electrode systems can match the operation of wet electrode systems with only a 30 % reduction in performance (Popescu et al. 2007). More recent work demonstrated that dry electrodes could yield performance comparable to wet electrodes in P300, SSVEP, and motor imagery BCIs (Guger et al. 2012; Edlinger and Guger 2013).

Despite such advances in wearable EEG technology, research has focused on systems which utilise on-scalp electrodes. This methodology is fundamentally limited, as it requires 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 to be robust for use in natural environments, the recording technology must be:

- **discreet**—not clearly visible or stigmatizing;
- **unobtrusive**—comfortable to wear and impeding the user as little as possible; and
- **user-friendly**—users should be able to attach and operate the devices themselves.

2 Ear-EEG

To expand the use of BCI, particularly in non-medical applications where core user requirements (unobtrusive, discreet, user-friendly) are paramount over performance, we have developed the Ear-EEG concept (Looney et al. 2012; Kidmose et al. 2013). The approach, as shown in Fig. 2, is radically new in that EEG is recorded from within the ear canal, which is achieved by embedding electrodes on a customized earpiece (similar to earplugs used in hearing-aid applications). Both in terms of the propagation of the brain electric potentials and the recording technology, Ear-EEG uses the same principles as standard recordings obtained from on-scalp electrodes. In electrophysiological terms, bioelectrical signals from the

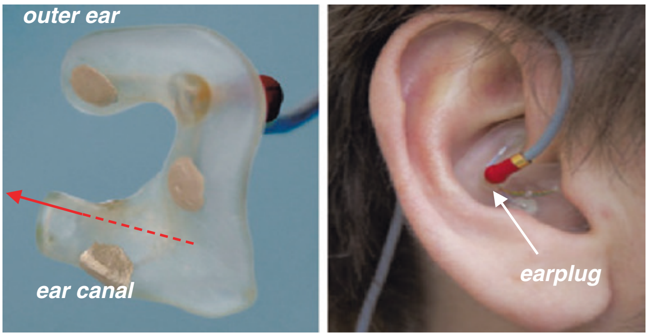

Fig. 2 *Left* The right Ear-EEG earplug with electrodes visible and an *arrow* indicating the direction in which it enters the ear canal. *Right* The earplug inserted in the right ear

cortex are attenuated by the cerebrospinal fluid, skull, and skin before reaching the ear canal, as is the case with conventional scalp measurements.

In addition to satisfying the aforementioned BCI user-requirements, crucial advantages of the Ear-EEG platform are as follows (Looney et al. 2012):

- the earpieces are personalized, comfortable to wear, discreet, and are easy to put in place by the users themselves, facilitating everyday use;
- 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.

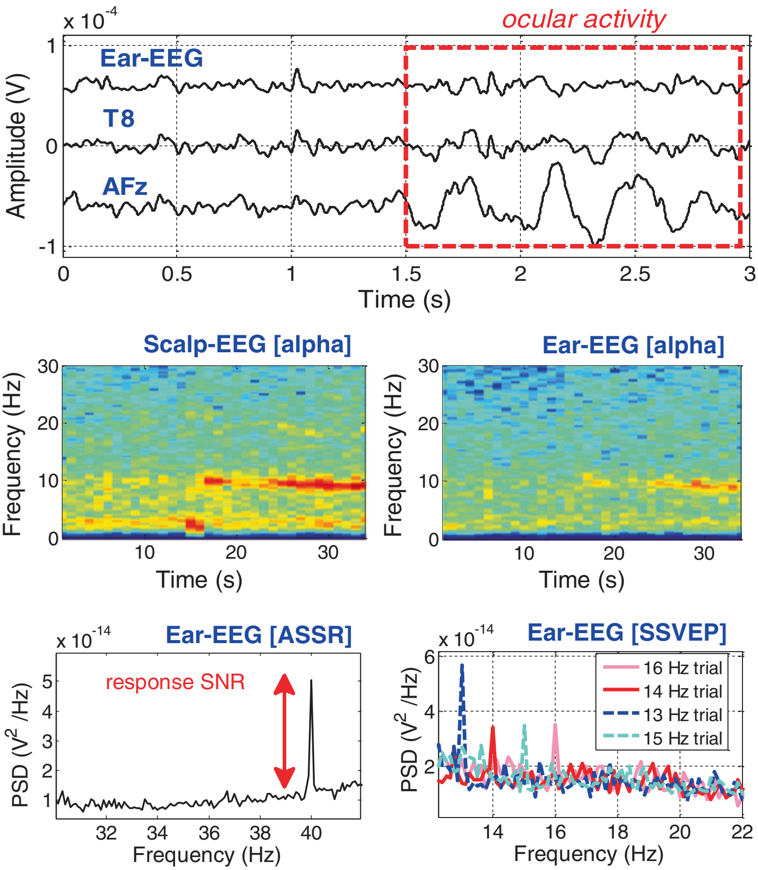

Fig. 3 *Upper* Time waveforms for scalp and Ear-EEG over 3 s with consecutive eye blinking starting at 1.5 s, Ear-EEG exhibits a suppression of ocular artifacts. *Centre* Time-frequency plots as subject closes eyes from 15–35 s, with increased activity visible for scalp (*Centre*, *left*) and Ear-EEG (*Centre*, *right*) in the alpha range (8–12 Hz). *Lower*, *left* 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 (Looney et al. 2012; Kidmose et al. 2013). *Lower*, *right* Ear-EEG steady state response to visual (13, 14, 15 and 16 Hz) stimuli, illustrating traditional communication SSVEP-based BCI (Looney et al. 2014)

The current in-ear prototype (see Fig. 2) comprises several electrodes, with areas of approximately 20 mm^2, made of silver (Ag) epoxy glue mounted onto a plastic earpiece [see Kidmose et al. (2013) for more details]. The earpiece does not enter the ear by more than 10 mm and does not approach the part of the ear canal surrounded by bone. Signal acquisition is performed via an external biosignal amplifier (g.tec g.USBamp). When comparing with scalp-EEG, both sets of electrodes are connected to the same amplifier; this facilitates the recording of several independent blocks of inputs, allowing a fair comparison between the two approaches.

The Ear-EEG approach has recently been rigorously validated (Looney et al. 2012; Kidmose et al. 2013) in terms of time, frequency and time-frequency signal characteristics for a range of EEG responses (see Fig. 3); its robustness to common sources of artifacts has also been demonstrated (see Fig. 3, upper). Comparative analysis of the alpha attenuation response (see Fig. 3, centre) shows that Ear-EEG responses match those of neighbouring scalp electrodes located in the temporal region. 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 Fig. 3, lower left). Responses to visual stimuli are also possible (see Fig. 3 lower right). 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.

3 Ear-EEG: Towards Continuous Brain Monitoring

The presented results were obtained using a simple prototype system, but with further developments Ear-EEG will be a tiny battery powered brain monitoring device with gel-free electrodes that, like a hearing aid, will perform both the recording and signal processing in situ (see Fig. 4). Moreover, to increase the functionality of Ear-EEG in BCI applications where the user state must be evaluated, other physiological parameters can be inferred by integrating additional non-invasive sensors onto the ear-based platform (Looney et al. 2012):

- cardiovascular function: ear-based PPG devices available (Poh et al. 2010);
- respiratory function: respiratory sounds can be recorded within ear canal (Pressler et al. 2002); and
- movement: accelerometers are sufficiently small size and low-power for in-ear use.

We have already established that Ear-EEG enables conventional communication BCI (see Fig. 3 lower right). Its potential in continuous brain monitoring is illustrated with two case studies via the Ear-EEG prototype shown in Fig. 2. 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). On-scalp reference and ground electrodes were placed at, respectively, chin and Cz (HTL study) and earlobe and Fpz (fatigue study) based on the 10–20 system. All ear-electrodes were inside the ear, including reference and ground [see Kidmose et al. (2013) for more details].

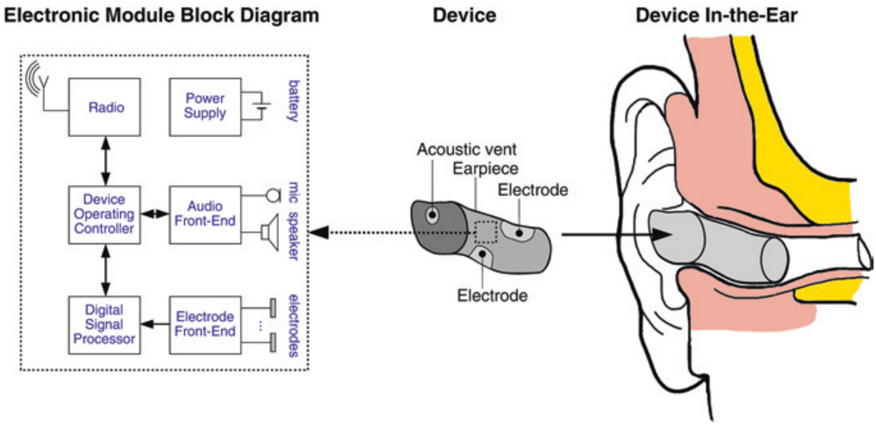

Fig. 4 An illustration of a future Ear-EEG device with an electronic module comprising instrumentation for the electrode signals, analog-to-digital conversion, a signal processing unit, battery, and a radio module

4 Fatigue Estimation

Many occupations and daily activities require prolonged periods of vigilance and concentration. In the transport industry, a lapse in concentration can be fatal. The Royal Society for the Prevention of Accidents estimates that driver fatigue accounts for 20 % of road accidents in Great Britain. Yet there is still no readily available device that can objectively and reliably detect a loss of sustained attention.

We have already shown in Fig. 3 (centre, right) that Ear-EEG can track the evolution of alpha activity with high accuracy. As increases in alpha power are also caused by drowsiness, we next demonstrate how Ear-EEG models drowsiness on a par with a scalp approach: highlighting its role in maintaining vigilance (e.g. phasic alert via a loudspeaker). Our study was based on the Oxford Sleep Resistance Test; a functional test of attention and drowsiness (Davies et al. 1997), wherein a subject was instructed to press a button in response to periodic visual stimuli. A missed stimulus (MS) event denotes the failure of the subject to respond in time to the stimulus and indicates an attention lapse. Fatigue was induced by reducing the sleeping hours of the subject and their vigilance was determined by detecting MS events, or consecutive MS events. Figure 5 shows the button-press errors and the corresponding levels of alpha power in EEG (filtered via a median filter) estimated using scalp- and ear-electrodes.[1] Observe the high similarity in alpha power for ear and scalp EEG and the clear increases in alpha power which accompany error

[1] The in-ear setup used to obtain the results shown in Fig. 5 was electrode ELB referenced to ELH (Kidmose et al. 2013).

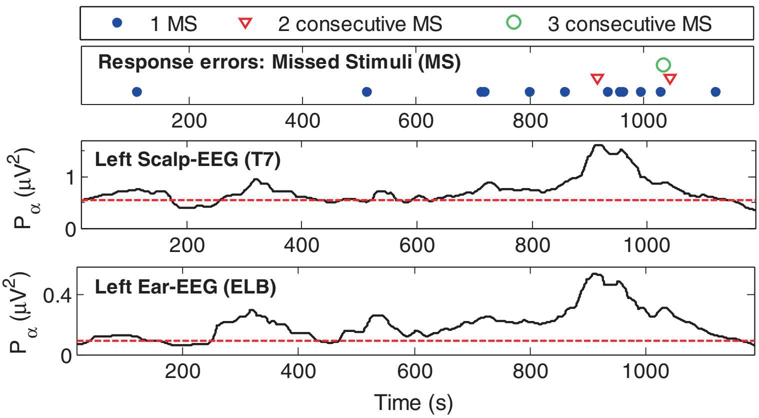

Fig. 5 Fatigue estimation. *Upper* Response errors: missed stimuli (MS) events, single and consecutive. *Centre* and *Lower* Alpha power (*solid black line*) for the scalp and ear electrodes respectively. For reference, the average alpha power of the subject estimated during a non-fatigue state is also given (*dashed red line*)

events and, for instance, how a rise in alpha power at 850 s precedes consecutive MS events. This result is consistent with prior results with on-scalp electrodes (Jung et al. 1997).

5 The Estimation of Hearing Threshold

The World Health Organization (WHO) estimates that hearing impairment affects more than 250 million people worldwide, making it the most common sensory deficit. The operation and fitting of modern hearing devices requires an accurate assessment of hearing capability known as the hearing threshold level (HTL). The HTL is estimated via behavioural hearing tests at an audiology clinic. However, in many cases, hearing loss is progressive or fluctuating (such as in Meniere's disease or auditory neuropathy) and requires continuous assessment.

A well-established HTL-estimation protocol is based on the auditory steady state response (ASSR) (Cone-Wesson et al. 2002). The Ear-EEG platform accommodates a loudspeaker (as in hearing aids) inducing ASSRs as illustrated in Fig. 3 (lower, left), the amplitudes of which reflect the level of the auditory stimuli. This enables a model of HTL and a reference for continuous hearing aid adaptation to match progressive/fluctuating hearing loss without an audiologist. Figure 6 depicts a high level of similarity between the SNR of ASSRs recorded[2] from a scalp

[2] The SNR of the ASSR is defined as the power spectrum ratio of the response peak to the background EEG [see also Fig. 3 (lower, left)].

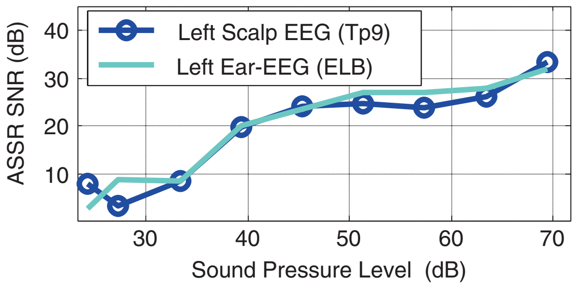

Fig. 6 Hearing threshold estimation. The SNR of the ASSR (an estimate of the response amplitude) for scalp and ear electrodes for ASSR-stimuli of increasing sound pressure levels (SPL)

electrode located in the left temporal region (Tp9) and a left Ear-EEG electrode [ELB referenced to ELH, see Kidmose et al. (2013)] for various ASSR-stimulus sound pressure levels (SPL).

6 Conclusions

Ear-EEG is a breakthrough in wearable sensing that has the potential to be used in non-specialist environments over long time periods—it is robust, discreet and comfortable. We have demonstrated the usefulness of Ear-EEG, with sensing as well as reference and ground electrodes embedded on the earpiece, for current and next-stage BCI—continuous brain monitoring. The estimation of hearing threshold and fatigue have great significance in quality of life and work for a sizeable population. This work illustrates how, when combined with appropriate electronics, the ear-based platform will open up radically new possibilities in future continuous monitoring applications.

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