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Ear-EEG from generic earpieces: A feasibility study

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Abstract— **The use of brain monitoring based on EEG, in natural environments and over long time periods, is hindered by the limited portability of current wearable systems, and the invasiveness of implanted systems. To that end, we introduce an ear-EEG recording device based on generic earpieces which meets key patient needs (discreet, unobstrusive, user-friendly, robust) and that is low-cost and suitable for off-the-shelf use; thus promising great advantages for healthcare applications. Its feasibility is validated in a comprehensive comparative study with our established prototype, based on a personalized earpiece, for a key EEG paradigm.**

I. INTRODUCTION

Electroencephalography (EEG) refers to the recording of electrical brain activity, and is a valuable and well-established tool within clinical practice, neuroscience, psychology and in brain-computer interface. Within clinical practice, EEG is widely used in the investigation of e.g. neurologic disorders and diseases in the central nervous system. Despite the clinical potential of brain monitoring based on EEG, current recording systems are bulky and cumbersome and require a trained person to setup and operate. This limits their use in outpatient applications where recordings must be made over long time periods and in natural environments. Recent improvements in low power electronics and dry electrode technologies are advances and have led to smaller and more user-centered systems, but on-scalp electrodes still require a means for stable attachment (cap, adhesive or headset), making the recording process uncomfortable and stigmatising. In order for EEG-based devices to be adopted more widely, and to enable long-term monitoring, the recording technology should be: **discreet** - not clearly visible or stigmatizing, **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 and **robust** - able to acquire good quality EEG signals under everyday life conditions [1].

We recently introduced the ear-EEG concept [2], a technology which satisfies core user requirements (unobtrusive, discreet, user-friendly, robust). This represents a significant step forward in wearable EEG whereby all electrodes (including reference and ground) are embedded on a personalized earpiece placed within the ear. The tight fit between the earpiece and ear ensures that the electrodes are held firmly in place, thus overcoming some critical obstacles in scalp EEG. Although the ear-EEG concept shows great promise in health monitoring, the fabrication process is time consuming, it fits only one individual and it is costly (wax impression of the outer ear, 3D scanning of the wax impression, CAD modeling and manufacturing of the earpiece).

We here introduce a form of ear-EEG based on generic earpieces which will fit any ear, can be used immediately and are low-cost. The generic platform retains many core properties of the personalized one and has great potential in healthcare applications. It is illustrated in the sequel that a prototype based on an earpiece of silicone rubber can be used to detect a key EEG paradigm, the auditory steady state response (ASSR). Comparative analysis between personalized and generic prototypes yields insight into how the electrode positioning affects recording quality in ear-EEG devices.

II. THE EAR-EEG CONCEPT

There exist a number of EEG-based applications, clinical and non-clinical, for which a small number of electrodes are sufficient, and for which a fully wearable recording platform is prerequisite. The ear-EEG concept exhibits a high degree of comfort and excellent long term wearability, at the expense of a reduced number of electrodes and thus a compromise in spatial resolution. A prototype based on personalized earpieces (see Fig. 1) has recently been rigorously validated in terms of time, frequency and time-frequency signal characteristics for a range of EEG responses; its robustness to common sources of artifacts has also been demonstrated. In general the characteristic of the ear-EEG signals are very similar to temporal region scalp electrodes, and it has been demonstrated that while the Ear-EEG amplitudes are typically 10 to 20 dB lower in amplitude compared to conventional on-scalp recordings, a similar signal-to-noise ratio is maintained [3]. Ear-EEG offers a unique balance between user needs and recording quality to enable long-term monitoring in natural environments – a key requirement in outpatient healthcare applications.

Independently of [2] a similar method was proposed in [4], where a more generic type of earpiece was disclosed. Whereas the method based on the individualized earpiece has been prototyped and validated, we have not found any results published from the method proposed in [4].

III. RECORDING PLATFORMS

The study is based on recordings from the following two recording platforms:

Personalized earpiece. The current ear-EEG system [3] employs individualized earpieces that are custom made for the user's ear using the same processes as that in the manufacturing of customized hearing aid ear-plugs. The

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earpieces are hollow, and with a ⌀3 mm hole at the end to reduce acoustic occlusion of the ear. On each earpiece are placed 4 silver electrodes each with an electrode area of approximately 20 mm^2. Fig. 1 shows the earpiece used in this study. See [3] for more details.

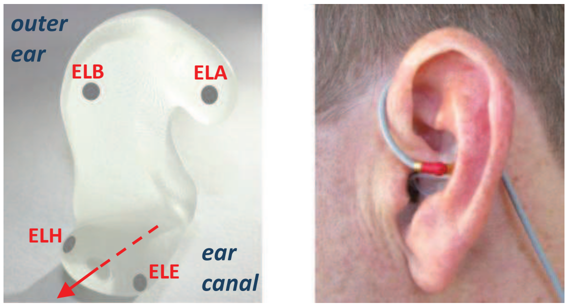

Fig. 1. The personalized earpiece, for the left ear, with electrode positions visible and an arrow indicating the direction in which it enters the ear canal (left) and a photo of the earpiece in the ear (right).

Generic earpiece. The generic platform proposed in this work is based on a conical shaped ear-plug made of a biocompatible silicone rubber. The length of the ear-plug is approximately 10 mm, with an inner and outer diameter of 7.5 and 10 mm respectively, with a ⌀1.5 mm through hole in order to reduce acoustic occlusion. There are 3 electrodes embedded on the outer surface with 120° degrees separation. The electrodes are made of a conductive silicone rubber (Wacker, Elastosil LR 3162), and have a surface area of approximately 15 mm^2. The electrodes are molded into recesses of the ear-plug, and are connected to a common connector by means of litz-wire. Fig. 2 (left) shows a sketch of the mechanics and Fig. 2 (right) shows a photo of the earpiece.

All recordings made using the two platforms follow the same setup procedure[1].

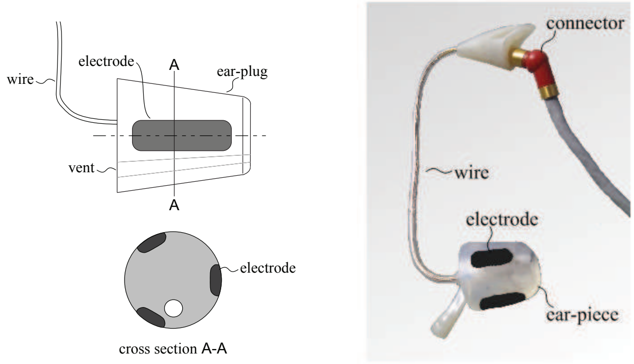

Fig. 2. A sketch of the mechanics of the generic earpiece (left) and a photo of the prototype (right).

IV. EAR-EEG RECORDINGS

The objective of this work is to characterize and compare EEG recorded from the two platforms and from different electrode configurations. For rigor of analysis and convenience, the comparison is based on an event related potential (ERP) that can be assumed to be the same across different experiments. To characterize the quality of the EEG recordings we consider the signal-to-noise ratio (SNR) of the evoked response *signal* relative to the *noise* (consisting of spontaneous background EEG, bioelectric artifacts and measurement noise). While transient ERP responses have their energy spread out in the frequency domain, steady state responses have only energy at the harmonics of the repetition frequency of the stimulus signal. For this reason, and because steady state response in general have higher amplitudes, it is convenient to base the study on steady state responses, and measure the SNR in the frequency domain. In this study the characterization of the EEG signals is based on auditory steady state responses (ASSR) induced by a white Gaussian noise signal amplitude-modulated with a 40 Hz or 80 Hz sinusoid.

The audio setup was gain calibrated (no equalizing) at 1 kHz, and the audio stimulus was presented at a sound pressure level of 70 dB RMS rel. 20 μPa. The EEG was recorded with a sampling frequency of 1200 Hz. The evoked response was estimated by averaging 256 time-segments of 1 sec. which results in an increase in the signal-to-noise ratio (SNR) of 24 dB. Along with the evoked response, the noise signal was estimated by changing the sign of the segments in every second segment in the averaging, whereby the deterministic (evoked) part of the signal was eliminated. The power spectrum density (PSD) was obtained as the squared absolute value of the discrete Fourier transform (DFT) of the averaged waveform.

For the personalized earpiece the ASSR was recorded from electrode ELB and ELE, using electrode ELH as common reference and electrode ELA as ground (common mode feedback), see Fig. 1. The power spectrum densities for the ASSR recordings using both 40 Hz and 80 Hz modulation frequency is shown in Fig.3. Considering the ASSR 40 Hz from electrode ELB and ELE, Fig. 3(a) and 3(b) respectively, it is observed that there is a significant difference in the SNR. Electrode ELB has 30 dB SNR at the first harmonic component, whereas electrode ELE has only 10 dB SNR. The same SNR difference between electrode ELB and ELE is observed for the ASSR 80 Hz in Fig. 3(c) and 3(d).

For the generic earpiece the ASSR was recorded with three different electrode configurations

(a) Recording from an ear-electrode relative to an electrode placed on the ear-lobe, and with a ground electrode placed on the mastoid point behind the ear. The external electrodes were conventional Ag/AgCl cup-electrodes, and the ground was used for common-mode feedback.

(b) Recording from one ear-electrode relative to another ear-electrode, and again with a ground electrode placed

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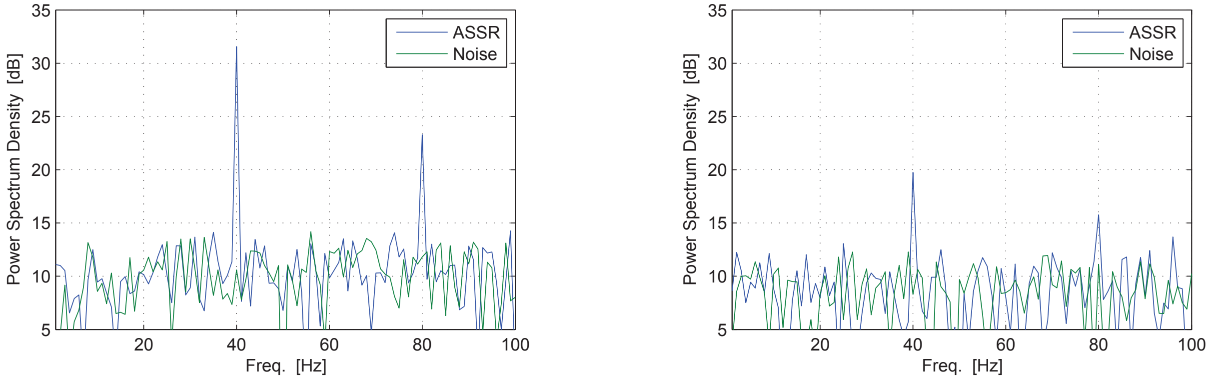
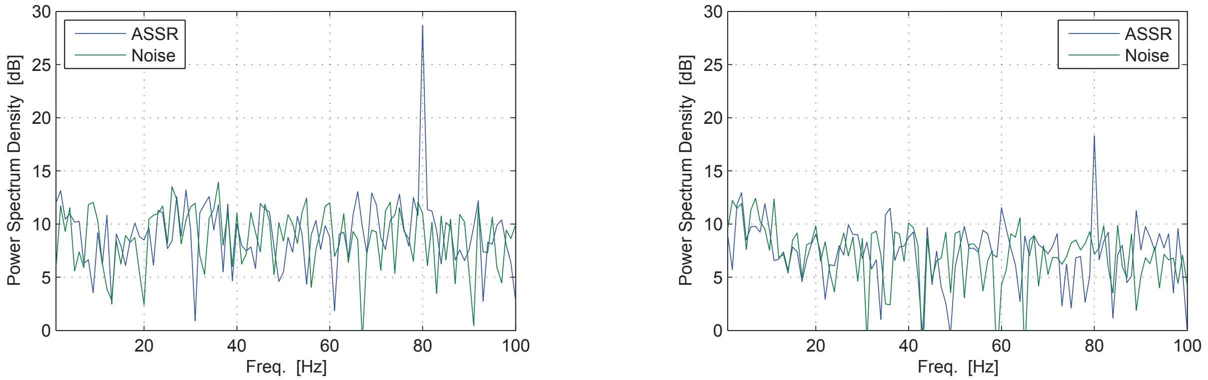
[1] Recordings from both the personalized and the generic earpiece were performed by the g.tec g.USBamp biosignal amplifier. Before inserting the earpieces, the ear canal was cleaned thoroughly with ethanol and prepared with abrasive gel, and conductive gel was applied to the electrodes. All recordings were made with low electrode impedances (<5 kΩ).



(a) Personalized earpiece, ASSR 40 Hz, electrode ELB.

(b) Personalized earpiece, ASSR 40 Hz, electrode ELE.



(c) Personalized earpiece, ASSR 80 Hz, electrode ELB.

(d) Personalized earpiece, ASSR 80 Hz, electrode ELE.

Fig. 3. Auditory Steady State Response (ASSR) recorded from the personalized earpiece.

on the mastoid.

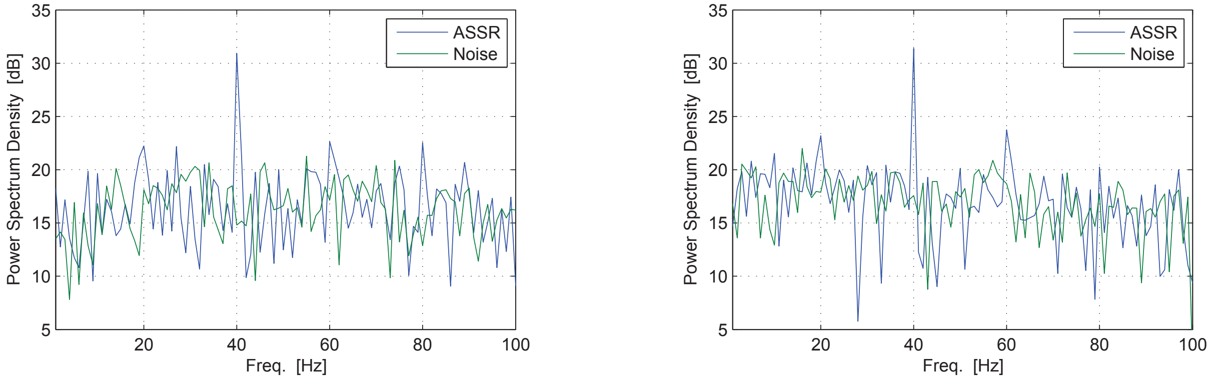
(c) Recording completely in-the-ear; that is, the signal was recorded from first ear-electrode, referenced to second ear-electrode, and with ground on third ear-electrode.

The power spectrum densities for the three ASSR recordings, with electrode configuration (a), (b) and (c), and with 40 Hz modulation frequency are shown in Fig. 4(a), 4(b) and 4(c). It is observed that recording (a) and (b) are very similar in terms of the noise level, noise shape and the SNR at the modulation frequency. It is remarkable that the signal level is the same as the effective electrode distance was considerably smaller in case (b) compared to (a). The SNR is in both cases approximately 15 dB. Recording (c) has a general noise floor that is approximately 3 dB lower than that in case (a) and (c); whereas the noise is uniformly distributed in recording (a) and (b), recording (c) exhibits a raise in the noise floor at low frequencies. It is further observed that the SNR at the modulation frequency is reduced to approximately 10 dB. It is conjectured that these differences between recording (b) and (c) are primarily related to the common mode feedback.

The power spectrum density for the ASSR 80 Hz recording, with the completely in-the-ear electrode configurations (configuration (c)), is shown in Fig. 4(d). The noise floor and the SNR at the modulation frequency are very similar to the 40 Hz recording.

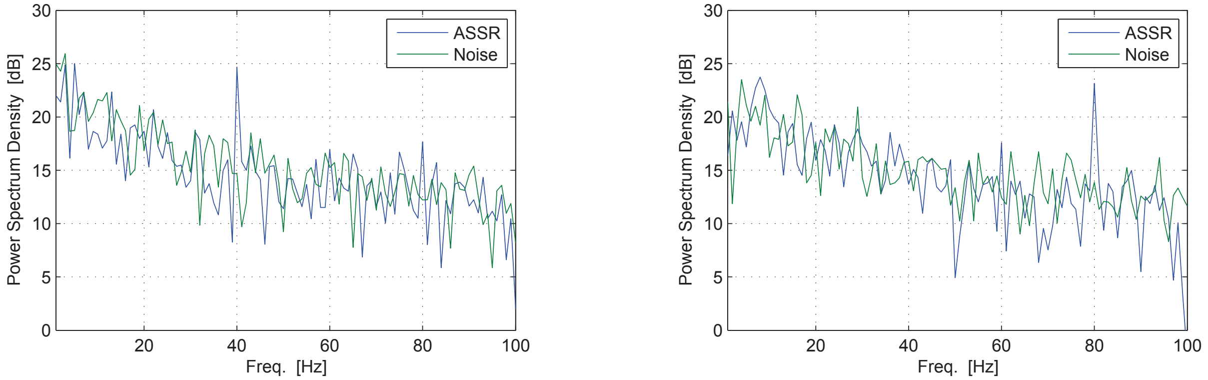
In comparing the ASSR recordings between earpieces it should be noticed that while the instrumentation is the same across all the experiments, there are significant differences in the basic signal acquisition; this includes differences in electrode positions, materials and areas, and possibly also differences in the electrode-gel-skin interfaces. In comparing the recordings from the personalized and generic earpieces the most similar conditions are the recordings obtained from the personalized earpiece electrode ERE, and the generic earpiece with electrode configuration (c). Thus the power spectrum densities in Fig. 3(b) and 3(d) are to be compared with Fig. 4(c) and 4(d). Observe that for both the personalized and generic earpiece, and for both the 40 Hz and 80 Hz modulation frequency, the SNR at the first harmonic component is approximately 10 dB. The noise floor in the personalized earpiece is approximately 5 dB lower compared to the generic earpiece, and the personalized earpiece does not exhibit a raise of the noise at low frequencies.

For rigor, we further performed a comparison between recordings from the personalized earpiece electrode ELB and the generic earpiece with electrode configuration (a); i.e. comparing Fig. 3(a) and 4(a). These recordings have similar electrode distances, with the most important difference in that for the personalized earpiece the signal is measured from the conchae (external ear) relative to the ear-canal, whereas for



(a) Generic earpiece, ASSR 40 Hz. Recording from an ear-electrode, referenced to an electrode on the ear-lobe, and with a ground electrode on the mastoid.

(b) Generic earpiece, ASSR 40 Hz. Recording from an ear-electrode, referenced to another ear-electrode, and with a ground electrode on the mastoid.



(c) Generic earpiece, ASSR 40 Hz. Recording from an ear-electrode, referenced to a second ear-electrode, and with ground on a third ear-electrode (All electrodes in the ear).

(d) Generic earpiece, ASSR 80 Hz. All electrodes in the ear.

Fig. 4. Auditory Steady State Responses (ASSR) recorded from the generic earpiece.

the generic earpiece the signal is measured from the ear-canal relative to the ear-lobe (external ear). In theory this difference should only influence the phase of the signals, not altering the power spectrum densities. Comparing the power spectrum densities in Fig. 3(a) and 4(a), it is observed that the amplitude of the first harmonic component is very similar, and the main reason why the SNR is 10-15 dB worse in Fig. 4(a) is due to the higher noise floor.

The best ASSRs are observed from the personalized earpiece electrode ELB. These recordings have an SNR that is approximately 20 dB better than those observed from the generic earpiece and the personalized earpiece electrode ELE. It is conjectured that this is mainly due to the larger electrode distances, and in particular the distance to the ground electrode.

V. CONCLUSION

This paper has demonstrated that it is possible to record EEG signals from both an personalized and generic ear-pieces. The highest signal quality, in terms of signal-to-noise ratio, was obtained from the personalized earpiece. However, for similar electrode configurations the signal quality was similar from the two types of earpieces. The superior signal quality from the personalized earpiece is mainly due to the much higher degrees of freedom to place the electrodes in the ear; thus, electrodes can be placed in larger regions of the ear, whereby larger electrode distances and areas can be obtained. The imminent integration of a recording and signal processing system into an ear-worn device, represent a significant step towards discreet, unobtrusive and user-friendly brain monitoring devices.

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