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An In-The-Ear Platform For Recording Electroencephalogram

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Abstract— **We introduce a novel approach to brain monitoring based on electroencephalogram (EEG) recordings from within the ear canal. While existing clinical and wearable systems are limited in terms of portability and ease of use, the proposed in-the-ear (ITE) recording platform promises a number of advantages including ease of implementation, minimally intrusive electrodes and enhanced accuracy (fixed electrode positions). It thus facilitates a crucial step towards the design of brain computer interfaces that integrate naturally with daily life. The feasibility of the ITE concept is demonstrated with recordings made from electrodes embedded on an earplug which are benchmarked against conventional scalp electrodes for a classic EEG paradigm.**

I. INTRODUCTION

Electroencephalography (EEG) refers to the recording of brain electrical activity, caused by the large dendritic currents from activated neurons, via electrodes placed on the scalp. Unlike functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), which are derived from blood hemodynamic responses, EEG provides a direct measurement of aggregated neural electrical activity at various spatial locations on the scalp. In contrast to fMRI where a stimulus response may take seconds to detect, EEG has a high temporal resolution and responses within 10ms of the stimulus onset can be recorded, making it an invaluable tool in, for instance, neuroprosthetics and brain computer interfaces (BCI) [1]. Other applications of EEG include the study of brain consciousness [2], selective attention [3] and brain and sleep disorders [4].

Despite the clear potential of EEG in the monitoring of brain activity, there are several problems which obstruct its widespread use:

1) Conventional recording systems are bulky with long leads connected between the head and amplifier. They often require specialized hardware and operation in a laboratory/clinical environment, thus limiting user mobility. It is instead desirable to use small unobtrusive devices which will not interfere with the user so as to avoid influencing their brain state [5]. So-called wearable EEG devices are designed to be minimally intrusive, comfortable and ergonomically acceptable and to perform long-term recordings over days or weeks [5].
2) Despite the advantages of existing wearable systems they still require a cumbersome setup process. Correct placement of the electrodes is essential as it ensures inter-session repeatability of recordings. With existing scalp-based recording devices, it is not possible for a user to achieve sufficient accuracy without the assistance of a trained person. The setup can take considerable time causing additional fatigue and inconvenience to the user.

The above problems motivated us to investigate an alternative EEG recording strategy, whereby multiple electrodes are placed in the ear canal, embedded on a custom made hearing aid earplug. The earplugs are CE approved and are comfortable to wear, providing a ready support for the electrodes; they are personalised so as to fit tightly and are straightforward to insert and remove. The electrical connection from the cortex to an in-the-ear (ITE) electrode is subject to just the same attenuating factors as in the case of scalp electrodes, namely from the milli-volt level voltages at the cortex attenuated through the cerebrospinal fluid, skull, skin and hair, to the micro-volt levels at the electrodes [6].

In Section II, we introduce the ITE design and describe, in depth, the location of the electrodes relative to the ear canal as well as its advantages over existing recording paradigms. In Section III, we show that EEG analysis based on the ITE electrodes obtains similar results to that based on the on-scalp ones, illustrating the feasibility of the ITE system as a truly wearable and convenient means of recording brain electrical activity.[1]

II. IN THE EAR EEG RECORDINGS

The proposed ITE recording system uses multiple electrodes embedded into an earplug to record electroencephalogram (EEG). The earplug is built on a personalised earpiece by Widex, produced based on the 3D imprint of the ear canal, as is common practice in hearing aid industry. It is designed and manufactured in accordance with CE approved hearing aid protocols. The mounted electrodes are made of silver chloride (AgCl) - the most commonly used EEG electrode material. Locations for the electrodes on the left earplug are shown in Fig. 1 (denoted by circles); connectors are also visible and denoted by 'output'.

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[1]Prior to the experiments, informed consent was obtained from the subjects, after the nature and possible consequences of the studies were explained.

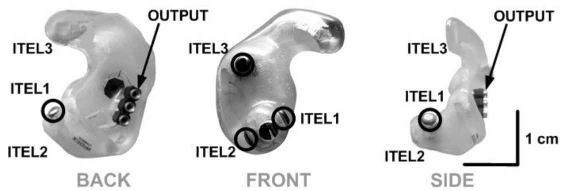


Fig. 1. The in-the-ear electroencephalogram recording system for the left ear (ITEL). Two or more electrodes (ITEL1, ITEL2 and ITEL3 in this case), pointing in different directions, are mounted on a standard custom made earplug, as shown on the three projected planes.

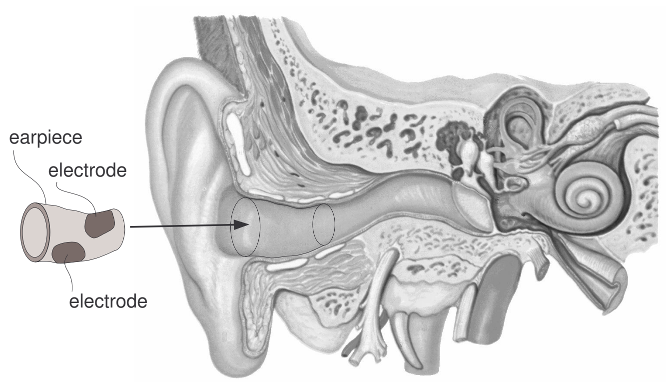


Fig. 2. The right in-the-ear (ITER) earpiece relative to the ear and ear canal.

The ear canal (from pinna to eardrum) is typically 26 mm long and is 7mm in diameter. Fig. 2 shows a sketch of the right ITE (ITER) earpiece and its approximate position relative to the ear and ear canal. The ITE does not enter the ear by more than 10mm and does not enter the part of the ear canal surrounded by bone. The earplug is CE approved and is a standard in commercial hearing aids - the ITE device is thus comfortable to wear and poses no possible harm to the eardrum. Appealing characteristics of the ITE approach over the standard EEG system include:

1) Straightforward setup process. The ITE electrodes are embedded in the hearing aid earplug which is inserted in the same way as standard hearing aids. This does not require any specialised training or long setup procedure.
2) Fixed electrode positions. The tight fit and rigid spatial location of the ITE electrodes offers enhanced repeatability of the experiments as compared with the standard on-scalp recording, and skin stretching and electrode movement artifacts are reduced.
3) Robustness to artifacts caused by the environment electromagnetic field. By Faraday's law, the alternating currents that power electric equipment (computers, lights) cause an inducted voltage in any loop given by $V_{MI} = 2\pi f S B$ where S denotes the area of the conducting loop, f the frequency of the field, whose projection onto S is given by B the magnetic field vector [6], [7]. For an EEG recording system, such conductive loops are formed by the long leads connecting the amplifier and electrodes and connections through the conductive head tissue. Fig. 3 shows two such inductive loop areas for the AFz electrode: the loop with respect to the reference electrode (in blue); and the loop with respect to the common electrode (in green - shaded). The induced voltage using standard recording equipment is given by[2] $V_{MI} \approx 1.5\mu V$, a level that clearly interferes with measured EEG. For ITE recordings using standard amplifiers, magnetic artifacts are dramatically reduced, as the reference and ground electrodes are typically on the earlobe and mastoid, giving a minimum inductive loop area. The ITE recordings therefore exhibit enhanced flexibility with respect to magnetic field sources.

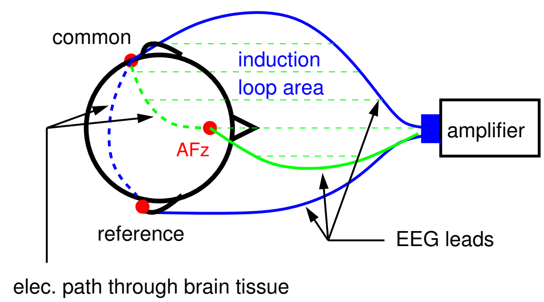


Fig. 3. Induction loops causing magnetic interference.

III. Comparison with Scalp Recordings

To assess the ability of ITE electrodes to record EEG with high fidelity, all recordings were performed simultaneously with on-scalp electrodes, using the same amplifier, leads, ground and reference electrodes. The experiments were performed on a subject, based on the ITEL1, ITEL2, ITER1, and ITER2 in-the-ear positions, and mastoid (M1 and M2), temporal (T7 and T8), and central (AFz and Cz) scalp electrodes (see Fig. 4). The reference position was the right earlobe while the ground position used was the chin.[3]

Fig. 5 shows 3s of the EEG data for both the ITE and scalp electrodes[4] - in general, the recorded EEG signal from ITE electrodes was weaker than that from most on-scalp electrodes, but more so too was the noise (compare the waveforms for ITER1 and AFz in Fig. 5), so that the ITE recordings exhibited similar signal-to-noise ratio (SNR) as the on-scalp electrodes. Observe similar waveforms for the period before the eyeblinks, and the electrooculogram (EOG) artifact suppression for ITE recordings after 1.5s.

[2]Assuming the cross-sectional area of human head is in the range of $S > 100cm^2$, a typical magnetic field of $B = 0.32\mu Wb/m^2$, and the mains frequency of $f = 50Hz$.

[3]As the primary aim of these experiments was to establish the feasibility of recording EEG from within the ear, for rigour we used a ground position that could not 'aid' the ITE recordings.

[4]The electroencephalogram for both on-scalp and ITE electrodes was recorded at a sampling frequency of 512Hz and then bandpass filtered with a 5th order Butterworth filter, so as to select the frequency range 1-30Hz.

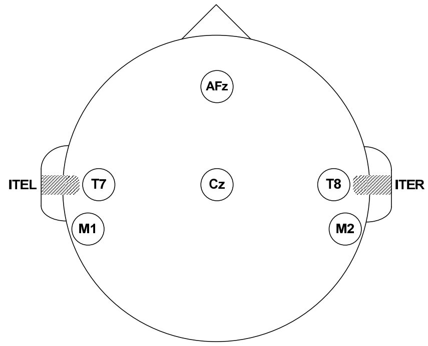


Fig. 4. Electrode positions for the left (ITEL) and right (ITER) in the ear electrodes and scalp electrodes in accordance with the 10-20 system [8] used in the experiments.

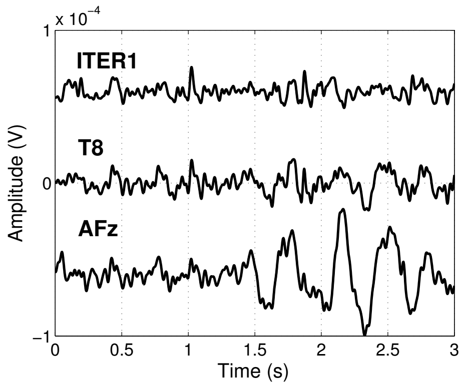


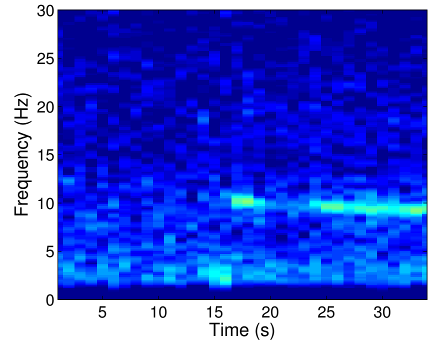
Fig. 5. Time waveforms of EEG recordings from on-scalp and ITE electrodes; the period of spontaneous EEG (0-1.5s) was followed by several eyeblinks starting at 1.5s.

A. Alpha Attenuation Study

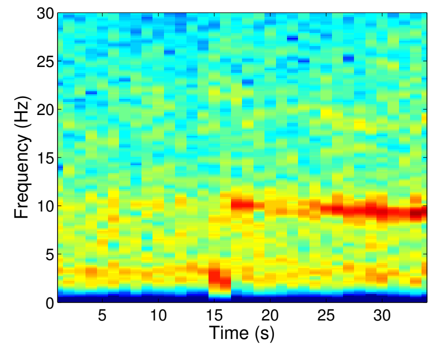
The potential of the ITE system in a typical brain monitoring context is now illustrated using a well known EEG response - the suppression of alpha activity when the subject opens their eyes. The alpha attenuation test (AAT) is often used when testing EEG recording equipment [9].

The subject was instructed to keep their eyes open until instructed by an auditory stimulus to close their eyes after 15s, eliciting a relative increase in alpha band power in both scalp and ITE electrodes. The data was recorded at a sampling frequency of 512Hz and bandpass filtered so as to occupy the frequency range 2-45Hz. Time-frequency spectrograms were obtained using the short time Fourier transform (STFT) with a sliding Hamming window of length 2s and an overlap of 50%.

The averaged spectrogram data obtained over 5 trials of length 35s are shown in shown in Fig. 6 for both scalp and ITE electrode recordings. Note the increase in alpha band power at 15s and an excellent match between the ITE and on-scalp electrodes.



(a) Electrode ITEL2



(b) Electrode T8

Fig. 6. Alpha attenuation study (AAT). The subject was instructed to keep their eyes open until instructed by an auditory stimulus to close their eyes after 15s.

A) Correlation. Expanding on these results, correlation analysis was provided for the 'eyes open' and 'eyes closed' cases. To obtain more accurate correlations, the frequency range considered was wider.[5] Table I(a) shows the correlation analysis for 15s of recorded activity averaged over 5 trials where the eyes of the subject were open and there were no EOG artifacts. The results show that, as desired, there was high correlation between the ITE electrode pairs. As expected, the degree of correlation decreased with distance, independent of whether the recordings were made in the ear canal or on-scalp. Table I(b) shows the correlation analysis for 15s of recorded activity averaged over 5 trials where the eyes of the subject were closed - the results follow the same pattern as those in Table I(a).

B) Coherence. Coherence analysis was also performed for the same data sets which reflects the degree of similarity between two signals across frequency. The coherence between x and y, for a frequency f, is given by [10]

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \tag{1}$$

where P_{xx} and P_{yy} are the power spectral densities of signals x and y respectively, and P_{xy} is the cross-spectral density between x and y. The value of the coherence index lies in the range $[0, 1]$, values close to 1 indicating that at frequency f the spectral contents of x and y are closely matched.

[5] A 4th order Butterworth notch filter was applied to remove interference in the frequency range 48-52Hz, and an additional 8th order Butterworth bandpass filter was applied to retain frequencies in the range 2-200Hz.

TABLE I

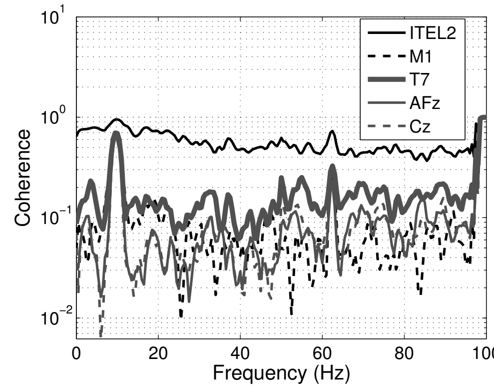
CORRELATION ANALYSIS BETWEEN THE ITE AND ON-SCALP ELECTRODES

(a) Correlation results when the eyes of the subject were open

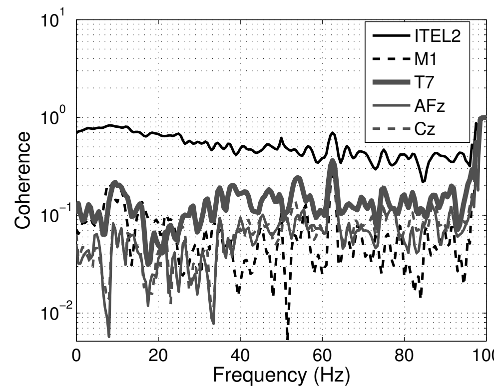
	ITEL1	ITEL2	M1	T7	ITER1	ITER2	M2	T8	AFz	Cz
ITEL1	1	0.99	0.95	0.83	0.81	0.81	0.79	0.76	0.60	0.60
ITEL2	0.99	1	0.95	0.83	0.81	0.81	0.80	0.77	0.60	0.61
M1	0.95	0.95	1	0.80	0.79	0.80	0.79	0.76	0.58	0.60
T7	0.83	0.83	0.80	1	0.75	0.75	0.73	0.82	0.79	0.81
ITER1	0.81	0.81	0.79	0.75	1	0.99	0.96	0.89	0.69	0.69
ITER2	0.81	0.81	0.80	0.75	0.99	1	0.96	0.89	0.69	0.69
M2	0.79	0.80	0.79	0.72	0.96	0.96	1	0.86	0.66	0.67
T8	0.76	0.77	0.76	0.82	0.89	0.89	0.86	1	0.85	0.86
AFz	0.60	0.60	0.58	0.79	0.69	0.69	0.66	0.85	1	0.94
Cz	0.60	0.61	0.60	0.81	0.69	0.69	0.67	0.86	0.94	1

(b) Correlation results when the eyes of the subject were closed

	ITEL1	ITEL2	M1	T7	ITER1	ITER2	M2	T8	AFz	Cz
ITEL1	1	0.99	0.93	0.80	0.77	0.77	0.75	0.71	0.50	0.50
ITEL2	0.99	1	0.93	0.80	0.78	0.78	0.76	0.72	0.51	0.51
M1	0.93	0.93	1	0.67	0.75	0.75	0.78	0.64	0.35	0.38
T7	0.80	0.80	0.67	1	0.68	0.68	0.61	0.84	0.82	0.84
ITER1	0.77	0.78	0.75	0.68	1	0.99	0.95	0.85	0.54	0.55
ITER2	0.77	0.78	0.75	0.68	0.99	1	0.96	0.86	0.55	0.56
M2	0.75	0.76	0.78	0.61	0.95	0.96	1	0.78	0.44	0.46
T8	0.71	0.72	0.64	0.84	0.85	0.86	0.78	1	0.81	0.84
AFz	0.50	0.51	0.35	0.82	0.54	0.55	0.44	0.81	1	0.96
Cz	0.50	0.51	0.38	0.84	0.55	0.56	0.46	0.84	0.96	1



(a) Coherence wrt ITEL1 (eyes closed)



(b) Coherence wrt ITEL1 (eyes open)

Fig. 7. Average coherence results with reference to ITEL1.

Fig. 7 shows the degree of spectral coherence between ITE electrodes and on-scalp electrodes for the subject. The Figure illustrates the average coherence over 5 trials for segments of length 15s when the subject's eyes were open (a) and closed (b). As with the correlation results presented, the degree of coherence between the ITE electrodes and the neighbouring on-scalp electrodes (T7, M1) was high, while it was lower for more distant on-scalp electrodes. These results are consistent with the degree of coherence between neighbouring and distant on-scalp electrodes. As desired the level of coherence in the alpha band is higher for the 'eyes closed' case, indicating that any shared activity between the ITE and on-scalp electrodes is EEG.

IV. CONCLUSION

We have introduced a new way of recording electroencephalogram (EEG) data based on electrodes which are placed within the ear canal (ITE). As a proof of concept we have established that it permits the extraction of key EEG activity (alpha attenuation) and have shown excellent correlation and coherence with on-scalp electrodes. This is all achieved with great convenience for the user (non-intrusive, cosmetically acceptable) while the adjacent hearing aid platform offers prospects in designing an integrated ITE recording and processing system, opening the possibility of both short- and long-term continuous (over days) use for standard brain monitoring and interfacing applications.

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