

Text of the presentation at:

2nd International Workshop on Sound Signal Processing Applications (IWSSPA-2025)

Design and demonstration of a low-cost AEP recording system based on consumer electronics: Applications for disseminating audiological concepts in schools and science museums.

Ángel de la Torre¹, Isaac M. Alvarez¹, María Raya¹, Juan A. Muñoz-Orellana²,
Juan Martín-Lagos³, Juan A. Torres-Lara⁴

¹*Department of Signal Theory, Telematics and Communications, University of Granada, Spain. Research Centre for Information and Communication Technologies (CITIC-UGR), University of Granada, Spain.*

²*Knowledge Transfer Office, University of Granada, Spain.*

³*ENT Service, Hospital Universitario Clínico San Cecilio, Servicio Andaluz de Salud, Granada, Spain.*

⁴*Parque de las Ciencias de Andalucía, Granada, Spain.*

E-mail: atv@ugr.es (A. de la Torre), isamaru@ugr.es (Isaac M. Alvarez)

Slide 1 -Title and authors:

Good morning, thank you very much. I'm Angel de la Torre and I will present an auditory evoked potentials recording system completely based on consumer electronics. This system has been used for dissemination activities in schools and in the science museum "Parque de las Ciencias de Andalucía". This presentation includes also a short demonstration.

Slide 2 - Motivation:

In our research group we investigate the auditory system with auditory evoked potentials, that is:

1. some audio signal is presented to the participant;
2. in the inner ear the sound is transformed into neural activity, which is transmitted through the auditory pathway from the auditory nerve up to the auditory cortex in the brain;
3. this neural activity (evoked by the audio stimulation) generates some electrical activity;
4. the electrical activity can be recorded with electrodes on the skin of the participant: this electrical activity evoked by the stimulation of the auditory system are the "auditory evoked potentials".

Recently, we have proposed two innovative procedures in the field of auditory evoked potentials:

1. Based on a Latency Dependent Filtering and downsampling, we simultaneously record the early and late response of the auditory pathway. This allows a comprehensive representation of the neural activity (from the cochlea to the brain) associated to the hearing process.
2. Based on a multi-response deconvolution paradigm, we model complex stimulation patterns as combination of several simple stimuli, categorize the stimulation events, and deconvolve the events in order to estimate the response to each category of stimulus. This allows a consistent analysis of the evoked potentials when they are elicited with complex stimulation patterns.

However, AEP recording is not simple in general. The AEP response consists in waves with amplitudes around one micro-volt. The recorded signal is affected by different types of noise (miogenic, electronic, etc.). The Power Line Interference (PLI) is a particular noise which significantly degrades the quality of the responses. In order to record good AEP responses, classically some solutions are considered: using an appropriate (usually expensive) recording system, record AEPs in a shielded room, avoid intensive power consumption in the recording area, etc. The correct allocation of electrodes is also important, since the electrode imbalance increases the PLI interference (because PLI is usually a common-mode interference).

This motivated (for years) a research line in our group oriented to the development of a robust, low-cost and flexible AEP recording system, appropriate for research. When we say “robust” we understand, minimally affected by noise, and particularly by PLI.

Slide 3 - Biopotential recording system:

Conventional biopotential recording systems are expensive. They are designed around a high quality differential amplifier with high common-mode-rejection-ratio (in order to reduce common-mode (CM) interference and particularly PLI interference). They usually include additional methods to reduce CM interference, like CM subtraction based on CM sensing, or including a driven-right-leg (DRL) circuit. Alternatively (or in combination) the AEPs can be recorded in a shielded room, the skin must be prepared in order to obtain low and balanced impedances, etc.

All these factors make acquisition of AEP responses expensive and complicate. However, if power line interference was not a problem...

- CM sensing or DRL circuits would not be necessary; shielded room would not be necessary; some electrode imbalance would be tolerated... and therefore electronic and experimental requirements would be simpler (and cheaper).
- Additionally, the relaxed electronic requirements would allow the use of standard electronic components (conventionally used in the field of amateur or professional audio), which can be acquired from an audio supply store.

Slide 4 - The PLI problem:

So, in this research line, with the objective of designing a robust, low-cost and flexible AEP recording system, we focused on the problem of the power line interference.

The power line interference is a 50 Hz (in Europe) or 60 Hz (in USA) periodical signal added to the recorded biopotential. This interference includes harmonics of the fundamental frequency (at 50, 100, 150, 200 Hz, etc.). However, it is not an exactly periodic interference, but a quasi-periodic interference, affected by some frequency drift. The origin of this frequency drift is in the control mechanisms implemented to adapt the power production to the power demand: when the demand is greater than the production the frequency decreases until the production is adapted to the demand (and vice-versa). The frequency drift is typically around plus-minus 100 mHz. Since the control mechanisms affect the

rotational speed of the generators, the effect is not exactly a frequency drift, but a time drift, and therefore, the frequency drift is proportional to the harmonic index (a frequency drift of 80 mHz at 50 Hz causes a frequency drift of 0.8 Hz at the 10th harmonic at 500 Hz).

If the PLI frequency was stable, PLI reduction would be easy. However, the frequency drift makes the PLI reduction procedures inefficient:

- In the case of interference subtraction, the amplitude, phase and frequency must be estimated dynamically.
- In the case of notch comb filters, narrow-band notch filters are inefficient, but wide-band notch filters causes significant distortion.
- In the case of adaptive notch-filters, parameters must dynamically be estimated for each harmonic.

Slide 5 - Our solution for PLI reduction:

After understanding the problem of the frequency drift, we have proposed a simple and efficient solution for the reduction of the power line interference:

1. We select an appropriate harmonic (with high SNR) appropriate for the characterization of the time/frequency drift of the PLI.
2. We apply a conventional phase demodulation to the selected harmonic, thus obtaining the instantaneous phase of the PLI for this harmonic.
3. We estimate the time-drift from the instantaneous phase of this harmonic.
4. Via non uniform resampling, we compensate the time drift. After the time drift compensation, the frequency of the PLI in the resampled signal is exactly equal to the nominal frequency, that is, the time drift compensation cancels the frequency and phase drift for all the harmonics.
5. Since after the time drift compensation all the harmonics are narrow spectral lines at their nominal frequency, the reduction of the PLI is really simple for this signal (with notch comb filters or with spectral cancellation via FFT).
6. Finally, the time axis is restored by applying the inverse compensation of the time drift (with another non uniform resampling), in order to transform the clean signal to the original time scale.

Slide 6 - PLI reduction (patent pending):

This slide illustrates the procedure of PLI reduction with a biopotential consisting in an electrocardiogram signal. In the top-left we can see the ECG signal, affected by the power line interference, and a detail. We can see the P-QRS-T components of the biopotential, as well as the 50 Hz oscillation of the interference. The power spectrum shows the harmonics of the PLI at 50, 100, 150, 200 Hz etc.

In the upper-right figure, we can see a detail of the power spectrum for several harmonics. We can see two effects of the time drift: on one hand, the harmonics are spread due to the frequency and phase fluctuation; on the other hand, the harmonics are deviated from their nominal frequency, due to the average frequency drift (for the analyzed time interval). Additionally, since the origin of the frequency drift is a time drift, the deviation is proportional to the harmonic index.

After the compensation of the time drift all the harmonics concentrate all the spectral power at their respective nominal frequencies, as observed in the bottom-right figure. Now, the harmonics are narrow lines at their nominal frequency. This makes the reduction of the power line interference simple and easy. In the bottom-left figure we can see the same ECG signal after the application of the PLI reduction method. The interference is canceled, the P-QRS-T components are

clearly observed, and no harmonics of the PLI are observed in the spectrum (there are, indeed, only some very low harmonics of 60 Hz).

This method is disclosed in a patent, currently under evaluation.

Slide 7 - PLI reduction (ECGs, AEPs) (article rev.):

This slide shows some experimental results reported in an article currently under revision. The plots in the left (in blue) represent ECG signals, while those in the right (in red) AEP responses. In the top panels, the biopotentials are represented without any procedure for PLI reduction. In the center, a PLI reduction based on conventional notch-comb filter (without time drift compensation) is applied. In the bottom, the PLI reduction based on the proposed method (notch-comb filter with time drift compensation) is applied. It can be clearly observed the effectiveness of the proposed method in both scenarios.

Slide 8 - AEP recording system (research version):

The efficiency of the PLI reduction method significantly alleviates the design constraints for a biopotential recording system. No driven-right-leg circuit or common-mode sense circuits are necessary, no shielded room is necessary, some electrode impedance imbalance is tolerated, etc., and the biopotential recording system can be designed using conventional audio electronic subsystems.

This slide shows the AEP recording system (the version used for research purposes). A computer is used for managing the recording (in the case of electrocardiogram signals) or both synchronous stimulation and recording (in the case of auditory evoked potentials). An USB audio interface (in this case, a UCX audio interface manufactured by RME) is used for analog-to-digital and digital-to-analog conversion, in order to capture the signal from the electrodes (in both cases) and also to send the audio stimulation to the headphones (in the case of the auditory evoked potentials). A microphone preamplifier is included (model FetHead manufactured by TritonAudio), in order to provide electrical isolation between the audio interface and the participant and to provide high quality preamplification of the recorded signal. Electrical isolation is complemented by power supply provided by a 12 V battery and including a USB isolator between the audio interface and the computer.

The cost of this modular biopotential recording system is conditioned by the audio interface (around 1200 Euros this model), since the other components (the preamplifier, 80 Euros, and the headphones, model RH300 manufactured by Roland, 160 Euros) are significantly cheaper.

Slides 9 and 10 - AEP recording system (demo version):

For the demo version, a cheaper audio interface is used (a Minifuse-4 manufactured by Arturia, 180 Euros). The modularity of the system allows the substitution of each component (for example, insertion earphones instead of headphones, a different preamplifier or a different audio interface). The picture shows the demo version of the AEP recording system with all the elements connected, as configured for an outreach activity.

Slides 11 - Workshop education / dissemination:

Using this concept of biopotential recording system, we have prepared a workshop with demonstration activities related to heart biopotentials (ECG) and auditory evoked potentials (AEPs). We start with ECG, because this signal is usually better known, and this biopotential is easy to be acquired and observed in real time. The auditory evoked potentials are responses of low amplitude, difficult to be observed due to the noise, and requiring some averaging or deconvolution procedure, in order to accumulate responses from a number of stimulation events and improve the signal to noise ratio.

The workshop includes a presentation of the fundamentals, including a description of the instrumentation for biopotential recording, a description of the anatomy and physiology of the heart, its electrical activity and the electrocardiogram, and a description of the anatomy and physiology of the hearing system, the electrical activity associated to hearing perception and the auditory evoked potentials.

The workshop also includes three experimental activities, demos performed in real time, the first one for recording the electrocardiogram; the second one for recording auditory evoked potentials using standard clicks for stimulation; and the third one for recording the AEP responses using synthetic speech for stimulation.

Slides 12 - ECG recording:

This slide presents a screenshot of the ECG demo. This demo represents, in real time, the ECG signal in one panel. Based on a heart-beat detection and synchronization procedure, a second plot superimposes the last detected heart beat (in black) and some previous ones (in red) synchronized in the center of the window, allowing a detailed representation of the ECG signal and the P-QRS-T components, as well as an intuitive perception of the changes in the heart rate. A third plot represents the heart rate (in black) and the average heart rate (in red) as a function of time (also updated in real time), and finally, some parameters about the experiment are presented (total time of the recording, heart rate, and some statistics of the heart rate). During the demo, the sound of the signal recorded by the electrodes is sent to an audio amplifier (allowing the audience to hear the signal in real time). The participant is asked to make some movements of the arms (generating a lot of myogenic activity which can be observed in the plots and can also be heard by the audience). The heart beats are observed and also the ECG signal (and the heart beats) can be heard by the audience. The participant is asked to make some movements in order to increase the heart rate, and then to sit down and relax in order to see the heart rate decrease. Finally the participant is asked to breath profoundly and relax in order to see the predominance of the parasympathetic nervous system, observed as large oscillations of the heart rate.

Slides 13 - AEP recording (clicks):

This slide presents a screenshot of the AEP recording demo, using clicks as stimulation. This demo provides click stimuli of different levels between 40 and 70 dB NHL at average rate of 44.4 Hz (inter-stimulus interval between 15 and 30 ms). The stimuli are presented in segments of 15 seconds. The EEG signal and the power spectral density are represented in real time. Every segment of 15 seconds, the responses are estimated from the EEG by applying the multi-response deconvolution, and the responses are represented in two panels: one of them for auditory brainstem responses, ABR, (latency in linear scale, range 0-20 ms), the other for auditory brain stem and middle latency response, ABR+MLR, (latency in logarithmic scale, range 0.5-200 ms). During the demo, the participant is asked to blink his/her eyes and to make facial movements, in order to allow the audience to see the myogenic noise, and to aware the participant about the importance of reduce the myogenic activity during the EEG acquisition. The stimulation is also sent to the audio amplifier in order to provide a sample of the stimulation pattern for the audience. The protocol is explained and it is remarked the low amplitude of the responses (compared to the ECG signal) and the importance of averaging, silence of the audience, and being patient in order to record during several minutes, while the responses are updated every 15 seconds. Once the instructions are clearly understood, the recording protocol starts again, the responses are progressively updated. When the recording procedure ends, the waves are discussed.

In these plots we can see the ABR responses in the left side and the ABR+MLR responses in the right side. In this example we can see the stimulation artifact (at 0.5 ms), the ABR waves V (at 6.5 ms) and VII (at 8.5 ms), and the MLR waves P0 (15 ms), PA (30 ms) and PB/P1 (55-60 ms). We can observe the changes in amplitude of the artifact (a reduction of 10 dB in the stimulation level causes a linear reduction, in a factor 3.16, of the artifact amplitude), and the changes of amplitude and latency of the evoked responses (reduction of amplitude and increase of the latency of the ABR components).

Slides 14 - AEP recording (speech):

The third demo includes AEPs elicited with synthetic phonemes. Four different stimulation patterns are included in this test: three synthetic phonemes (/a/, /i/ and /s/) and also a burst of clicks (which, compared with the others, sounds like a raspberry blow). The vowels and the click burst are composed of short events (corresponding to the glottal pulses in the case of the vowels, or the clicks in the case of the click burst). We have estimated the responses to the short events (glottal pulses or clicks) for these patterns (/a/, /i/ and click burst), and responses to the long events (phonemes or burst) for all of them (/a/, /i/, /s/ or burst). The responses to the short events include the ABR and MLR components (responses obtained for a latency range 0.5-200 ms). The responses to the long events include also cortical responses (latency range 0.1-1000 ms). The demo, as the previous one, provides a real-time representation of the EEG and the spectrum, and the responses to the short and long events, updated after each segment of 15 seconds.

In these plots, in the left side, we can see the stimulation artifact, the wave V and some MLR components evoked by the short-term events (glottal pulses or clicks), and in the right side we can see clear cortical components evoked by the long-term events (phonemes or click-bursts).

[After the description of the three demos, these ones related to AEPs (with clicks and with synthetic phonemes) were performed in the conference room]

Slides 15 - Performance for high-school students (UGR-ETSIIT feria de las ingenierías):

This picture shows the presentation of the workshop for a group of high-school students, in April 2025, including real-time recording of biopotentials.

Slides 16 - Performance for telecommunication engineering students (UGR-ETSIIT):

This picture shows the presentation of the workshop for a group of telecommunication engineering students, in May 2025. This workshop included technical information about electronic instrumentation for biopotential recording and related signal processing, as well as real-time recording of biopotentials.

Slides 17 - Performance for primary school students (Parque de las Ciencias):

These two pictures are performances at “Parque de las Ciencias de Andalucía” a science museum in Granada. The first one (left) was an activity for primary school students, including description of the heart activity and the hearing system and real-time recording of biopotentials (June 2025). The second one is a workshop entitled “Mi cuerpo eléctrico: taller de biopotenciales cardíacos y potenciales evocados auditivos” (“My electrical body: workshop on cardiac biopotentials and auditory evoked potentials”). This workshop was included in the framework of the activity “Verano con Ciencia” (“Summer with Science”), a science summer-camp for children, which took place in the science museum during July 2025. The workshop includes a description of the electrical activity in the human body, fundamentals of the heart activity, fundamentals of hearing perception, and experiments with real-time recording of heart biopotentials and auditory evoked potentials.

Slides 18 - Workshop performances:

The total number of dissemination activities includes:

- Activities with primary school students: 3 performances.
- Activities with secondary school students: 3 performances.

- Activities with university students: 1 performance. Some interest is expressed for several university studies.
- Activities at the science museum: 2 performances weekly during July 2025 (8 performances). Importantly, some of these performances (including the real-time acquisition of biopotentials) were conducted by the staff of the museum (experienced in science communication, but without formal education as engineers and not involved in the development of the biopotential recording system), demonstrating the usability of the proposed system with limited technical training.

Slides 19 - Conclusions:

And finally, summarizing this presentation,

- The algorithm proposed for PLI reduction is efficient and allows the design of simple biopotential recording systems.
- Thanks to this algorithm, we have designed a modular, robust, low-cost and flexible biopotential recording system.
- The biopotential recording system provides biopotentials with good quality, for both, electrocardiogram signals and auditory evoked potentials.
- The cost, the quality and the flexibility of the proposed system make it appropriate for research, as well as for educational or dissemination purposes.
- The workshop has attracted the interest in the educative community at different levels (primary, secondary and university) and in the science museum “Parque de las Ciencias de Andalucía”.
- The outreach activities in the science museum conducted by the museum staff demonstrate the usability of the proposed biopotential recording system. The quality, low-cost and flexibility of the system, together with its usability, make it very useful not only for research, but also for education and dissemination.
- The biopotential recording system and the workshop provides an opportunity for giving basic concepts of audiology and hearing health to the global society. Previously, an activity like this would have been very difficult due to the inherent technical complexity associated to the recording of auditory evoked potentials.

Slide 20 - Acknowledgments and thanks:

The authors acknowledge the participation of the volunteers in the recording sessions. Here you can see the sources of support for this study, and our web and emails. Detailed description of the methods, the AEP recording system, and the outreach activities, can be found at: <https://wpd.ugr.es/~sig.proc.audiology/dissemination>

Thank you very much for your attention.