Educational approach of a BAER recording system based on experiential learning

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Abstract

Brainstem Auditory Evoked Response (BAER) represents the electrical activity of the auditory nerve associated to a stimulus. The recording process of this signal is a challenging milestone that requires the development of multidisciplinary competences. Current medical devices able to record BAER are expensive and are not usually flexible enough for education purposes. This paper presents a full description of a BAER recording system designed and developed in our research group. The performance of this system is evaluated by (a) the recording of a very low amplitude synthesized signal similar in morphology to an evoked potential, (b) an analysis of the quality of the recordings in terms of the number of averaged responses and (c) the recording of BAER from eight normal hearing adults and an analysis of the influence of intensity of stimulation over the biological responses. In addition, this paper proposes the described BAER recording system to be used as a teaching tool in the context of electronics engineering, telecommunication engineering, computer sciences, and audiology studies. The low-cost and open nature of this system is appropriate for education purposes. The BAER recording system described in this paper has been used in a laboratory session. The results obtained on a satisfaction survey given to the students reveal that the use of experiential learning as pedagogical model has a great impact on the motivation of students and proves its efficiency to enhance retention and improve cognitive skills. The educational advantages of our system in comparison to other biomedical devices are discussed on this paper.

Key words: Brainstem Auditory Evoked Response (BAER), evoked potentials, signal processing, laboratory, MATLAB, experiential learning.

1 Introduction

In the hearing process, the transmission of information from the inner ear to the primary cortical area involves the discharge of action potentials along the auditory pathway. The electrical response of the auditory system associated to a short stimulus show several waves that occur within the first 10 milliseconds after the presentation of a stimulus. These waves are known as brainstem auditory evoked potentials and correspond to synchronous discharges of action potentials from groups of neurons placed at different points at the auditory pathway [1]. Evoked potentials are identified by roman numerals as proposed Jewett in [2]. The most extended application of Brainstem Auditory Evoked Response (BAER) signals is the estimation of hearing threshold due to the non-invasive nature of the process of recording and the independence from the state of attention of the subject [1] [3].

Brainstem Auditory Evoked Potentials are recorded through the stimulation of the auditory system by presenting acoustic stimuli and the recording of the associated electrical response. This biological response is captured by surface electrodes situated on the skin at different positions on the head. A high amplification of the recording needs to be performed due to the low amplitude of the waves (usually less than 1 μV). This signal is contaminated by several sources of artifacts such us neuro-muscular activity of the subject, noise associated to the amplifier and electromagnetic and radiofrequency interferences [4]. The methodology used to reduce the effects of these artifacts is the average of a large number of biological responses in order to improve the signal to noise ratio.

Currently, there exist several clinical systems able to record BAER. However, most of them are not flexible enough for education purposes since they only allow users to control a few parameter settings, the use of artifact reduction techniques is limited, and give no access to raw recorded data [5] [6]. This paper presents in detail an inexpensive open BAER recording system. This system provides a flexible control of the parameters: users are able to specify the intensity of stimulation, set the analog to digital sample frequency, define the stimulation technique, select the number of biological responses involved in averaging, set the band-pass filter settings, or implement advanced artifact rejection techniques. In addition, this system gives total access to raw recorded data, which means that advanced processing of data can be implemented offline. Digital signal processing has been developed in MATLAB (The Mathworks, Inc.). This programming framework has been proved to be efficient as a didactic tool [7].

Three experiments have been performed to test the efficiency of the system. First, a very low amplitude digitally synthesized signal similar in morphology to an evoked potential has been recorded. Second, an analysis of the quality of evoked potentials obtained by averaging a different number of responses has been carried out. Third, BAER from eight normal hearing subjects have been recorded at different intensities of stimulation and an analysis of the latencies of the most important waves is performed.

On the field of education, learning methodologies based on experiential learning can be employed as a complement of traditional textbook-based learning. This paper proposes the implementation and evaluation of a BAER recording system as a teaching tool in a laboratory framework. The aim of this laboratory is to help students understand specific concepts of audiology, analyze the agents that influence evoked potentials, gain experience on electronics instrumentation, improve analog and digital signal processing skills, understand the effect of impedance and noise in real life applications and learn adequate noise reduction processing methods. The performance of the laboratory activities that compose the BAER recording system is supported by the experiential learning strategy [8]. A laboratory session has held at the University of Granada in which the BAER recording system described on this paper was used to help students understand the most important concepts and theoretical models studied in audiology lectures. The laboratory comprised the performance of several activities: (a) an introduction in which the elements that compose the BAER recording system were presented, (b) the placement of the electrodes on the head, (c) the recording of BAER at different number of averaged responses and (d) the recording of BAER at different intensity levels. A satisfaction survey of the laboratory was given by the students.

The rest of the paper is structured as follows. Section 2 describes in detail the hardware elements and software modules that compose the BAER recording system. Section 3 presents results of the evaluation of the system, confirming an adequate performance. Section 4 points out the skills and competences expected to be acquired by the students through the implementation of the activities of this laboratory and describes the laboratory session performed at the University of Granada. Finally, the main conclusions of this work are exposed on section 5.

2 System description

This section presents the description of the system. The process of BAER recording and the elements involved in this process are introduced on section 2.1. Section 2.2 describes in detail the hardware items of this system. The software modules that compose the digital signal processing of this system are presented on section 2.3. Finally, section 2.4 performs a cost analysis of the necessary materials to deploy this system.

2.1 Recording of BAER

The system that we have developed uses a laptop including MATLAB, an external audio sound card, an amplifier, a pair of headphones and computer routines that perform the digital signal processing. These elements are shown in figure 1. The process of BAER recording is described on the following steps:

1. A sequence of short bursts (see section 2.3.1) is generated by the laptop for stimulation and synchronization purposes. This signal is sent synchronously through the left and right outputs of an external Analog-Digital / Digital-Analog (AD/DA) sound card. The right output of the AD/DA sound card is connected to its left input, so that the system can determine the exact moment in which a stimuli is produced by the recording of the synchronization signal. The left output of the sound card is connected to a pair of headphones (section 2.2.4), through which the stimulation signal elicits the stimulation of the auditory system of a subject.
2. The electrical response is collected by three Ag/AgCl surface disc electrodes (see section 2.2.2). The electroencephalogram (EEG) captured by the electrodes is pre-amplified by a factor G_1 = 25, band-pass filtered (150 - 3000 Hz), and amplified by a factor G_2 = 130. Therefore, the gain of the amplifier for the band-pass frequencies is set at about G_{amp} = 3250 (70 dB) (see section 2.2.1).
3. The filtered and amplified biological response and the synchronization signal are synchronously recorded by both right and left inputs of the external AD/DA sound card. Both signals are sampled at a frequency of 25 kHz and stored using 24 bits of quantization (see section 2.2.3).
4. The final step is digital signal processing. This stage includes the scaling of the input signal (section 2.3.3); the synchronization of the biological response with its corresponding stimulus; the average of auditory responses (see section 2.3.5) and the use of other additional features to enhance the SNR ratio of the evoked potentials or reach other advanced functionalities (see section 2.3.4).
5. Users have total access to raw data and a flexible control of the parameters following a few steps on the interactive multimedia interface (see section 2.3.6).

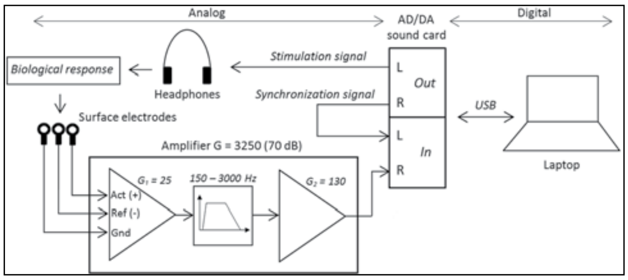

Figure 1. General scheme of the system.

2.2 Hardware system

This section describes the hardware elements involved in the process of BAER acquisition. These components are amplifier, electrodes, AD/DA sound card and headphones.

2.2.1 Amplifier

The low amplitude of BAER signals imposes an amplification of about 70 dB in order to be recorded by the AD/DA sound card. The amplification of this signal is performed through a biopotential amplifier that is described on this section. Figure 2 shows the electronic circuit diagram of the amplifier.

The amplifier comprises four stages: preamplification, band-pass filtering, amplification and active ground circuitry. Preamplification provides a moderate gain in order to adapt the input signal and prevent saturation on later stages. Band-pass filtering stage is designed to eliminate those frequencies out of the scope of the evoked potentials, amplifying only the band of interest (150-3000 Hz). Amplification is performed when the input signal is adapted and filtered, reaching the desired level of amplitude. The active ground circuit increases the Common Mode Rejection Ratio (CMRR). Electric networks generate an electric field that can be induced on the amplifier, on cables and on the subject, producing a common mode voltage in the subject. In case the subject is connected to ground, the common mode voltage would be the multiplication of the impedance of the electrode and the induced current, which

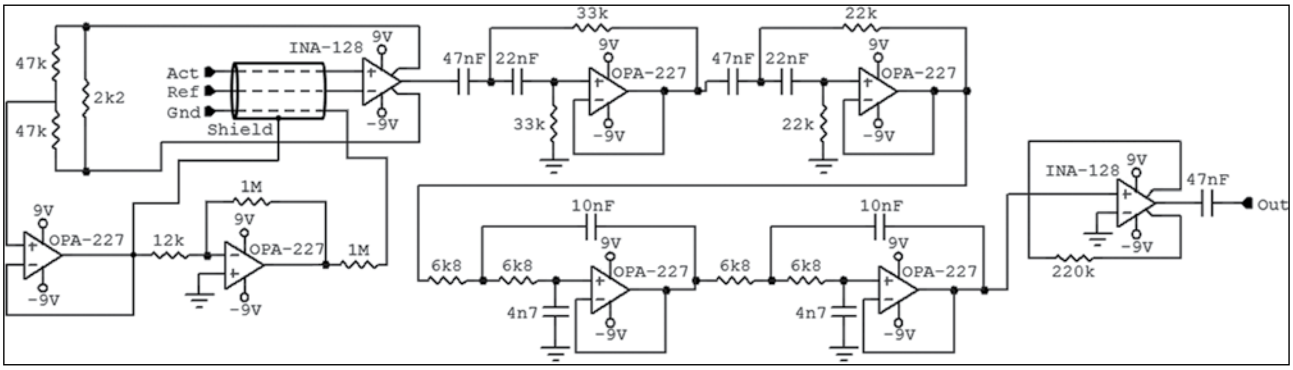

Figure 2. Electronic circuit diagram of the amplifier

would flow to ground only through the subject because of the high input impedance of the amplifier. Common mode voltage is amplified, inverted and inserted back into the subject by the active ground circuit, performing an important reduction on the common mode voltage.

Preamplification and amplification stages are based on the instrumental amplifier INA128 (Texas Instrument). This differential amplifier has been chosen because of its high CMRR (120 dB), low power, low noise voltage ($8\,nV/\sqrt{Hz}$), an easy control of the gain, and a lineal behavior of the gain and CMRR on the band of interest. Band-pass filtering stage is composed of four second order Sallen-Key filters (2 x high-pass & 2 x low-pass). Operational amplifiers used on band-pass filtering and active ground stages are OPA227 (Burr-Brown from Texas Instrument). OPA227 is characterized of a very low noise voltage ($3\,nV/\sqrt{Hz}$), high CMRR (130 dB) and high precision.

The Bode diagram on figure 3 presents the frequency response of the amplifier. Linearity of the amplifier has also been studied. A sinusoidal input signal was inserted on the amplifier with the intention of obtaining a slightly saturated output signal. The frequency of the input signal (1.167 kHz) was chosen in order to avoid delay on the output signal. 5 milliseconds of both input and output signals were recorded. Figure 4 displays the X-Y graph of the experiment. Linearity of the amplifier can be analyzed on this figure. This figure confirms that the behavior of the amplifier is especially lineal when the input signal is bounded within the range [-500 +500] μV, a common situation on this application considering that the input signal when recording BAER do not usually exceed 10 μV.

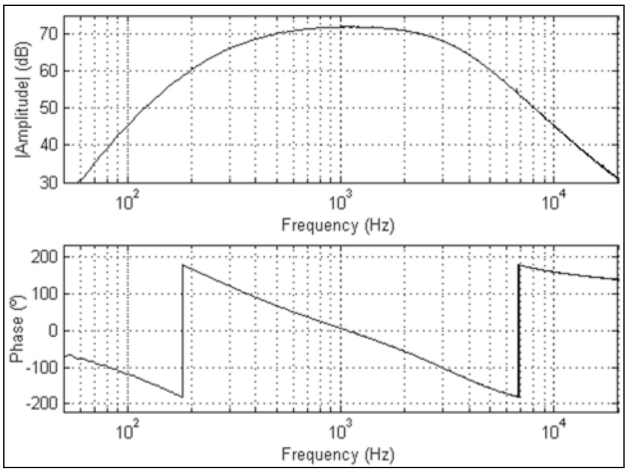

Figure 3. Bode diagram of the amplifier

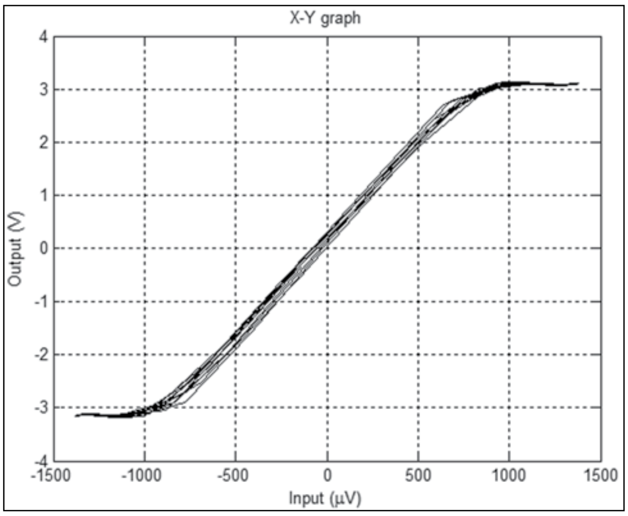

Figure 4. Linearity study. X-Y graph

2.2.2 Electrodes

Auditory brainstem potentials are recorded using surface electrodes placed at different positions on the head. Electrodes perform the function of transforming ionic currents (mechanism of conduction of bioelectrical signals on tissues) into electrical currents. Electrodes commonly used on the field of BAER acquisition are silver - silver chloride (Ag/AgCl), composed by a silver conductor (electrode) immersed into a silver chloride salt dissolution (electrolyte). When the electrolyte is rich on chloride ions, its impedance is near to linearity. Electrolyte is used, therefore, as a mean of union between the electrode and the skin. Electrolytic paste is used between the skin and the electrode in order to reduce impedance.

Since electrodes are the first elements on signal acquisition, noise generated at them is of high importance. Contact impedance between electrodes and skin must be minimized in order to reduce the noise affecting the recorded signal. It can be done by the elimination of layers of grease and dead cells. These layers can be removed by a softly scrape of the skin.

Positioning electrodes on the head plays an important role. Figure 5 shows the correct position. Active electrode is placed in vertex, in middle line near hairline. Reference electrode is set on the contralateral mastoid, due to its low innervation and poor muscular tissue. Active and reference electrodes are connected to the differential input of the amplifier. Ground electrode is placed on the forehead, in middle line. This electrode acts reducing the common mode voltage gain.

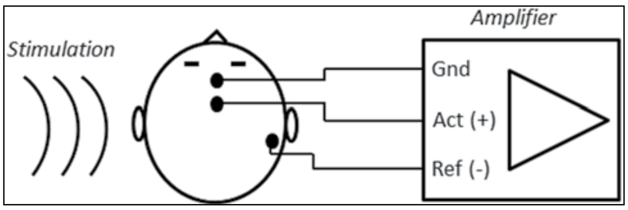

Figure 5. Position of electrodes on the head.

2.2.3 AD/DA sound card

An external sound card has been chosen to act as interface between the digital and analog systems. This type of devices has the advantage of simplicity and a better performance than most of sound cards integrated on laptops. The external sound card is connected to the laptop through the USB port.

Sampling rate has been set on 25 kHz in order to prevent aliasing. 24 bits of quantization allow reaching a very high resolution level; nevertheless, the use of 16 bits of quantization is also permitted in case it is desired to reduce the size of the file for its later processing and storing. Table 1 presents the main features and parameters of the AD/DA sound card set for this application.

Table 1. Features of the AD/DA sound card.

Feature	Value
Sampling rate	25 kHz
Input range	-3V / 3V
Output range	-2.5V / 2.5V
Bits of quantization	24
Input resolution	1.36 V

2.2.4 Headphones

Headphones act as an electro-acoustical transducer, transforming the electrical energy of the stimulation signal into acoustical energy (sound) that stimulates the auditory system of the explored subject. Monaural stimulation of the auditory system of a subject is provided. Circumaural standard headphones have been chosen for this application in order to reduce the effect of the background noise in the recording room.

2.3 Software system

This section describes the digital processing steps necessary for the recording of brainstem evoked potentials. Figure 6 shows a diagram of the software modules involved in this process.

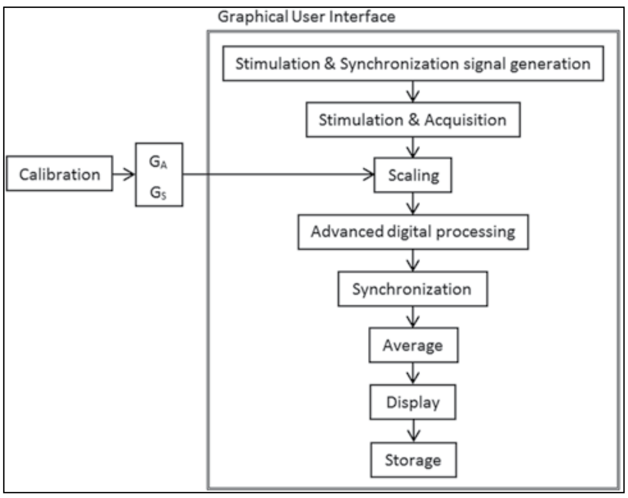

Figure 6. Software modules diagram.

2.3.1 Stimulation & synchronization signal generation

The aim of the Stimulation & synchronization signal generation module is the generation of the signal responsible for (a) the stimulation of the auditory system of a subject and (b) the synchronization process. The stimulation & synchronization signal is composed of a train of short bursts each one consisting on a biphasic click. Biphasic clicks provoke a synchronous discharge of a large number of hair cells due to its short duration (200 μs) and its wide frequency spectrum. This fact makes easier the identification of the biological response. Parameters like stimulation rate, intensity and number of stimulus considered for averaging can be controlled by the user.

2.3.2 Stimulation & Acquisition

The Stimulation & Acquisition module performs synchronously two actions: (a) the reproduction of the stimulation & synchronization signal through the left and right outputs of the AD/DA sound card; (b) the recording of the synchronization signal and the electroencephalogram (EEG) by the left and right input of the AD/DA sound card respectively. By default, sampling frequency is set to 25 kHz and the system uses 24 bits of quantization; nevertheless, users can change these parameters in order to control the precision of the recordings.

2.3.3 Scaling

A scaling process is required to measure the amplitude in volts of the brainstem auditory evoked potentials. Figure 7 shows a scheme of the elements involved in the process of scaling. A_R represents the amplitude in volts of the raw electroencephalogram recorded by electrodes. G_A is the gain of the amplifier. Therefore, the amplitude in volts of the signal after amplification (A_V) is $A_V = A_R * G_A$. A_X represents the non-dimensional signal after sampling. The gain of the sound card in the process of conversion from analog to digital is represented by G_S. This gain is related to the level of intensity of the input line in the audio settings of the laptop. Medium intensity level is recommended. The function of the module Scaling is to convert the recorded signal A_X into its corresponding real value in microvolts. This procedure is performed according to equation 1.

$$V_{calibrated}\ (\mu V) = A_X * \frac{1}{G_S} * \frac{1}{G_A} * 10^{6} \quad .... (1)$$

The process of scaling requires the system to be calibrated. The calibration of the system consists of determining the value of G_S and G_A. The gain of the amplifier for the band-pass frequencies (G_A) is obtained directly from the Bode diagram. The gain of the AD/DA sound card (G_S) can be measured by the recording of a few waves from a sinusoidal signal whose maximum value in volts is known (V_{hi}) and the correlation with its corresponding recorded value (X_{hi}), as the following formula indicates: $G_S = X_{hi} / V_{hi}$.

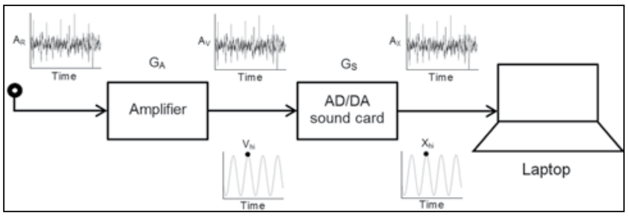

Figure 7. Parameters involved in the scaling and calibration process

2.3.4 Advanced digital processing

The process of recording BAER involves the "Advanced digital processing" step. This module incorporates optional high-level functions to enhance the SNR of the evoked potentials, such as digital filtering, the implementation of artifact rejection techniques or any other operation over the EEG.

2.3.5 Synchronization, Average, Display and Storage

The module "Synchronization" uses the recording of the synchronization signal to determine the samples on the EEG where stimulation occurs. The "Average" module computes the mean of the auditory responses. The function of "Display" is to visualize the result in a suitable scale. The "Storage" module saves the result and other important parameters into a file.

2.3.6 User interface

The process of BAER recording can be managed from a Graphical User Interface (GUI). This interactive framework allows a non-experienced user to record evoked potentials following systematically a few simple steps. Programmers can design the structure of this multimedia platform and include any parameter that involves the process of BAER recording using the MATLAB Graphical User Interface Development Environment (GUIDE). This tool simplifies the process of designing GUIs.

Figure 8 presents an example of GUI. On this figure, the first step is the generation of the stimulation & synchronization signal. Parameters like the number of stimulus, the stimulation rate and intensity level of stimulation can be controlled. Relevant information like the period of the stimulation signal and the duration of the test are displayed on the screen. On this platform, users can also visualize the evoked potentials and choose the name of the file where results are stored.

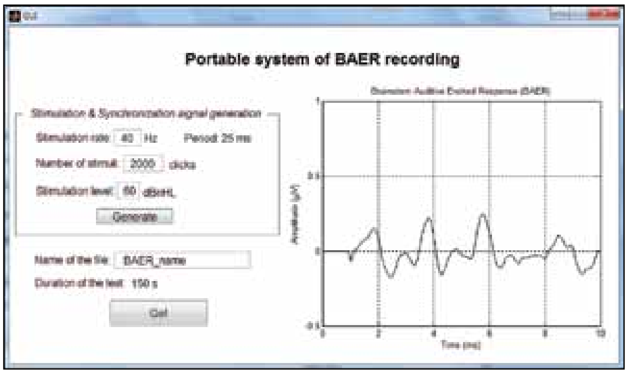

Figure 8. An example of front-end of the system

2.4 Cost analysis

Table 2 shows a rough cost of the necessary materials to set up the biometric signal processing laboratory proposed on this paper. The laptop and the license of MATLAB are not included in this table since they are common elements of any signal processing laboratory. The price list considered as reference to build this table was taken from a well-known international electronics supplier. This table points out that the cost of the system for BAER recording described on this section is much lower than other standard medical devices, whose price can reach several thousands of dollars.

Table 2. Rough cost of the hardware elements of the BAER recording system.

	Rough cost
Amplifier electronics	200 $
Reusable electrodes and electrolytic paste	200 $
Circumaural headphones	30 $
External AD/DA sound card	50 $
TOTAL	480 $

3. Assessment of the system

Three experiments have been performed in order to check the viability of the system. First, a synthesized signal similar in shape and amplitude to a biopotential has been recorded. Second, the minimum number of averaged responses in order to obtain recordings with enough Signal to Noise Ratio (SNR) to identify the main waves of BAER is analyzed. Third, brainstem evoked potentials have been recorded from eight normal hearing adults and biological conclusions have been obtained through an analysis of the latencies of the main waves of BAER.

Recording of a pseudopotencial

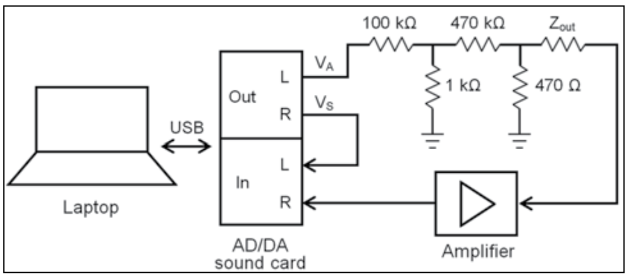

Figure 9. Elements involved in the process of recording a pseudopotential

The aim of this experiment is the simulation of the recording of a brainstem auditory evoked potential. Figure 9 schematizes the connections of the necessary elements to perform this experiment. A signal of a similar morphology to a BAER has been digitally synthesized. Figure 10 shows the "pseudopotential" that we have designed for this purpose. A high stimulation artifact is introduced on the pseudopotential to test a possible saturation of the amplifier. A burst of pseudopotentials (V_A) and a synchronization signal (V_S) are synchronously sent through both left and right outputs of the AD/DA sound card (Figures 10 and 11). The amplitude of the pseudopotential has been reduced by a voltage divider of a factor 10^5. Z_{out} represents the output impedance of the source since the input impedance of the amplifier is considerably higher (1 MΩ). The output impedance simulates the contact impedance of the electrodes with the skin. The noise of the input signal of the amplifier increases along with the output impedance Z_{out}. The burst of low-amplitude pseudopotentials is amplified, recorded by the AD/DA sound card, and digitally processed following the same procedure as obtaining BAER (section 2.3).

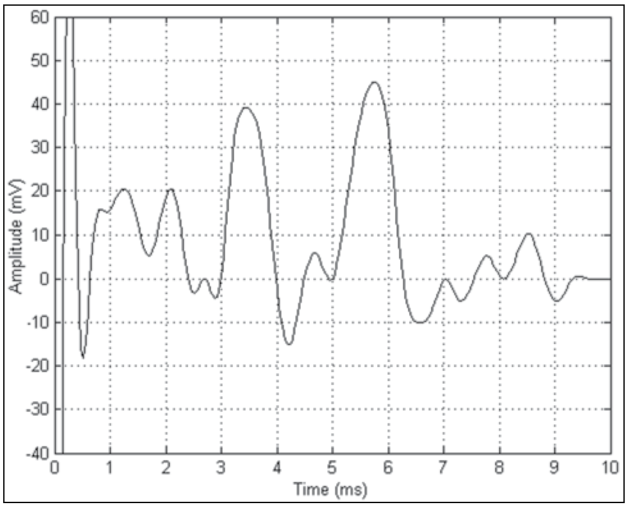

Figure 10. Synthesized pseudopotential

On this experiment, the amplitude of the wave V on the burst of pseudopotentials in V_A was 50 mV in order to have 0.5 μV after the voltage divider. The output impedance was set on Z_{out} = 4.7 kΩ, simulating a common contact impedance between electrodes and skin. The recorded pseudopotential is shown in figure 12. Digital blanking was used to eliminate the effect of the stimulation artifact. No saturation of the amplifier was observed. Although there exist some differences in morphology in comparison to the synthesized pseudopotential (figure 10), every wave on the recorded pseudopotential have been retrieved, remain on the same latency and are easily identified. This fact entails that the system is able to record signals of amplitudes lower than 1 μV.

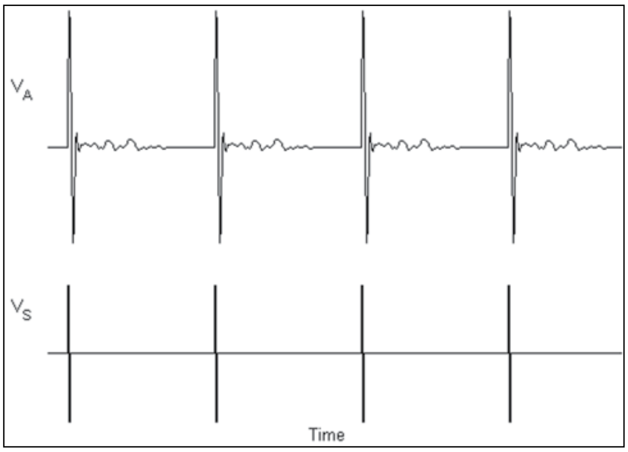

Figure 11. The burst of pseudopotentials (V_A) and the synchronization signal (V_S) are sent synchronously through the left and right outputs of the AD/DA sound card

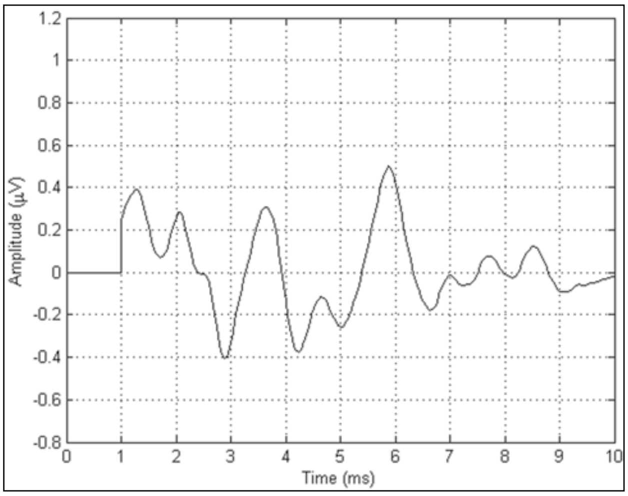

Figure 12. Retrieved pseudopotential

SNR analysis

Suppression of non-synchronous artifact is based on the average of biological auditory responses. A large number of responses increases the signal to noise ratio, but extends the necessary time for recording. Therefore, we have performed an analysis to find the appropriate number of averages that leads to high quality recordings spending a reasonable exploration time.

Figure 13 presents recordings of BAER obtained from a normal hearing adult at an intensity of 70 dBnHL by averaging different number of responses. This figure shows that the quality of the recordings improves as the number of responses increases. The main waves of BAER begin to be identified from the average of 200 responses and are easily recognized from 1000 responses. This fact suggests that 1500 is a suitable number of averages to be able to distinguish the main waves of BAER, reaching a balance between recording time and quality of the recordings.

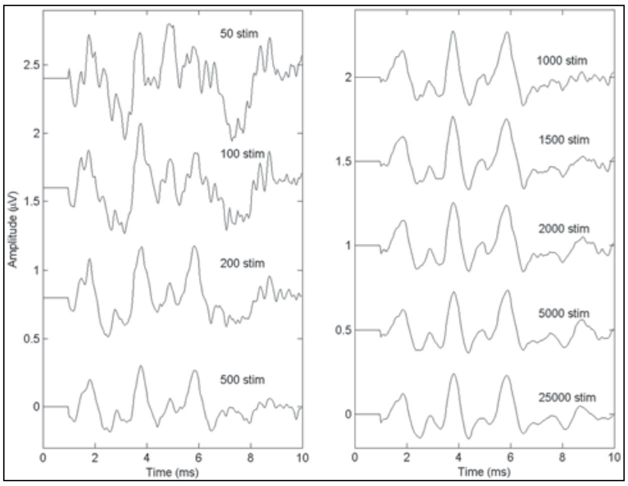

Figure 13. Brainstem auditory evoked potentials. Influence of the number of biological responses considered on average

BAER analysis from a group of subjects

Figure 14 displays BAER at different intensities of stimulation recorded over eight normal hearing adults of both sexes, aged between 23 and 33. Intensities of stimulation involved on this study are 10 dBnHL, 30 dBnHL, 50 dBnHL and 70 dBnHL. Interstimulus interval was set on 25 milliseconds. These signals have been obtained averaging 4000 responses in order to increase the quality of the recordings.

Figure 14 highlights the variability of the evoked potentials related to amplitude, latency and morphology of the waves. These differences among subjects are normal [9]. Changes on intensity of stimulation affect amplitude and latency of the peaks, as shown on figure 14. A reduction on the intensity of stimulation produces a decrease in the amplitude of all components of auditory evoked potentials, especially on wave I. The decrease on the amplitude of wave V occurs more slowly, a fact that is used to find the hearing threshold of a subject. The decrease on intensity of stimulation also causes an increase on the latencies of the waves.

The latencies of the main waves of the evoked potentials of figure 14 are presented on table 3. Wave V can easily be identified at 70, 50 and 30 dBnHL; but on some subjects, wave III does not appear at low levels. The standard deviation (table 3) shows that the variability of latencies among subjects is small. The mean values on the same table expose that latencies increase as intensity of stimulation decrease.

The influence that intensity of stimulation has over latencies of BAER waves has been analyzed through a statistical hypothesis test. Latencies of waves III, V and interpeak latency III-V at 70

Table 3. Mean, standard deviation and p value of latencies III, V and interpeak latency III-V

	Lat III (ms)			Lat V (ms)			Lat III-V (ms)		
Intensity (dBnHL)	70	50	30	70	50	30	70	50	30
Subject 1	3.88	4.16	4.88	5.76	6.12	6.88	1.88	1.96	2.00
Subject 2	4.00	-	-	6.04	6.24	7.00	2.04	-	-
Subject 3	4.04	4.50	4.88	5.96	6.20	6.76	1.92	1.70	1.88
Subject 4	4.04	4.68	5.32	6.20	6.48	7.30	2.16	1.80	1.98
Subject 5	3.90	4.06	4.76	5.88	6.12	6.72	1.98	2.06	1.96
Subject 6	4.08	4.28	5.12	6.00	6.20	7.00	1.92	1.92	1.88
Subject 7	3.88	4.28	5.12	5.98	6.20	7.06	2.10	1.92	1.94
Subject 8	3.68	3.96	-	5.64	5.92	7.16	1.96	1.96	-
Mean	3.94	4.27	5.01	5.93	6.18	6.98	1.99	1.90	1.94
Standard deviation	0.13	0.25	0.20	0.17	0.16	0.19	0.09	0.12	0.05
p - value	-	0.0053	$5 \cdot 10^{-8}$	-	0.0083	$2 \cdot 10^{-8}$	-	0.12	0.23

dBnHL have been chosen as reference. The significance level has been set on 0.05, according to many biostatistics applications [10]. The p-values shown on table 3 indicate that intensity of stimulation is a conditioning factor that influences the latency of waves III and V. On the other hand, there is no clear evidence that intensity of stimulation affect the interpeak latency III-V. Several studies support this result [11-12].

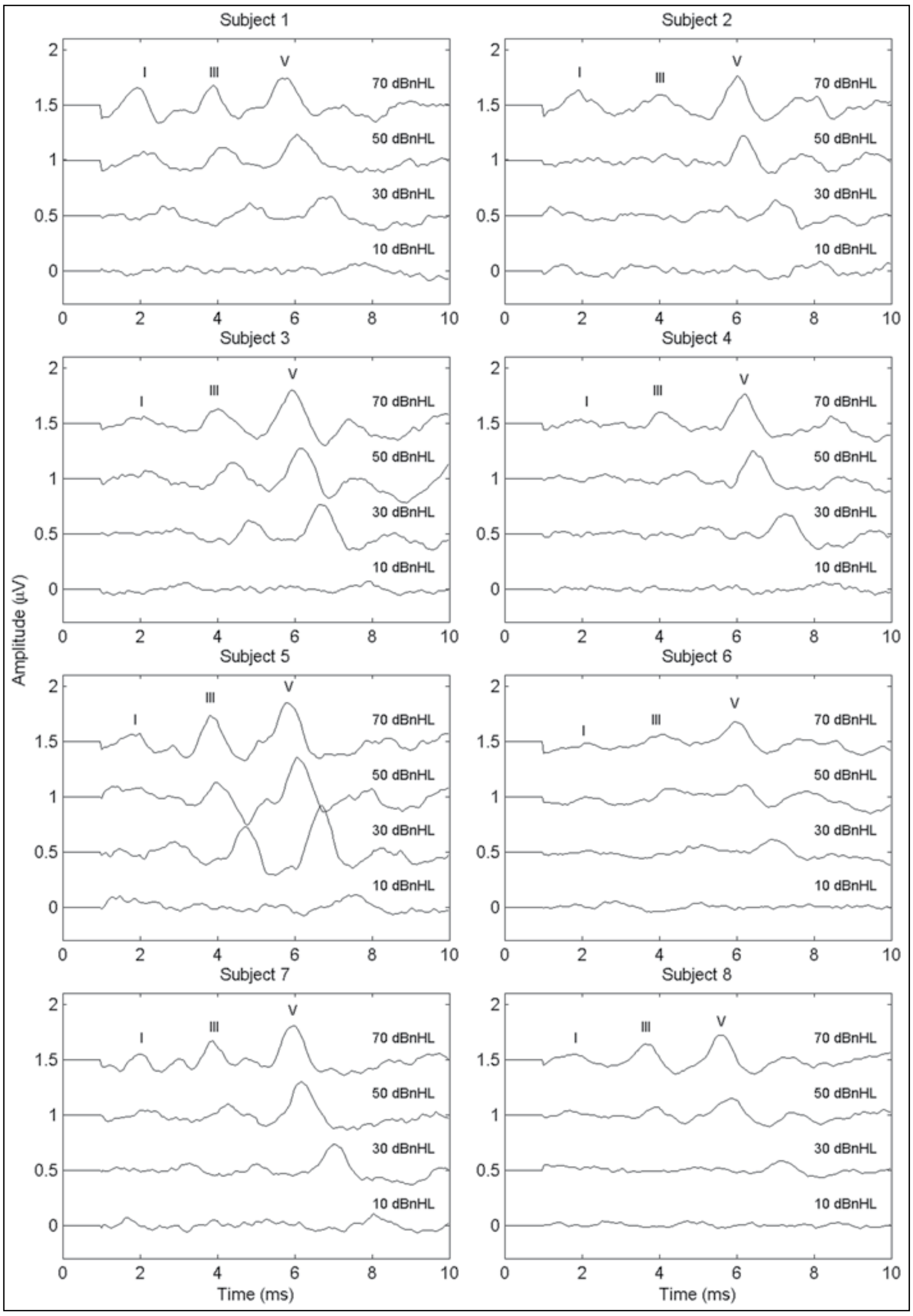

Figure 14. Brainstem auditory evoked potentials recorded over eight normal hearing adults. Influence of intensity level of stimulation.

4. Educational approach

The use of new technologies in education is a transversal competence that is being promoted by the application of the European Space for Higher Education of the Bologna Declaration. The system described in this paper aims to immerse students into a real-world laboratory exercise with a significant impact on their education. The development of the system for BAER acquisition described on this paper is especially addressed to technical profile students with an approach to biomedical applications. A basic knowledge on the fields of audiology, electronics, signal processing theory and programming skills in MATLAB is required as background education. If necessary, an overview on any of these matters should be provided to students before starting the lab activities. This laboratory suits perfectly on last years of degrees in electronics engineering, computer sciences, biomedical engineering and telecommunication engineering. This laboratory may also fit well in specific masters such as bioengineering and medical physics, multimedia systems, neuroscience, biomedical instrumentation and Ear, Nose and Throat (ENT) studies. This laboratory will help students gain specific skills and competences depending on their field of study. Furthermore, they will have the perspective of being involved in a multidisciplinary project.

Electronics engineering students are expected to (a) design and implement a low noise & high gain instrumental amplifier; (b) calibrate the system and (c) characterize the amplifier in terms of its frequency behavior, linearity, consumption, noise spectral density and noise power as a function of the impedance of the source. These activities will help them improve their ability on the field of biomedical instrumentation, learn to specify the performance of a lineal system through its electronic characterization, understand the importance of the input and output impedances of the electronic modules and the relevance of an adequate treatment of noise. Moreover, electronics engineering students will also start to be familiar to analog and digital advanced signal processing techniques and the process of biological signals recording.

The activities of telecommunication engineering students will be focused on (a) signal acquisition; (b) configuring of the audio settings on the process of AD/DA conversion performed by a sound card, such as the sampling rate or the number of bits of quantization; (c) the estimation of the quality of a biological recording in terms of SNR; (d) digital filtering of the electroencephalogram; (e) the averaging of biological responses and (f) the use of advanced artifact rejection techniques. These students will also interact with the electronics of the system and will realize that their work contributes to the development of a biomedical application.

Computer sciences students will program the digital signal processing routines designed by telecommunication engineering students that are necessary for recording BAER. On these laboratory sessions, students will make progress on their programming skills using MATLAB, learning new functions useful for other disciplines. Furthermore, computer sciences students will design and program a Graphical User Interface, so that medical doctors and other users of non-technical education profile are able to record auditory evoked potentials. The development of these laboratory activities will make computer sciences students be more aware of the relevance of electronics and signal processing on an application with a clinical purpose.

The main role of students of audiology is the recording and the analysis of brainstem auditory evoked potentials. Audiology students will apprehend the influence that factors like stimulation intensity or stimulation rate has over the amplitudes and latencies of BAER. In general terms, these students will gain a better understanding in audiology, and more specifically, on the hearing process. These students are expected to perform statistical hypothesis tests to propose biological conclusions and give a physiologic interpretation of the results. This activity will help students enlarge their experience in statistical tests to reach conclusions with a certain confidence interval. This laboratory will also make students understand the process of BAER recording in detail and be more aware of (a) the importance of electronics, (b) the importance of a correct electrodes placement in order to reduce the output impedance of the signal source, (c) the large number of possibilities and new functionalities that the digital signal processing offers and (d) the importance of a friendly interactive user interface.

The assessment of the system is also a laboratory activity with a high educational approach. It can be performed not only by recording brainstem auditory evoked potentials from a subject, but also simulating the recording of a digitally synthesized signal with similar shape to a biopotential, i.e. a pseudopotential. The successful recording of a low-amplitude pseudopotential is a challenging laboratory activity. This activity requires no electrodes placement and gives students a high degree of freedom: (a) the shape of the pseudopotential can be digitally synthesized in MATLAB; (b) the amplitude of the pseudopotential can be controlled by the output level of the signal and by the voltage divider; (c) extra noise can be added to the signal by increasing the output impedance Z_{out} or by digital means, where users can also control its spectral distribution; and (d) other parameters like the sampling rate, the number of bits of quantization and the number of responses considered for averaging can also be controlled.

The pedagogical methodology proposed to achieve the goals of this lab is experiential learning. This didactic strategy is founded on the gain of knowledge directly from experience [8]. It is well known that experiential learning activities develop a better understanding of a subject, enhance retention and improve cognitive skills [13]. The mission of teachers is to help students organize their ideas, schedule the milestones to complete, lead them to solve specific technical problems and evaluate their results and motivation. This way of learning creates an educational environment that encourages students to be committed with this experience.

The system described on this paper can be used as an educational tool. Furthermore, because of its open nature, it can also be used for research to investigate the process of hearing and other advanced auditory features. Indeed, this system has already been successfully used obtaining BAER at high rates of stimulation [14].

Assessment of the proposed educational approach

A laboratory activity was performed on the Master of Multimedia Technologies framework at the University of Granada (Spain). This master provides education in digital processing methods of audio and video signals, audiology, the development of man-machine interfaces, etc. Students enrolled on this master come usually from technical profile degrees such as computer sciences, electronics engineering and telecommunication engineering. The laboratory session was held after twelve hours of lectures in audiology in which students learnt about anatomy and physiognomy of the auditory system, the process of recording otoacoustic emissions and brainstem auditory evoked potentials, the use of auditory evoked potentials for clinical diagnosis, etc.

The aim of the laboratory was to involve the students in a BAER recording session and help them consolidate the most important concepts studied on lectures. The lab comprised the performance of four activities. Activity 1 consisted of a short introduction in which the elements of a BAER recording system were presented and the types of noise that affect the recording of BAER were theoretically analyzed. Activity 2 entailed the placement of the electrodes on the head of a subject and the connection of the hardware elements of the BAER recording system: laptop, external AD/DA sound card, headphones and amplifier. Activity 3 involved the recording of biological responses associated to 2000 acoustic stimuli and the presentation of BAER at different number of averaged responses: 50, 100, 200, 500, 1000, 1500 and 2000. Activity 4 performed the recording of auditory evoked potentials at the stimulation levels: 10 dBnHL, 30 dBnHL, 50 dBnHL and 70 dBnHL. Nine students participated on this laboratory.

Students were asked to answer a test of knowledge before and after the laboratory session. This practice pursued a double intention: on one hand, the contents learned by the students were evaluated before and after the laboratory; on the other, the initial test prepared the students for the kind of education expected to receive on the laboratory session, helping them focus their attention on the most important contents and therefore, increasing their motivation and interest. The questions that composed the test of knowledge are presented on table 4. Figure 15 shows the percentage of correct answers to the questions of the test of knowledge before and after the laboratory session. Partly correct answered questions count half of the value of a correct answer. Figure 15 shows that students have given more correct answers to the questions of this test after the performance of the laboratory activities than before. Every question has been correctly answered by more than 70 % of the students on the test after the laboratory session.

Table 4. Questions of the test of knowledge.

Tag	Question
Q1	What are the main elements involved in a standard BAER recording system?
Q2	What is the correct placement of electrodes on the head?
Q3	What is the methodology used to reduce the effect of non-synchronous artifact?
Q4	What types of artifact commonly affect the recording of BAER?
Q5	What is the influence of the intensity level on the amplitude and latency of the waves of auditory evoked potentials?

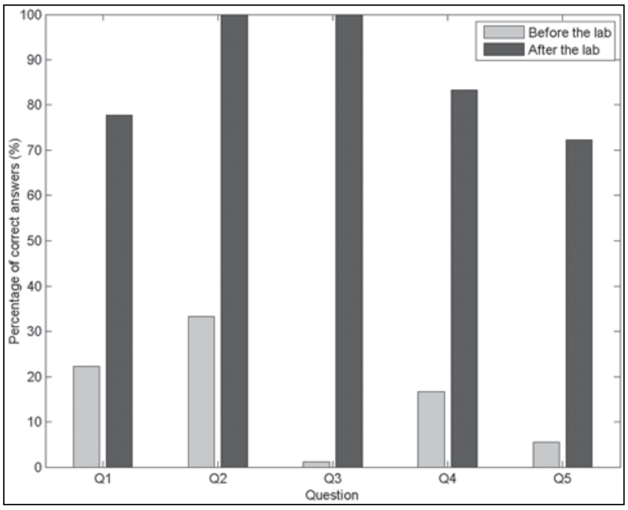

Figure 15. Test of knowledge results. This figure shows that the percentage of correctly answered questions increase after the laboratory session.

Finally, students were asked to complete a satisfaction survey in order to evaluate the efficiency of the laboratory. This evaluation was performed by the measurement of the level of agreement of the students to different statements. Statements and results of this survey are presented on table 5. Level 1 corresponds to “I strongly disagree” and level 5 to “I strongly agree”. Column “evaluation” on table 5 shows the mean and standard deviation of the evaluations of the students. In general terms, table 5 evidences that the laboratory had a high level of acceptance by the students. This table also shows that the students think that the laboratory session was useful to help them understand important concepts studied in lectures, that the laboratory was interesting and that they would recommend it to other audiology and bioengineering students. Students were also asked about their personal opinion of the laboratory, giving answers such as: “practical exercises favor a better comprehension of theory”, “my participation in this laboratory has helped me understand and remember the things explained in lectures” or “this lab makes easier the understanding of theoretical models studied in class”.

5. Conclusion

This paper proposes the implementation and assessment of a flexible, low cost and high performance system for acquisition of Brainstem Auditory Evoked Response (BAER). This system is proposed to be used as a didactic tool for the study of auditory evoked potentials in a biomedical, electronics and signal processing laboratory. The hardware and software elements that compose the recording system are thoroughly presented to describe the process of implementation. In order to verify that our system is capable of recording biological responses, a low amplitude pseudopotential was successfully recorded. The improvement of the quality of the BAER signals as the number of responses increases has been evaluated. In addition, BAER from eight normal hearing subjects were recorded at different levels of stimulation. The influence of the level of stimulation over the latencies of the main waves was statistically evaluated, reaching conclusions consistent with other studies.

Although there already exist other medical devices able to record BAER, most of them are expensive

Table 5. Satisfaction survey results. The evaluation column represents the mean and standard deviation of the level of agreement of the students to each statement. Level 1 corresponds to “I strongly disagree” and level 5 to “I strongly agree”

Statement	Evaluation	
	Mean	Std. Dev.
This laboratory helped me understand the overall performance of a standard BAER recording system	4.6	0.5
Thanks to this lab, I learned the correct placement of the electrodes on the head to record BAER.	4.7	0.7
This laboratory helped me understand the different types of artifact involved in the recording of evoked potentials, as well as the digital signal processing methods used to reduce their effect.	4.0	0.7
I grasped the way in which the number of averaged auditory responses affects the quality of the recorded BAER.	4.3	0.7
This laboratory helped me assimilate the effect that the level of intensity has on the amplitudes and latencies of auditory evoked potentials.	4.3	0.7
In general terms, the contents of this laboratory were presented in a suitable and systematic way.	4.1	0.6
This laboratory session was interesting.	3.9	0.9
The level of difficulty of this lab was appropriate.	4.6	0.5
My motivation and interest in the subject has increased after this lab.	3.5	0.5
I recommend this laboratory to other audiology and bioengineering students	4.4	0.7
I consider that the concepts entrenched on this lab are useful for other audiology and bioengineering students.	4.3	0.5

and suffer from a lack of flexibility, making them inappropriate for education purposes. The laboratory we propose is especially addressed to technical profile students from degrees such as electronics engineering, telecommunication engineering, computer sciences and audiology studies. The development of the activities that compose this BAER recording system in a signal processing laboratory presents several educational advantages. The pedagogical model proposed to be followed is experiential learning, in which students learn basically from their own direct experience. This approach intends to help them comprehend complex concepts and improve retention. A laboratory session was performed on the Master in Multimedia Technologies framework at the University of Granada. This laboratory session comprised the performance of several activities that, according to the self-evaluation given by the students, helped them understand, assimilate and consolidate theoretical concepts studied in lectures.

One of the contributions of this article is to provide the necessary knowledge to implement and evaluate a high performance, low-cost and flexible BAER recording system. The results of this work suggest the use of the described BAER recording system as a didactic tool in an audiology, electronics and signal processing laboratory framework because of its low-cost and open nature. The laboratory experience and the analysis of the satisfaction survey results show the educational utility of our system and confirm that an educational strategy based on experiential learning contributes positively to the comprehension and consolidation of knowledge by the students.

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