UNIVERSITAT POLITÈCNICA DE CATALUNYA
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TOWARDS A NEONATAL BRAIN STETHOSCOPE: A FRAMEWORK FOR QUANTIFYING THE ACCURACY OF SUBJECTIVE AND OBJECTIVE DETECTION OF NEONATAL BRAIN INJURIES, AND INTEGRATION OF A BLUETOOTH COMMUNICATION SYSTEM

A Degree Thesis

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by

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AUDIOVISUAL SYSTEMS ENGINEERING

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Abstract

The goal of this project is to work in different aspects of the development of a neonatal brain stethoscope. This tool is expected to be an alternative to the current devices, which are expensive and require a very specific training to be used.

First, an interactive web interface has been developed to assess the detection of neonatal brain injuries by the users using an alternative interpretation method framework. The webpage presents the currently-used visual method, based on visualisation of electroencephalogram (EEG) traces, and an alternative way that also includes a sonification output and an AI-assisted decision support.

Secondly, a connection has been established between an acquisition board and a portable device using Bluetooth Low Energy (BLE). This allows to wirelessly receive and store in real time the EEG signals that come from the electrodes through the acquisition board.

Resum

La finalitat d’aquest projecte es treballar en diferents aspectes del desenvolupament d’un estetoscopi cerebral per a nounats. Aquesta eina està concebuda com a alternativa als sistemes actuals, que resulten cars i el seu ús requereix un entrenament molt específic.

Primer de tot, s’ha desenvolupat una interfície web interactiva per a analitzar i valorar la detecció per part dels usuaris de dany cerebral en neonats emprant un mètode alternatiu d’interpretació. La pàgina web inclou el mètode gràfic actual, que correspon a la visualització de senyals electroencefalogràfics (EEG), i també una forma alternativa d’interpretar les senyals, fent ús tant de la seva representació acústica com d’un suport de decisions emprant un sistema assistit per intel·ligència artificial.

En segon lloc, s´ha establert la connexió entre una placa d’adquisició i una tauleta tàctil, fent ús de la tecnologia *Bluetooth Low Energy.* Això permet, sense necessitat de cables, rebre i emmagatzemar en temps real els senyals EEG que provenen dels elèctrodes a través de la placa d'adquisició.

Resumen

La finalidad de este proyecto es trabajar en diferentes aspectos del desarrollo de un estetoscopio cerebral para recién nacidos. Esta herramienta está pensada como alternativa a los sistemas actuales, que generalmente son caros y cuyo uso requiere un entrenamiento muy específico.

En primer lugar, se ha desarrollado una interfaz web interactiva para poder analizar y valorar la detección de daño cerebral en neonatos por parte de los usuarios utilizando un método alternativo de interpretación. La página web incluye el método gráfico actual, que corresponde a la visualización de señales electroencefalográficas (EEG), así como una forma alternativa de interpretar las señales, utilizando una representación acústica de éstas y un soporte de decisiones haciendo uso de un sistema asistido por inteligencia artificial.

En segundo lugar, se ha establecido una conexión entre la placa de adquisición y una tableta táctil, utilizando la tecnología *Bluetooth Low Energy*. Esto permite, sin necesidad de cables, recibir y almacenar las señales EEG que provienen de los electrodos a través de la placa de adquisición.

To my parents, for being supportive during all these years and for giving me the opportunity of studying what I like the most.

Acknowledgements

I would like to specially thank Dr. Andriy Temko and Dr. Emanuel Popovici for allowing students to enjoy of the opportunity of working in this project. Also, my sincere thanks to Dr. Climent Nadeu for facilitating this experience which, in general terms, has permitted me to expand my knowledge in the field of Telecommunications Engineering. Finally, many thanks to Sergi Gómez and Mark Edward O’ Sullivan for being supportive and helpful with any doubt that I had during the realisation of the project.

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1. Introduction

1.1. Project Overview and Goals

The following project is carried out at the Embedded Systems Group of the Department of Electrical and Electronic Engineering at University College Cork (UCC) and in the Irish Centre for Fetal and Neonatal Translational Research (INFANT) centre. It is developed under the Welcome Trust funded project, under the PI Dr. Andriy Temko.

This work is mainly divided in 3 blocks, all of them correspond to a project based on the development of a new product, the Neonatal Brain Stethoscope [1], which is defined as an innovative tool to detect seizures in newborn babies. This tool is expected to be an alternative to the current devices, which are expensive and require a very specific training to be used.

A figure clarifying this main project is shown below.

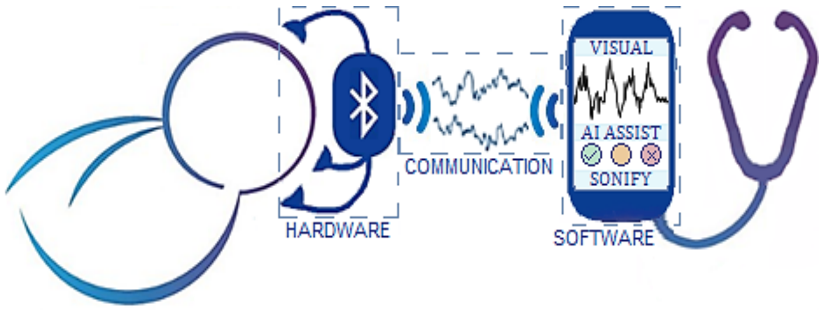

Figure 1.Scheme of the Neonatal Brain Stethoscope

To be clearer about which parts correspond to the work that is presented here, a diagram block is included. The blocks marked with a red box correspond to the activities carried out in this project:

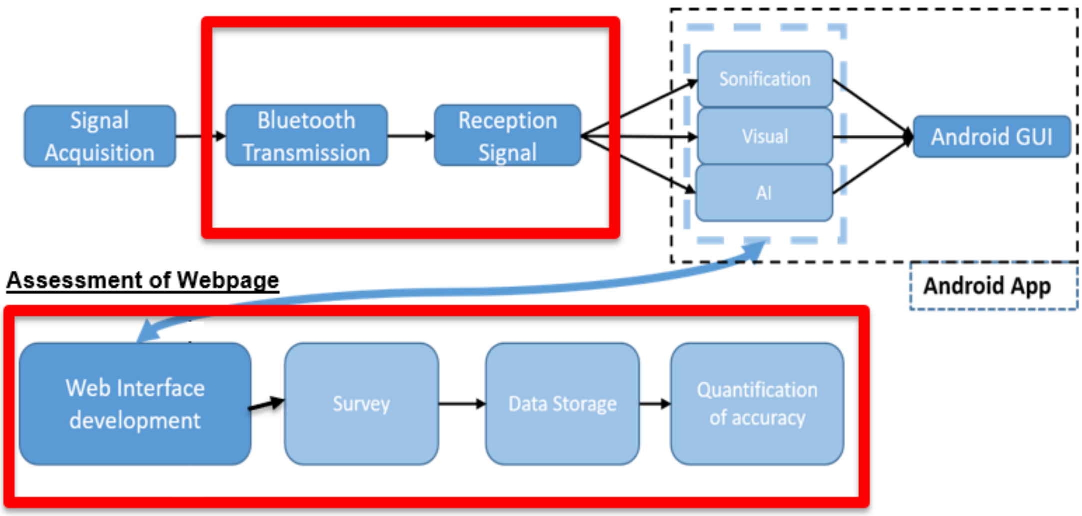

Figure 2. Diagram Block of main project

One of the main blocks described in the following project is defined as Bluetooth Transmission. It is based on the establishment of a wireless connection between an acquisition bio-sensing board and a portable device. The goal behind this part of the project is to assure that a wireless transmission is performed in real time. This will allow to create a cheap and portable wireless system able to acquire and record neonatal Electroencephalogram (EEG) signal.

Moreover, another important block consists on assuring that every obtained signal from the previous connection is EEG. In other words, develop an algorithm to assess to quality of EEG signal by pre-processing the signal before any other procedure is applied to the signal, taking into account the limitations that Android may have in terms of hardware.

Both blocks are thought to be a part of an Android application, to be developed by Eduard Salgado, that can process EEG data in real time. For instance, as explained in [1], the idea is to generate an audio output from the EEG traces, apart from using AI to obtain the seizure probability.

Finally, an interactive web interface is defined. The main goal of this block is to assess the perceptual accuracy of seizure detection in EEG traces. The obtained results can determine which method can help clinical personnel in medical environments for seizure detection.

Therefore, the project main goals are:

- Establish wireless connection between the acquisition system and a mobile platform to allow a cheap and portable system to be used.

- Develop an Android algorithm for assure that every received signal from the acquisition board is purely neonatal EEG.

- To finalise the development of a web interface to quantitatively assess the discriminability of various algorithms to discriminate neonatal EEG. To make it user friendly, while assuring the anonymity of the users. Finally, to allow results to be saved in an easily accessible format.

- Using the developed web interface to perform the survey of clinical personnel in the NICU, and assess and quantify the experience of clinical end users regarding the chosen EEG signal sonification algorithm by analysing the obtained results

1.2. Project Background

It is stated that brain injuries in newborn babies represent a serious global issue. Not only for clinicians, but also for the parents of the infants. The Worldwide Health

Organisation estimates that each year more than 3 million deaths are registered due to this topic.

Moreover, approximately a third of the neonatal seizures are clinically visible, leading to a high number of undetected cases, not only because of the nature of the signal itself, but also an expert clinician is needed. In addition, the main problem with the detection is time. The whole process, which consist firstly in monitoring an infant for several hours after the electrodes have been placed, is in need of a specialist to check this amount of data in order to conclude whether there has been a seizure or not during the recording. That could imply that a seizure is detected after a long period of time, which in many cases would imply that irreversible brain damage may have been done to the infant due to a seizure event. There are not enough neuro-physiologists and the expertise is not available in a 24 basis during the 7 days a week. Neonatologists feel unsupported in interpretation of brain signals.

Although a simpler form of Electroencephalogram (EEG) monitoring is now being used, called amplitude integrated EEG, it has been shown that its accuracy for detection of seizures is limited and heavily relies on the experience of a doctor with considerable subjectivity of interpretation. Furthermore, the equipment used for EEG monitoring in the NICU implies an investment of €20,000-€50,000 which is not available in the developing world.

The project in this thesis is carried out under the research project funded by Wellcome Trust called Sound-Based interpretation of neonatal Brain Growth and Status. It focuses on development of a neonatal brain stethoscope. This stethoscope device is thought to acquire EEG signals to later transmit it to a portable equipment. Also, the EEG signal interpretation is facilitated using a sonification technique and AI in the form of a probabilistic meter, which varies its colour depending on the chances of having detected a seizure.

The thesis project establishes Bluetooth connection between the acquisition board and a portable device, which needs to be integrated in one single system of the main project.

1.3. Project Requirements and specifications

Project requirements:

- Ease in the usage and storage of results obtained from the web interface to quantify and assess objectively and subjectively the detection of seizures in neonatal EEG.
- Web interface must be user-friendly to avoid users to leave the interface before doing the survey.
- Adequate wireless connection between acquisition system and mobile platform, for instance a tablet.
- Intuitive interface in portable device to connect it to the acquisition board.

Project specifications:

- Minimal delay between the acquisition of the signal and the moment the user desires to obtain a sample of EEG after being sonified.
- Avoidance of loss of information during transmission of signal from acquisition system to portable device.

Specification of the project	Objective
Delay between board and portable device	< 1 minute
Transmission of EEG signal without loss of information	-

Table 1. Project Specifications and Requirements

1.4. Work plan

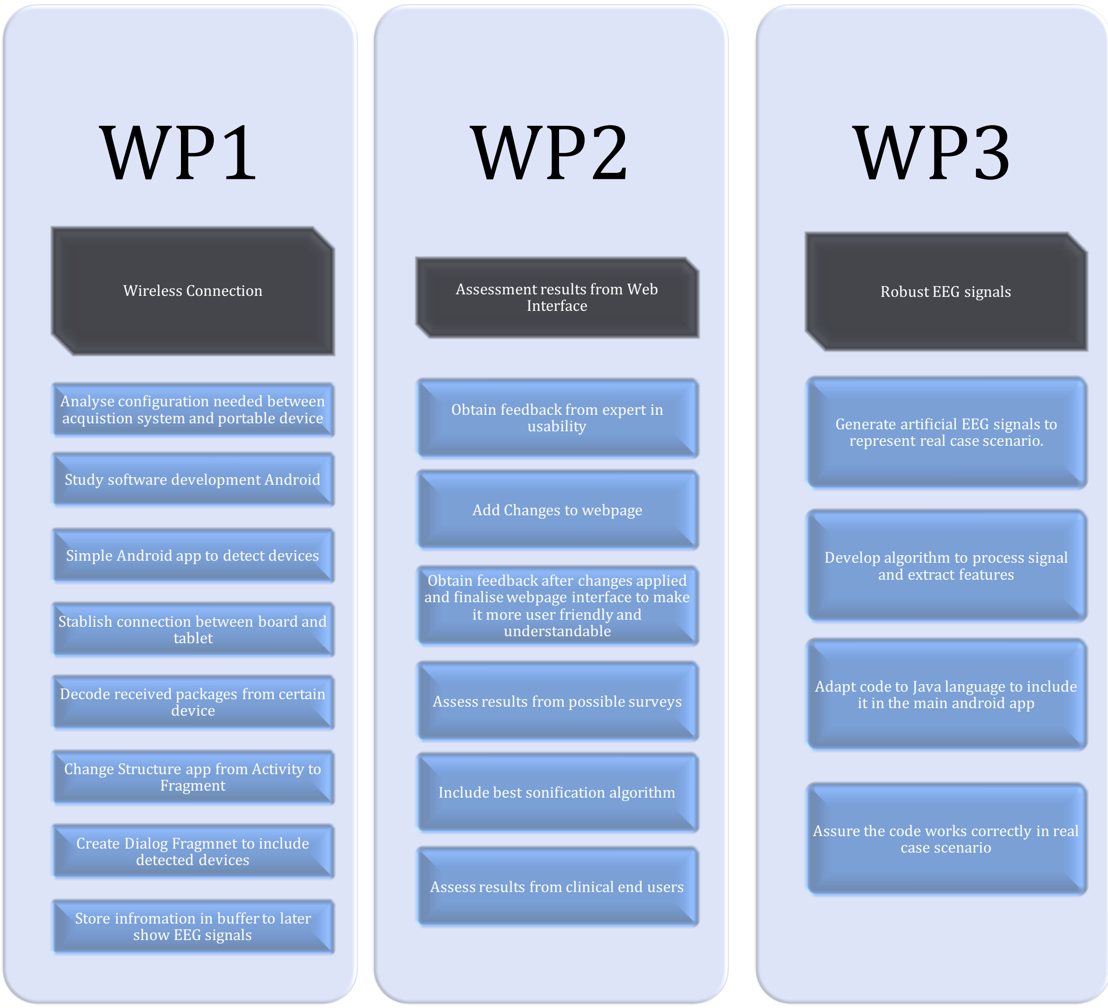

Figure 3. Detailed Work Plan

The detailed description of the different work packages and milestones are specified below, in Appendix I, page 30.

1.5. Gantt Diagram

		Name	Duration	Start	Finish
1		⊟WP1: Wireless connection	132 days?	27/11/17 08:00	29/05/18 17:00
2		Configuration acquisition board	3 days?	27/11/17 08:00	29/11/17 17:00
3		Background Android Study	13 days?	29/11/17 08:00	15/12/17 17:00
4		Simple Android application	20 days?	18/12/17 08:00	12/01/18 17:00
5		Bluetooth Connection	5 days?	13/01/18 17:00	19/01/18 17:00
6		Decode received packages	3 days?	20/01/18 17:00	24/01/18 17:00
7		Avoid loss od information when transmitting	1 day?	25/01/18 17:00	26/01/18 17:00
8		Change structure of algorithm	20 days?	26/01/18 17:00	23/02/18 17:00
9		Create DialogFragment	5 days?	23/02/18 17:00	02/03/18 17:00
10		Interact with acquisition board	43 days?	02/03/18 17:00	02/05/18 17:00
11		Avoid loss of information in final version	19 days?	02/05/18 17:00	29/05/18 17:00
12		⊟WP2 : Assessment of results from Web interface	110 days?	29/01/18 08:00	29/06/18 17:00
13		Feedback from expert in usability	40 days?	29/01/18 08:00	23/03/18 17:00
14		Adaptation of code from Montserrat Anglès	22 days?	24/03/18 08:00	24/04/18 17:00
15		Final feedback and adding of minor changes	3 days?	24/04/18 17:00	27/04/18 17:00
16		Assessment of results for choosing optimal sonification algorithm	10 days?	20/05/18 08:00	01/06/18 17:00
17		Include optimal sonification algorithm	11 days?	01/06/18 08:00	15/06/18 17:00
18		Assessment of results from clinical end users	11 days?	15/06/18 08:00	29/06/18 17:00

Figure 4. Gantt Diagram. Part 1

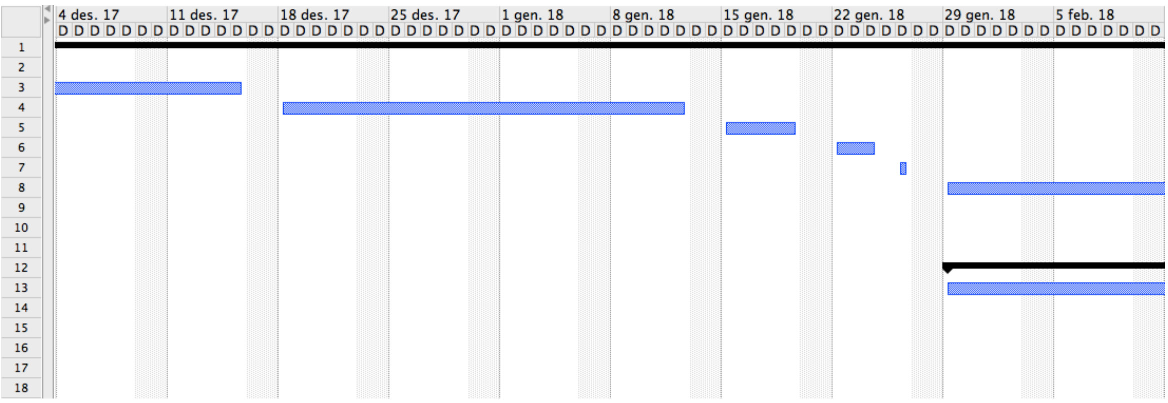

Figure 5. Gantt Diagram. Part 2

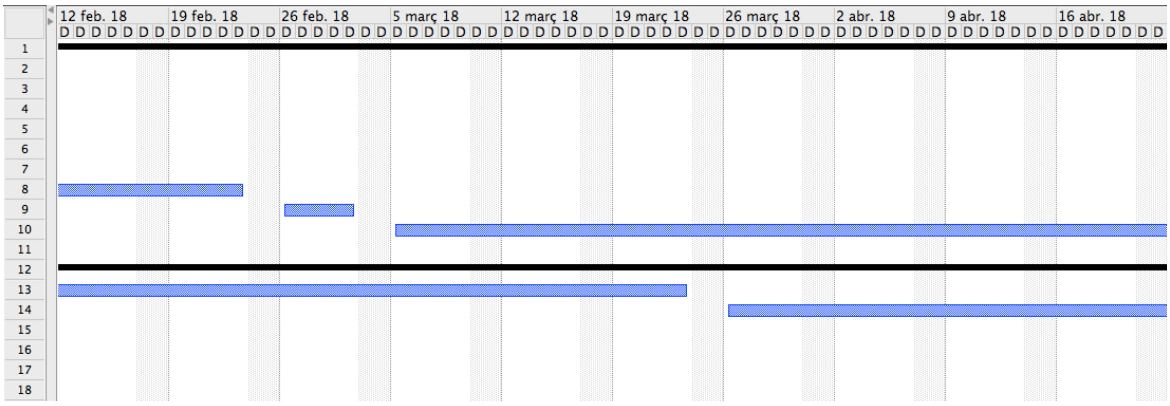

Figure 6 Gantt Diagram. Part 3

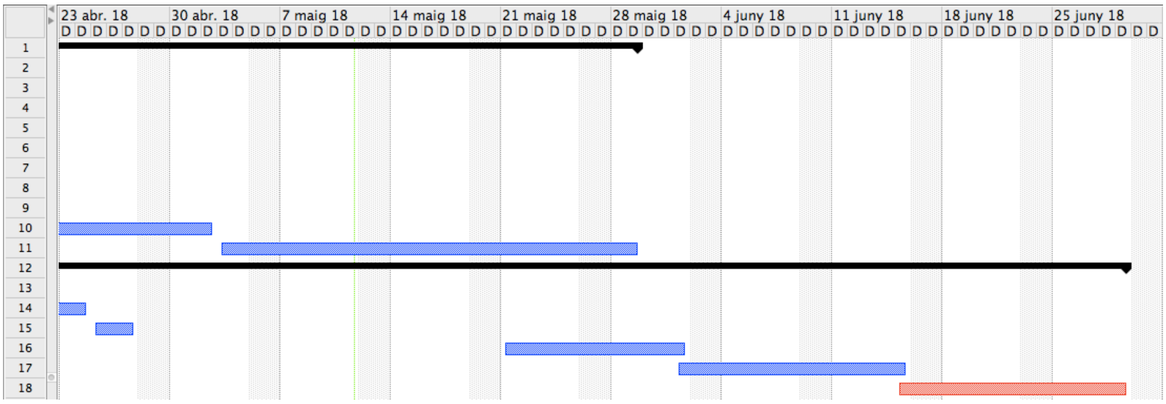

Figure 7 Gantt Diagram. Part 4

1.6. Incidences and Deviations

The estimated time related with the first work package, defined as the development of the wireless connection between the acquisition board and the portable device, increased considerably. This occurred since some internal tasks were not considered during the definition of the work plan, which has led to more time needed to finalise it.

In WP1, the structure of how an Android application was supposed to be developed was at first confusing due to the lack of experience in this field. However, after some weeks of study of software development in Android, the first application able to establish a connection between the acquisition board and a mobile device was developed. By the time the correct functioning of the app was assured, it was necessary to implement the algorithm in the main application.

The idea of developing a separated application was mainly to avoid any possible interference with the work that Eduard Salgado was conducting. The implementation implied that limited space for executing the algorithm was given, which implied that the application had to be first developed as an Activity, mainly because of the lack of knowledge, to later use another structure known as Fragment. This is because a Fragment is thought to be executed while the main activity, which is the core of any application, is running. This structure is widely used to reduce power consumption. Optimisation of the code was performed at the same time that the structure of the code was changed.

Long delay to finalise WP1, mainly because of problems with the decoder part. To finally understand the correct flow of it, an implementation of code in MATLAB was done.

The WP2 defined in the Project Plan, which was the development and tuning of sonification algorithms, was assigned to another member of the team, Sergi Gómez. The main reason behind this decision is because sonification algorithm was required more urgently than planned. Subsequently, WP2 was changed for WP3 and WP3 consisted in the development of an algorithm which will assure the robustness of the system through development of simple and efficient (digital signal processing) DSP artifact rejection algorithms. The idea behind this work package was to be able to identify segments of neonatal EEG or channels which have been corrupted by artifacts or do not carry useful information, to only allow processing of clean EEG segments by the app for visualisation, sonification and AI-based interpretation.

Regarding the WP2 defined in the Critical Review, it is important to mention that several subtasks were added. Another student, Montserrat Anglès, started working on the usability of the webpage and also on the usability of the Android app during March. The feedback provided by that student from her interaction with app development experts and clinicians is reflected in an upgraded webpage version.

The fact that many changes were needed to be applied were not fully considered when the work package was redesigned. It implied that more time than expected was needed. In addition, some issues with storing the data from the survey, included in the webpage, were found, leading to a loss of information at the beginning.

WP3 has suffered a delay because of the packages WP1 and WP2, and it is thought to be completed during the the following months thanks to an extension of the contract.

This part of the project will be first developed using MATLAB and then implemented in Android and integrated in the main app. The development of a DSP in Android will have its limitations, which will be needed to be considered when coding.

2. State of the art of the technology used or applied in this thesis:

2.1. Background

Even though amplitude integrated EEG (also known as aEEG), which is a logarithmically-scaled, temporally-smoothed display of the EEG, is used nowadays as an alternative form of EEG monitoring for NICU personnel, continuous EEG (also known as cEEG) is still preferred when it concerns to seizure detection [2].

While the usefulness of aEEG is questioned when used in newborn patients, a sonification method [3] has been presented as an alternative which does not require an exhaustive training and allows the user to focus in other aspects which may require the usage of the visual sense [4]. Moreover, acoustic signal obtained from EEG, being understood as a subjective interpretation method, it is seen as a useful tool when it comes to seizures detection.

Studies with convolutional neural networks (CNN) has also been carried to provide an objective method of EEG signals [5], working as an interpretation technique to increase the accuracy of detection of seizure events.

To ease the visualisation of EEG signals can be filtered in frequency. It is known that the dominant frequencies of a seizure event vary between 0.5Hz and 6Hz. Using a band-pass filter between 0.5 and 8Hz maximises the perception of the frequency of a seizure [6]. Furthermore, mains hum at 50Hz is also filtered. This filtering is used to ease the visualisation of EEG signals.

In this project, the sonification output obtained from [3], the AI-assisted decision support from [5] and the enhancement of visualisation method by using a band-pass filter in cEEG are present as an alternative method framework to the current visualisation of cEEG. Both methods are included in the webpage interface to quantify their accuracy.

Regarding Bluetooth Technology, the technology used in this project is Bluetooth Low Energy. It provides a reduced power consumption while transmitting information at the same range in comparison with Bluetooth Classic. Its data rate is lower than its previous version, but it is widely used in health and sport sectors. Since Android API (Application Programming Interface) level 18, BLE is possible to be included and programmed in any Android device whose operating system is higher than the API mentioned before. In our case, the acquisition board works using BLE technology.

2.2. Transmission of data

The used OpenBCI bio-sensing board obtains EEG raw data from the electrodes that are connected to the pins of the board. A total of 4 channel can be registered. Every second it acquires data from the channels, whether they have an electrode attached to it or not. The board stores the samples retrieved from each channel in packets to later send it to the receiver using Bluetooth technology. It is stated that a total of 101 packets can be sent every second. Each packet has a size of 20 bytes, where the first byte is always used for assigning an ID to the packet.

Regarding the content of each packet, it varies depending on the configuration selected. For instance, it is allowed to use different encodings to compress the information to sent more data using the same amount of packets.

The first option given is to include raw data in each packet. Raw data is represented with 3 bytes, using Big Endian format, meaning that the most significant bit (MSB) is stored in the first byte. Taking into account that data from the 4 channels can be retrieved, only one sample per channel is included. From the 20 bytes available, 12 bytes are used for the raw data of all channels, leaving a total of 7 bytes without being used. This implies that only one sample per channel can be included in each packet. For this case only 100 packets are sent every second, leading to a transmission rate of 100Hz, equal to the sampling rate used for this configuration.

The encoding scheme used in the development of the project, which allowed to send more information, is called 19-byte delta compression.

To clarify the concept of 19-byte delta compression, first the delta encoding will be explained. This encoding allows to send all the acquired samples per second. Delta encoding is based on the storage of the difference between two successive samples of data [7].

The first sample, which will allow to decode the rest of data, is equal to the first value in the original stream, whereas the following values after encoding, named deltas, correspond to the subtraction of the previous sample to the actual value.

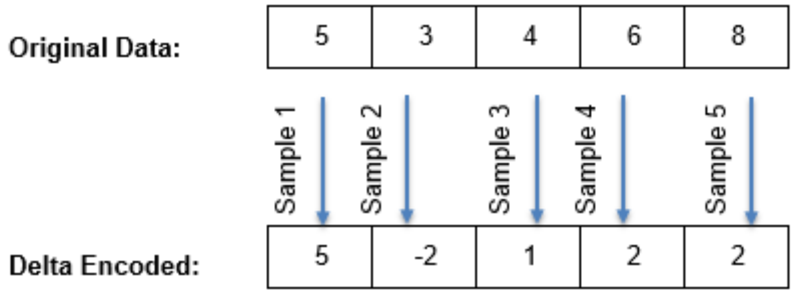

Figure 8. Delta Encoding

Once de Delta Encoding is explained, the reason why is called 19-byte is presented below:

Byte\bit (MSB first)	7	6	5	4	3	2	1	0
0	P	A	C	K	E	T	I	D
1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1
3	1	1	1	2	2	2	2	2
4	2	2	2	2	2	2	2	2
5	2	2	2	2	2	2	3	3
6	3	3	3	3	3	3	3	3
7	3	3	3	3	3	3	3	3
8	3	4	4	4	4	4	4	4
9	4	4	4	4	4	4	4	4
10	4	4	4	4	1	1	1	1
11	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	2
13	2	2	2	2	2	2	2	2

14	2	2	2	2	2	2	2	2
15	2	2	3	3	3	3	3	3
16	3	3	3	3	3	3	3	3
17	3	3	3	3	3	4	4	4
18	4	4	4	4	4	4	4	4
19	4	4	4	4	4	4	4	4

Figure 9. Scheme of 19-byte delta compression

Before explaining the compression, it is important to mention that the packets, as stated before, are represented by an ID, stored in the first byte. This first packet sent every second has ID 0, however the rest of packets, for this specific configuration, has ID from 101 to 200.

Firstly, the first packet sent every second, which has ID 0, gathers one sample of raw data from the 4 channels. These value are stored internally in the acquisition board to codify the following samples, using delta encoding.

Before sending the second packet, raw data is again acquired from the electrodes. Later, delta encoding is applied to these samples, using the previous samples. Afterwards, the raw data that was acquired is stored internally to keep track of the previous value, and also to apply the same encoding to the next samples retrieved.

The next step consists on only taking the 19 low significant bits(LSBs) from each of the obtained deltas; this is because the difference between two consecutive samples can be represented with less bits than 24, meaning that is not necessary to send redundant information. Once this operation is performed, the sign information from each delta is stored in the LSB of these final 19 bits corresponding to each delta, that way only a bit of resolution is lost.

As it is seen in the scheme above, each packet contains 2 samples from each channel. This means that the operation described above is performed twice. Only after all the operations are performed, the second packet is sent. To store the new data in the packet bit-wise operations are used, that way is possible to have information from different samples in the same byte, as seen in the scheme.

The board sends a total of 100 packets delta encoded, with IDs from 101 to 200. After the packet with ID 200 is sent, a new packet with ID 0 is sent again. That way, if for any reason there is a loss of packets, integrity of data can be ensured every second.

The decompression scheme implies to do the inverse process.

In this case first the values from the packet with ID 0 are stored to calculate the values from all the following packets. By the time the next packet arrives (with ID 101) the first step consists on retrieving the deltas from the packets. This implies using bit-wise operations to know the exact delta value. Once this operation is done for all channels, the next step consists on checking the sign information in the LSB. Depending on the value, 0's or 1's are appended to the most significant bit (MSB). Afterwards to recover the original 24 bits value, the addition of the previous channel value (for this example, the one with ID 0) is performed. This operation is performed until another packet with ID-0 is received, when a raw data sample is sent again. Like it has been stated before, that way it is assured that if any packets has been lost during transmission, you can recover the original signal without prolonging the error to all the samples.

To start the transmission, it is required to send an ascii 'b' from the portable device. If no more data is required to be received, then an ascii 's' is sent. Afterwards, the OpenBCI Ganglion sends a packet with ID 207, meaning that it is the last packet transmitted for that connection.

2.2.1. EEG data interpretation

As it is stated in [8], once the decompression is performed, it is necessary to apply a scale factor to the obtained value. The equation used to transform the analogic signal captured by the board to digital data values is described below:

$$Data\_CH_n = \frac{\Delta CH_n}{1.2V} * 2^{23} * 51 * 1.5 \qquad (1)$$

This is the equation applied before the packets are being transmitted

However, in the decompression scheme, where a volt value is required, the equation needs to be modified obtaining the following equivalence:

$$\Delta CH_n = \frac{Data\_CH_n * 1.2}{2^{23} * 51 * 1.5} [V] \qquad (2)$$

2.3. <u>Android and SDK</u>

Regarding the operative system chosen for connection establishment between the acquisition board and the portable device, Android is the only option available, mainly because Eduard Salgado is following the previous work of another student, who created the first prototype of part of the system using Android.

Moreover, a Fragment architecture is presented to stablish communication between the OpenBCI Ganglion and the tablet. The reasons why it has to be a Fragment is because it only represents a task during a certain period of time while the main Activity is executed, it is not necessary to have different activities when the intention of receiving data Is to be able to work with it in real-time.

This part of the project has been developed using Android Studio v3.1.1 targeting the API level 26 (codename Oreo). By choosing this SDK level in the assured that new devices can be compatible with the application.

Finally, the minimum API level needed to run the application is level 18. This is because the platform support for Bluetooth Low Energy, including all the libraries provided for its implementation, were added when API level 18 was released, allowing smartphones or this technology, but also connect to them to retrieve data.

2.4. Webpage Interface

A webpage interface is mainly divided in two parts, front-end and back-end. The front-end is basically all the elements that any user can directly see represented. However, the back-end is in charge of internal operations where the user has no direct access.

Nowadays many webpages are mainly developed in HTML and JavaScript. However, the actual trend is to use a prebuilt webpage for quick website creation. This implies that minor changes are done to deploy the website as soon as possible. Also, no coding knowledge is required.

The back-end of the web interface has been built using mainly PHP. PHP, defined as PHP Hypertext Preprocessor has been demonstrated to be a useful tool in terms of dynamic content. Considering the requirements for the web interface, using only another programming language would have limited the possibilities of data retrieval. The information from the surveys are safely stored in a MySQL database.

MySQL is a relational database which is faster and more reliable than any other relational database systems. It is defined as a client/server system, which means that it is possible to any client (for instance the users of the webpage) to indirectly perform any data query. The queries are normally programmed and executed when the user interact with certain element of the webpage.

Moreover, its configuration is intuitive, and it was possible to store the data since the very beginning due to its scalability. In addition, the table structure offered allows the data to be stored in order, allowing performing queries for retrieval of data for future analysis.

3. Methodology / project development:

3.1. Software

As it has been stated before, all the information provided by the SDK included in the API level 18 have been mainly used for the development of a simple interface to allow Bluetooth transmission. It included a set of tools and libraries to interact with the acquisition bio-sensing board.

Regarding the webpage interface at first it was necessary to configure an Apache Service, basically to interact with any developed page and manage the necessary web services. In this case, because a dynamic web page was needed, PHP was used as a programming language.

Finally, to store the information that was retrieved from the webpage an open source relational database was used(MySQL).

In early stages of the webpage interface, a captcha was added to increase the security of the platform. For this task, an external open-source known as

Securimage [9] was used. However, to simplify the execution of the final version of the webpage, this option was finally discarded.

To have a record of the used algorithm in both parts of the project, a *Github* account have been used. Due to the confidentiality of the code the repository has been set as private. Moreover, although it may seem as a difficulty for other members of the project to access to the different code developed, the fact of configuring it as a private is mainly to avoid the access from users outside the project. If the other members receive an invitation to collaborate then it is accessible for them

All the software used for developing this project did not imply an economical cost.

3.2. Hardware

The acquisition bio-sensing board used in this project is called OpenBCI Ganglion, it includes a radio module which works using BLE. All the testing had to be done in a Samsung tablet A7 10.1. Apart from being the only device available device, the main reason for this is since Eduard Salgado has developed the main application using a specific layout for tablet devices. If any other device was used for the development of this part of the project, by the time Bluetooth was added to the main application, some incompatibilities could have occurred.

For the web development a Personal Computer with Windows Operating System has been used.

3.3. Project Development

3.3.1. Web Interface

The idea behind the web interface was to elaborate an online survey to be easily accessible from anywhere. This basically allows a faster retrieval of data by accessing directly to the server where it was stored.

Since the very beginning it was thought to include multiple interpretations of neonatal EEG signal as alternatives to the visual method (cEEG traces visualisation), by assessing the quality and accuracy of these subjective and objective methods by non-EEG experts.

During the early stages of the interactive website the code was only written in HTML, which demonstrated to be inefficient for the required task. A dynamic web interface was thought to be implemented and HTML did not offer this opportunity by itself. Once a detailed planning of what the webpage should include was made, PHP was chosen as the main language programming. You can add HTML using PHP, but it also allows to be internal operations that the user does not really see.

The first prototype of the webpage was simple and mainly included 5 pages written in PHP. It was intended to be used as a web-portal to compare the accuracy between the visual method and a sonification method, where the audio samples were generated using the Phase Vocoder.

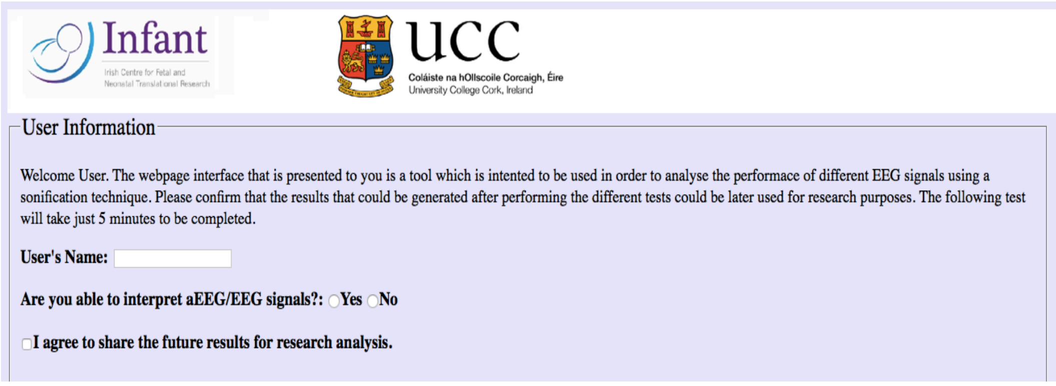

Figure 10.First Stage of the Webpage. Start page

The first page was mainly to retrieve some information about the user. Moreover, the next page included training samples. The idea was to let any possible end-user to have an idea about which were the characteristics of Seizure and Non-Seizure. The following two surveys where 10 questions of each method. The first test was randomly chosen, meaning that you could start answering random generated questions using the sonification method or the visual method.

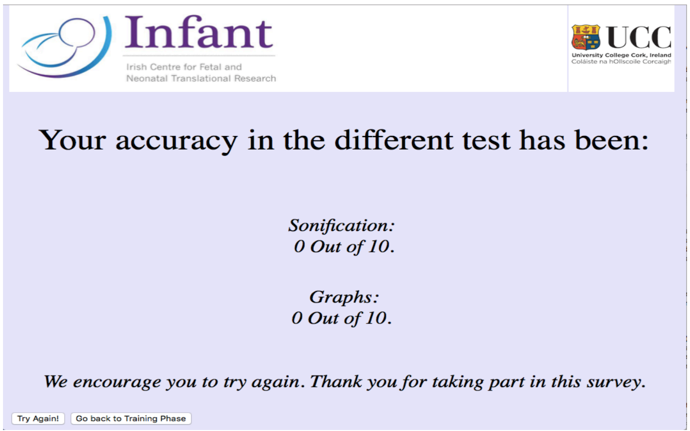

Figure 11. First Stage of the Webpage. Last page

The answers were submitted after the user answered all the 20 questions (10 in each part). The last question consisted on showing the users which the accuracy of his answers in each test was.

The database used to generate both images and audio files where obtained from NICU in CUMH.

As it is explained in [6], this database is formed by 100 seizures and 100 non-seizure segments, created on purpose for future study, using multichannel EEG from 18 new-borns patients, where even though having numerous seizures annotated, only a small percentage was annotated on a per-channel basis.

Moreover, a codification of the filenames was conducted. This was implemented to avoid users to download the different files to know which type of signal they were observing. The results would not have been realistic.

This version of the webpage was thought mainly to be used as soon as possible. Even though the back-end part was correctly implemented and no bugs where found during its deployment to the server, it was not user-friendly at all

In February another student, Montserrat Anglès was told to oversee the front-end part of the webpage, based on the advises that an expert in web design gave her. After different meetings to agree which should be the new elements to add to the website to make it more interactive the final stage of the interface was developed.

The concept changed completely, adding a new interactive way of doing the survey. This implied the creation of new functions to enhance the response from the user.

The next stage consisted in changing the structure to adapt it to the new requirements. First of all, instead of answering 10 questions in the same page in each of the surveys, the idea of showing only one question per window has been executed. Moreover, the user is supposed to answer as many questions as required in both tests, taking the survey as a game developed in html code by Montserrat Anglès.

Later the different elements corresponding to the front-end part, mainly the game, where included in the already built back-end.

Furthermore, the second test of the survey has been changed to include the probabilistic output generated by a CNN algorithm [5] and the audios generated with Phase Vocoder algorithm [3].

Having done this step, it has been necessary to assure that the data was correctly submitted to the database.

Some of the files that Montserrat created where needed to be changed to PHP, especially those extra pages that worked as link between the different stages. The reason behind this change is related with the fact that some information from the first pages needed to be stored in the database, but when using HTML files, this information was lost. Performing this change it is possible to keep the data stored in the session.

Once the different modifications were added, a final test was being carried to assure that the flow of the website worked perfectly and the queries to the database were correctly done.

The challenges that were found during the development of this part, are mainly related with the correct storage of survey responses in the database. Moreover

3.3.2. Bluetooth Communication

The idea behind the Bluetooth transmission was to stablish a wireless transmission between the acquisition bio-sensing board and a portable device, for instance a tablet.

This allows a freedom of movement for clinical personnel disposing of a real-time interaction.

The first stage of this part of the project was mainly used for learning. There was no previous knowledge in Android app development which implied that it was necessary to know the basics of Android first.

Once this learning step was done, a first prototype of the Android application was built, based on the specifications described in the SDK. For instance, the first prototype was a whole Android application divided in different activities. Each activity was used for different tasks, the first activity was used for discovery of new devices, whereas the second activity oversaw connection and data retrieval.

Once the connection was established, the decodification algorithm began to be developed.

As it has been previously stated, the packets were of 20 bytes, where the first byte corresponded to the ID of the packet, the packets were treated differently depending on its first byte value.

If the packet is of ID 0, the values corresponding to each channel were subtracted, and each one was stored in a Buffer of a fixed length. Afterwards, for every new packet with different ID the bytes were transformed to a binary string containing all the data received from the packet, to later select the corresponding 19 bits for each channel. The substring was transformed from 19 bits to 24 bits taking into account the value of the LSB, in order to append 0's or 1's whether it was a positive or negative value. Then the decoding was applied to the value by adding the value of the previous channel. The process was repeated and restarted every second, when a sample of ID-0 was received.

The first check only consisted on receiving all the packets, it was not checked if the decoding part was correctly done because it was expected to use a framework developed by Mark O'Sullivan.

The next step was to adapt the code to be easily used by Eduard Salgado, to implement it in the application that he was developing. Knowing that he was working with Fragments, and that the Bluetooth part could only be a part of the whole system, the code was changed to be understood as a Fragment instead of Activity. If this change was not made it would have affected to correct performance of the application.

This meant an update of the code, since many functions that can be used when working with an Activity, cannot be used when defining a Fragment, this is because the lifecycle of each element is different. Moreover, optimisation of the algorithm was performed to be able to work faster in the decoding part.

All changes where implemented in Eduard Salgado early stage interface to later be easy to include the Bluetooth part in the correct part of the code. However only the layout was maintained because it was only needed as a template for including the code.

The main optimization is seen in the way the received data is treated. In this case the packets with ID - 0 does not suffer any modification, and the subtraction of values form each channel is performed. Each value is then stored in an ArrayList. This element from the Object class allows to store data in an Array without specifying the length. That way, more samples can be stored to be used later if necessary.

Firstly, a Dialog Fragment was created to list all the possible devices which the user can pair in order to receive/send data. At first it was not working correctly but after some modifications in the definition of the fragment it was possible to detect nearby peripherals.

Once this part was stablished, the pairing and definition of the Bluetooth Service were added.

When the decodification was about to be included, it was seen that it was not working perfectly. Some specifications were unclear by the time it was needed to change the code to Fragment. Also, because everything was now included in one single Fragment in comparison with before were two activities where defined, some packages were lost.

After weeks struggling with the decoder it finally appeared to be working the way it must. It was seen that the algorithm presented an error with bit-wise operations.

To see if the data received it was mandatory to implement a Library which could allow real-data plotting. For this purpose and open graphic source known as *MPAndroidChart* was used.

Even though the code has been optimised it is seen that some loss of packages, mainly because of the interval connection stablished. Alternatives are thought to be implemented in future work.

4. Results

4.1. Bluetooth Transmission

Regarding the transmission of data, even though the decodification is done correctly, there exist loss of packets.

To test its correct performance, instead of trying with an EEG signal, a sine wave was generated using a function generator. With this experiment it was wanted to check that the input signal is equivalent to the output result. If EEG signal was used, it would not have been allowed to check this correspondence.

A sine wave of 1Hz and 20mVpp is sent from the function generator. However, the signal that is shown in the screen does not really correspond to the original one.

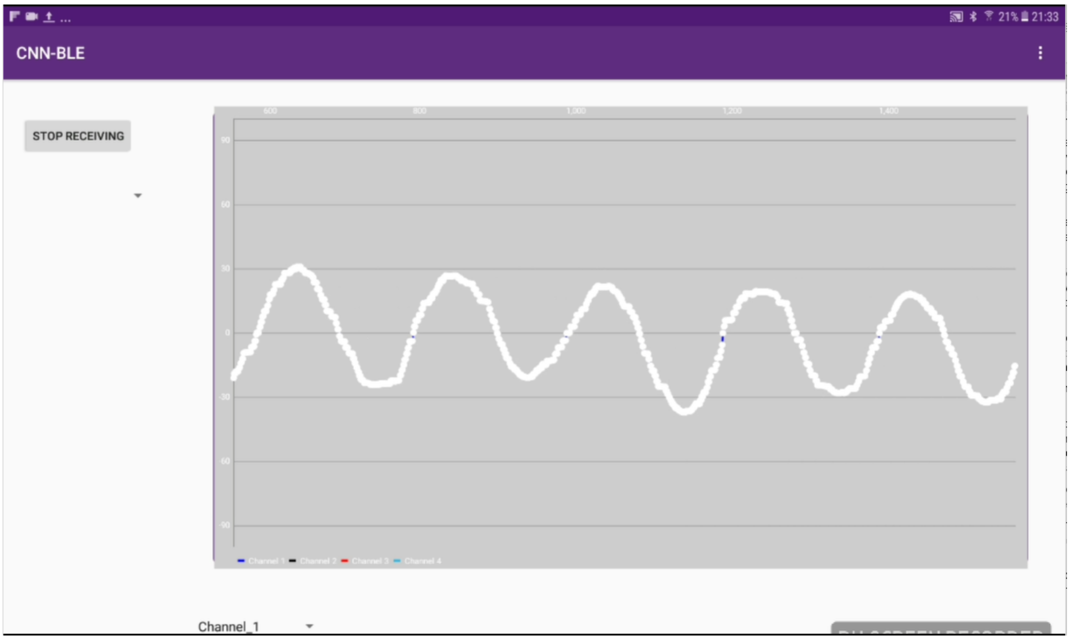

Figure 12. Data received from board in real time

This is mainly because of electric interference at 50Hz which leads to obtain a signal that does not fully correspond to the original one. Despite this issue, a sine wave is still visualised. A filter must be applied to avoid this interference.

In addition to this, it is seen that there is a packet drop. Although it may seem that the packet drop is represented in the points that is shown a gap between two consecutives values, probably to packet loss occurred before. Because of the delta compression, the error is dragged until a new packet with ID-0 is received.

The decoding, as stated, works correctly, the errors that are found correspond to external issues related mainly with the Bluetooth Service and the interval of connection.

The power consumption of the connection, one of the requirements of the project, was proven in [1] to be low in comparison with the CNN.

However, in that case the connection between the tablet and the OpenBCI was being done using a single application for that purpose.

In later work the consumption of power usage can be again calculated when the whole system is integrated in only one application.

4.2. Webpage interface

Regarding the webpage interface, the data has been proven to be stored correctly. In the image below there is a representation of the database.

+ Options

←T→	SessionID	File ▲ 1	ExpertiseFlag	Results	TestNumber	GT	Date
Edit Copy Delete	8hbvdmgkn1ocfijfd2ugbvq0l1	002	0	1	1	0	2018-05-08 11:11:25
Edit Copy Delete	ric9afmql5u6estvb7c96amhg0	003	0	0	1	0	2018-05-08 11:25:28
Edit Copy Delete	c449oqa8m5lpum3439er1mjrj7	003	0	0	1	1	2018-05-08 22:00:22
Edit Copy Delete	c10eirjt90c75ch261kv70hep6	004	0	1	1	0	2018-05-06 22:42:25
Edit Copy Delete	8hbvdmgkn1ocfijfd2ugbvq0l1	005	0	1	1	0	2018-05-08 11:12:02
Edit Copy Delete	nt5mbbguia27q6p2rfd7cutaq6	006	0	1	1	1	2018-05-08 12:14:48
Edit Copy Delete	8hbvdmgkn1ocfijfd2ugbvq0l1	007	0	1	1	0	2018-05-08 11:11:17
Edit Copy Delete	8hbvdmgkn1ocfijfd2ugbvq0l1	007	0	0	1	1	2018-05-08 11:11:35
Edit Copy Delete	nt5mbbguia27q6p2rfd7cutaq6	008	0	0	1	0	2018-05-08 12:14:11
Edit Copy Delete	8hbvdmgkn1ocfijfd2ugbvq0l1	008	0	1	2	0	2018-05-08 11:15:30
Edit Copy Delete	c449oqa8m5lpum3439er1mjrj7	009	0	1	1	1	2018-05-08 22:02:01
Edit Copy Delete	nt5mbbguia27q6p2rfd7cutaq6	009	0	1	2	1	2018-05-08 12:15:45
Edit Copy Delete	c10eirjt90c75ch261kv70hep6	009	0	0	1	0	2018-05-06 22:45:54
Edit Copy Delete	8hbvdmgkn1ocfijfd2ugbvq0l1	009	0	0	1	0	2018-05-08 11:11:57
Edit Copy Delete	c10eirjt90c75ch261kv70hep6	010	0	0	1	1	2018-05-06 22:43:27

Figure 13. Database with information stored from surveys

The fields that have been defined in the database allow to retrieve data easily. Although it has been not possible to quantify the assessment from non-end users, it is thought to be conducted in future works.

5. Budget

For this budget it will only be taken into account the cost per hour of the personnel and the Hardware used to develop the project. The energy cost of the actual workplace will not be included, mainly because the workplace corresponds to a university, making it difficult to know the exact consume of energy.

The average salary of a Junior Software Engineer in Cork, Ireland is, at the time of writing, €28,930 per year. The number of hours dedicated to this project is approximately 8h per day during 5 days per week in a total of 5 months, which makes a total of 800h.

Regarding the acquisition board, the price corresponds to €200. In addition, the tablet, model Samsung Galaxy Tab A7 has a cost of €199. Moreover, the computer is estimated to cost approximately 1000€.

Device	Units	Price per unit(€)	Total Price(€)
OpenBCI Ganglion	1	200,00	200,00
Android Software	1	0	0
Portable Device, tablet	1	199	199,00
Computer	1	1000,00	1000,00
Website cost	1	10/year	10
			1409,00

Table 2 Detailed Price of Items used in Project

Personnel	Quantity	€/hour	Total €
Junior Engineer	1	13,698	10958,33

Table 3. Salary of a Junior Engineer in Cork, Ireland

The software does not imply any cost, basically because the information given by OpenBCI Ganglion is accessible to everyone. Moreover, the software used for implementing the Android app is free to use.

Regarding the webpage interface, at first there was no cost because it was hosted in the university servers. However, the last version of the webpage is hosted in an external server. For this reason, the host price is included.

6. Conclusions and future work:

In this project, different functionalities have been developed for the production of a neonatal brain stethoscope.

First, an interactive web interface has been developed to assess the detection of neonatal brain injuries by the users. Concerning that, the anonymity of the information has been proven, not only with the codification of the files, but also because no personal information from the user is gathered. It also fulfils the requirements from clinical personnel.

The webpage was disseminated among the attendants of the recent Pediatric Academic Societies Meeting that took place in Toronto in May 5-8th. Unfortunately, few responses were gathered. Therefore, it has not been possible to reliably quantify the accuracy of the detection using the newly developed tool. As my work in Infant Research Centre will continue during the following months I expect to be able to carry out that statistical quantification.

However, since the webpage is already developed, if any change is required, the amount of necessary time needed to update it will be minimal. For example, the current sonification method can be easily replaced by alternative techniques.

Secondly, a connection has been established between an acquisition board and a portable device using Bluetooth Low Energy (BLE). This allows to wirelessly receive and store in real time the EEG signals that come from the electrodes attached to the acquisition board. Not only connection but decoding of the packets was necessary to obtain data to work with in later stages of the system.

However, as it has been stated, there is some packet loss. This is not related with the Bluetooth transmission itself, but with the Android operating system and the characteristics of the tablet. Fixing this issue will be the main priority in my future work in the research centre.

WP3, which was defined as the development of a robustness system for EEG signals, is an important block that needs to be added to the prototype. It will not only assure that the received signals are EEG (not noise) but also it will prevent the storage of data which can somehow be corrupted. Future work includes the development of a DSP algorithm for that purpose.

Some of the planned tasks were not completed, but the extension of the contract in the hosting institution until the end of July will suppose an opportunity to finalise these tasks and continue working with different aspects of the project.

The results of the Bluetooth transmission stated in this project are reflected in the abstract *"Neonatal Brain Stethoscope: Design and validation of a low-cost EEG acquisition & interpretation system prototype"*, which will be presented in The 7th Congress of the European Academy of Paediatric Societies (EPAS 2018), and also in the conference paper *"Neonatal EEG interpretation and decision support framework for mobile platforms*", which will be presented in the 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEEE EMBC 2018), both already accepted.

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Appendix 1:

Work Packages and Milestones

Work Packages:

Project: Neonatal EEG sonification for discriminating brain injuries	WP ref: 1
Major constituent: Wireless connection	
Short description: Implement the necessary code to connect the EEG signals acquisition system with a portable device.	Start event:27/11/2017 End event: 07/03/2018
Internal task T1: Analyse configuration needed in order to connect acquisition board with tablet computer, being able to send the information optimally. **Internal task T2**: Study software development in android. **Internal task T3:** Develop simple android application taking into account IT1. **Internal task T4**: Stablish wireless connection between both elements of the final system. **Internal task T5:** Decode packages from acquisition board to get the values of the different EEG channels. **Internal task T6:** Check that no information is lost during the wireless connection. **Internal task T7:** Change structure of algorithm to work with fragments instead of activities (Android). **Internal task T8:** Create a DialogFragment to Include all detected devices using the Bluetooth system. **Internal task T9:** Interact with selected device and allow communication between them. **Internal task T10:** Store information in buffer to later show values using Graphic methods.	Although many of the tasks have been already done, it is important to include the task that during the project plan presentation were not included. Because of these additional tasks, the amount of time spent developing this part has increased considerably. Apart from that, the only thing left is to assure that the information is correctly stored, which should not take longer than 2-3 days.

Project: Neonatal EEG sonification for discriminating brain injuries	WP ref: 2
Major constituent: Assessment of results from Web Interface	
Short description: Finalise web interface development to make it user friendly and understandable and assess discriminability of various sonification algorithms. Finally, Integrate the best sonification technique in the web interface to analyse the experience of personnel in the NICU.	Start event: 07/03/2018 End event: 04/05/2018
Internal task T1: Obtain feedback after expert in usability and Montserrat Anglès know which changes may be done. **Internal task T2**: Add the necessary changes to make the web interface user friendly and understandable. **Internal task T3:** adapt code developed by Montserrat Angles from HTML to PHP. **Internal task T4:** Obtain another feedback to know if these changes were useful and if more changes are needed to be performed. **Internal task T5:** Assess results from possible surveys that may be performed to select optimal sonification technique. **Internal task T6:** Include optimal sonification algorithm to allow personnel in the NICU to test a different way of detecting seizures. **Internal task T7:** Assess results from clinical end users.	The whole work package is thought to be done after work package 2. However, it is known that the first internal task will have to be done while work package 2 is in progress. New internal tasks have been added since Montserrat Anglès will work in collaboration with experts in a usability study. After this study is done, many changes have been done to enhance user-s experience. Another feedback may be necessary afterwards, and the following changes will be applied to the webpage to finally see the response from clinical end users.

Project: Neonatal EEG sonification for discriminating brain injuries	WP ref: 3
Major constituent: Robustness EEG signals	
Short description: Develop an algorithm to assure that the registered signal is purely EEG without containing any kind of artefacts which could difficult the later analysis	Future Work
Internal task T1: Generate EEG signals with different artifacts to represent a real case scenario. **Internal task T2**: Develop algorithm in Matlab to process signal acquired to get some features which could help with the filtering of signals. **Internal task T3:** Adapt the code to Java language to include it as a part of the main android application. **Internal task T4:** assure that the code works correctly using skin impedance simulator to test different electrodes that a student has developed.	The deliverables have completely change in this case but are correctly updated below in the Milestones table. Moreover, the processing part is thought to take most of the time due to its importance to assure that an optimal system is developed.

Milestones

WP#	Task#	Short title	Milestone / deliverable	Date (week)
1	1	Configuration acquisition board	Study different configurations acquisition board	29/11/2017
1	2	Background Android Study	Software development in Android study	15/12/2017
1	3	Simple Android Application	Detect devices via Bluetooth from the portable device	12/01/2018
1	4	Bluetooth Connection	Stablish wireless connection between acquisition board and portable device	19/01/2018
1	5	Decode received packages	Get values of the different EEG channels of the acquisition board	24/01/2018
1	6	Avoid loss of information	Check that no packages are lost during transmission of information	26/01/2018
1	7	Change structure of algorithm	Build the algorithm as a fragment instead of an activity.	23/02/2018
1	8	Create a DialogFragment	Create a DialogFragment to store all the detected devices	02/03/2018
1	9	Interact with acquisition board	Allow the receiving of packages and decode information correctly	02/05/2018
1	10	Avoid loss of information in final version	Assure that no packages are lost during the connection between acquisition board and portable device	For future work
2	1	Feedback from expert in usability	Add changes to webpage interface based on the opinion of the expert	23/03/2018
2	3	Adaptation of code from Montserrat Angles	Change code from HTML to PHP	24/04/2018

2	4	Final feedback and adding of minor changes	After previous changes applied, get feedback from different users to apply minor changes.	29/04/2018
2	5	Assessment of results for quantifying optimal interpretation technique	Analysis of results from different interpretation techniques	For future work
2	6	Include optimal sonification algorithm	Include optimal sonification algorithm in webpage for last surveys	For future work
2	6	Assessment of results from clinical end users	Analysis of results from the optimal sonification algorithms	For future work
3	1	Simulation of EEG signals with artefacts	Generate artificial EEG signals with artefacts to	For future work
3	2	Development of small algorithm in Matlab	Develop code to process artificial signals and be able to extract features which could help to filter them	For future work
3	3	Adaptation of code to Java language	Include final algorithm in the main android application	For future
3	4	Assure robustness works as expected	Make sure that the algorithm registers and stores those EEG signals without artefacts.	For future work

Glossary

- EEG: Electroencephalogram
- CNN: Convolutional Neural Network
- SDK: Software Development Kit
- APK: Android Application Package
- BLE: Bluetooth Low Energy
- LSB: Low Significant Bit
- MSB: Most Significant Bit