A Device Supporting the Self Management of Tinnitus

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Abstract. Tinnitus is an annoying ringing in the ears, in varying shades and intensities. Tinnitus can affect a patient's overall health and social well-being (e.g., sleep problems, trouble concentrating, anxiety, depression and inability to work). Usually, the diagnostic procedure of tinnitus passes through three steps, i.e., audiological examination, psychoacoustic measurement, and disability evaluation. All steps are performed by physicians, by using dedicated hardware/software and administering questionnaires. The paper reports on the results of a one-year running project whose aim is to directly support patients in such a diagnostic procedure by using a specific device and their smartphone.

Keywords: Tinnitus · APP · Device · Audiometry · Acufenometry

1 Introduction

Tinnitus is commonly known as a complex of annoying ringing, buzzing or hissing in the ears, in varying shades and intensities [5]. It can affect a patient's overall health and social well-being at different levels, from sleep problems, trouble concentrating, anxiety, up to ongoing depression and inability to work [3,10]. Usually, the diagnostic procedure consists in three main phases, i.e., diagnosis and accurate audiological examinations, psychoacoustic measurement of tinnitus, and evaluation of disability. All phases are performed by physicians, by using dedicated and complex hardware/software and administering questionnaires.

The paper reports on the first results of a one-year and on going project whose aim is to directly support in such a diagnostic procedure. In particular, the paper describes an hardware device that can be connected to a smartphone/tablet, able to execute (a part of) the procedure to diagnose tinnitus, as controlled by a dedicated APP that automates both the execution of the examinations and the administration of the questionnaires that measure the disability induced by tinnitus.

The novelty of our project is that it directly addresses patients instead of health professionals and provides an integrated tool (hardware/software) able

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to perform the audiological and psychoacoustic measurements as well as the evaluation of disability. It is worth remarking that devices controlled by smartphone/tablet APPs are not common and only available to physicians (see, e.g., [7,13] for devices concerning the audiological examination).

The paper is organized as follows. Section 2 introduces the necessary background on tinnitus, its clinical evaluation for measuring the impact of tinnitus in different aspect of quality of life. Section 3 describes the ad-hoc developed hardware device, in terms of its hardware and firmware. Section 4 briefly discusses the APP and how the automated examinations are implemented. Finally, Sect. 6 ends the paper.

2 Background

2.1 Tinnitus

Several definitions of tinnitus are available from the scientific literature. According to Del Bo et al. [5], "[...] tinnitus are sound sensations perceived by the individual, not supported by external sources, acoustic or electric, and acoustic apparatus caused by their activities or by alterations of the mechanisms of sensory processing [...]".

Tinnitus can affects a patient's overall health and social well-being [10]. Even moderate cases can interfere with the ability to work and socialize. The American Tinnitus Association (ATA) conducted a survey of its membership in 2014, to evaluate how ATA members experience tinnitus. Over 1100 people responded to the survey: the majority (about 36%) were annoyed of tinnitus (without a significant impact on life quality) or barely noticed it; others reported on sleep problems, trouble concentrating and anxiety (18%, 16% and 13%, respectively); the remaining – with smaller percentages – reported on social isolation, ongoing depression and inability to work [3].

The subjective nature of the disorder and the limited knowledge of the pathophysiology render extremely problematic the systematization of tinnitus. The classification is therefore an open question, nevertheless in recent years have been proposed "operational" approaches that takes into account the most relevant clinal features as those aspects that have the greatest impact on the quality of life of the subject [4]. Objective tinnitus can be heard by the examiner [9] and can be generated from vascular, muscular or respiratory sources and also from the temporo-mandibular joint. On the basis of the most recent acquisitions, a more detailed "pathogenic" classification for subjective tinnitus was proposed: (i) *Conductive* in case of myocardial twitch of the middle ear or disturbance of tubal ventilation; (ii) *Sensorineural* when we have an anomaly in the inner ear or sensory organ (cochlea and associated structures), vestibulocochlear nerve (cranial nerve VIII) or neural part; and, finally, (iii) *Central* when in presence of primary intracranial tumours, multiple sclerosis, traumatic brain injury and closed secondary "ghost sound".

2.2 Clinical Evaluation

Usually, the diagnostic procedure includes the following three main phases:

1. Diagnosis and accurate audiological examinations performs through an Audiometry (see Subsect. 2.3) and others like Tympanometry and Otoscopy (that are not used in our approach);
2. Psychoacoustic measurement of tinnitus by means of an Acufenometry (see Subsect. 2.4).
3. Evaluation of disability through Questionnaires (see Subsect. 2.5). Together with the previous, this is a further important phase, since it allows to identify patients that are seriously invalidated by the tinnitus [1,16].

2.3 Audiometry

In order to clearly understand how it is performed an audiometry test, it is necessary to introduce some definitions about pure tone, frequency and intensity (loudness). A pure tone is a sound having a single specific "frequency" which is a scientific term to describe a specific aspect of a signal [15]. Intensity of the pure tone is considered the loudness of the sound and is measured in decibels (dB). By far, the most common dB scale used in audiology is the dB HL scale. This scale is referenced to the average hearing of young adults, where "0 dB HL" means the average threshold of audibility of normally-hearing young adults.

Then, the state of the art describes three types of audiometries, as follow:

- Pure Tone Audiometry (PTA) is the procedure that uses pure tones to assess an individual's hearing. Pure tones are generated at different frequencies and intensities by an audiometer and presented to the patient via headphones or, in some cases, through loudspeakers. Depending on the transducer through which the stimuli is presented, the audiometry can be either air-conducted or bone-conducted, detailed below.
- Air Conduction Audiometry (ACA) is defined as the test for assessment the hearing of sound wave travelling through air. This mode of signal presentation assesses the entire auditory system [15]. The general method for air conduction pure tone audiometry goes as follows. The patient is instructed to listen carefully for a beeping sound (pure tone): when heard, even if very softly, he/she is asked to raise the hand. The intensity (loudness) of the tone in each frequency is decreased gradually, until the patient no longer responds. This routine is repeated for all test frequencies in both ears. The Lowest Audible Intensity (LAI) is then defined as the patient's threshold for the particular frequency. Such a procedure then establishes an air conduction pure tone threshold curve for each ear called audiogram. If there is any degree of hearing loss measured at any frequency in either ear, bone conduction pure tone testing must be performed [2].
- Bone Conduction Audiometry (BCA) testing stimulates the cochlea directly, bypassing the outer and middle ear. Bone conduction pure tone audiometry is performed using process as in air conduction audiometry, but the tones

are presented via a bone conduction headset [2]. This type of testing is used to determine whether a hearing lost is reflective of a cochlear/neural deficit (call "sensorineural" [15]) or an outer/middle ear dysfunction ("conductive"). If bone conduction thresholds indicate a hearing loss but one which is less severe than is indicated by air LAI, the loss is termed a "mixed" hearing loss.

2.4 Acufenometry

As mentioned earlier, acufenometry is performed to determine frequency and intensity of the tinnitus. First, the determination of the frequency of the tinnitus is carried out by asking the patient to compare the frequency of a test-sound (i.e., a pure tone) with that of the tinnitus. Two tones are presented alternately to both ears while the frequency is changed (increased or decreased) until the patient finds out the one closest to the tinnitus. Then, the determination of the intensity is instead established by means of the comparison between the test-sound with tinnitus. A pure tone at the previously identified frequency is firstly sent at subliminal levels to the other side ear. Then, the intensity is increased until the patient hears it. In this way the "threshold of perception" of a signal is established and taken as the reference level of 0 dB.

2.5 Questionnaires

Some questionnaires can be distinguished to help in the diagnosis of tinnitus. Most common ones are presented below:

- Pittsburgh Sleep Quality Index (PSQI) is a self-administered questionnaire which assesses sleep quality and disturbances over a 1-month time interval [14]. It is made up nineteen individual items that measure seven domains: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction over the last month.
- Khalfa Hyperacusis Questionnaire (Khalfa) is a tested and validated tool, suitable to quantify and evaluate various hyperacusis symptoms. It is made up of 14 questions, each with four possible answers ("no", "rarely", "often" and "always"). The scoring procedure yields to a total score and 4 grades of tinnitus [8].
- Tinnitus Handicap Inventory (THI) [11] is a self-administered questionnaire to evaluate the impact of tinnitus on the quality of life. It is made up of 25 questions, each with 3 possible answers ("no", "sometimes" and "yes"). According to the scores THI determines a grade (up 5) of severity.

3 The Device

3.1 The Electronics

A device responsible for generating the pure tone associated to the audiometry and acufenometry processes was designed and developed for this project. The

device is composed of a set of components as seen in Fig. 1 and they are described as follow:

- USB Connector -FTDI232- is the component that converts between USB and TTL serial protocols. This component permits to establish the communication between the device and the smartphone.
- Microcontroller Unit (MCU) -ATMEGA328P- is an 8 bits monocomponet of AVR-family. It is where the firmware is execute and it controls the rest of components.
- Signal Generator -AD9850- is a DDS wave generator that generates sinusoidal waves of 1 Vpp and programmable phase by means of serial/parallel protocol.
- Digital Potentiometer -MCP4551- which includes a volatile memory and I2C interface to control the volume. Its function is to attenuate the sinusoidal signal in order to control the level of intensity of the tone.
- Air/Bone Amplifiers -TPA2012- are a D class stereo amplifiers of 2 channels of 1.5 W and 8 Ω. It has 2 digital inputs to adjust output gain from 6 dB to 24 dB.

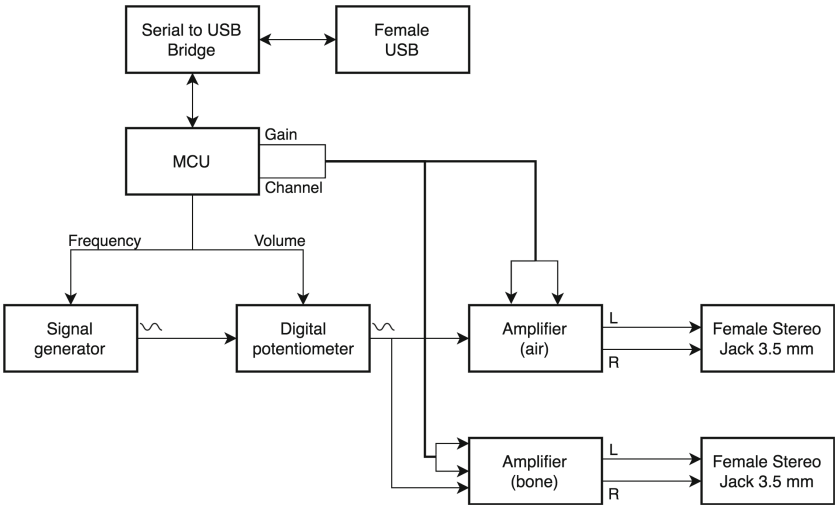

Fig. 1. Device block diagram. This device is able to perform air and bone audimetry.

When the device has to generate a pure tone signal with a given frequency and intensity, the MCU indicates the frequency of the sinusoidal signal to the signal generator module. The signal then passes through the digital potentiometer module, whose resistance is established according to the intensity indicated by the MCU. The output of the digital potentiometer is the input signal modified as to reach the volume.

The resulting signal is then sent to the amplifiers. There are two amplifiers: one associated to air mode and another one associated to bone mode. The amplifier for the selected mode (air or bone) amplifies the signal according to the gain indicated by the MCU; this signal is then sent to the selected channel (left or right), while the remaining channel receives a muted signal. The output is directed to a female stereo jack 3.5 mm module, which is connected to the corresponding headset. The two different and programmable amplifiers are present so to enable the device to be used with different headsets.

This hardware device connects as a peripheral to the patient's smartphone by using the USB On-The-Go (OTG) connection. Thanks to that, the device does not need its own battery, which is itself a cost-reducing benefit, but still maintains its characteristic of mobile device. This is a valuable advantage of the device with respect to common audiometers.

The connection also serves to provide the device with the information required to generate the corresponding signals received from the APP. Between the USB and the MCU there is a Serial to USB bridge that allows two-way communication, similar to a serial port, which facilitates communication between the two devices.

3.2 The Firmware

The firmware is executed by the MCU (ATMEGA328P as explained before) which is compatible with the Arduino bootloader, so the firmware has been implemented using Arduino. The firmware structure is described by the state diagram shown in Fig. 2.

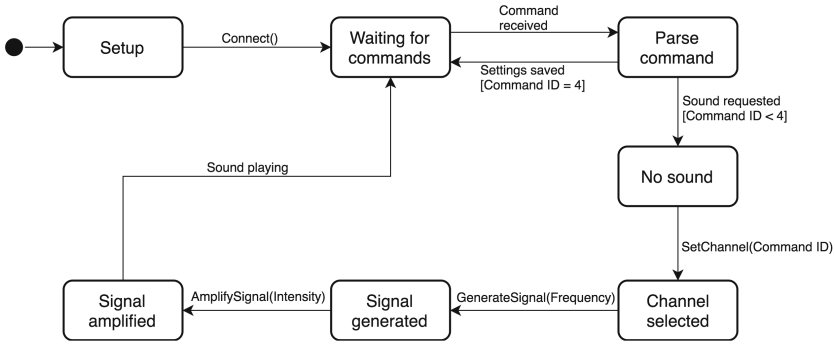

Fig. 2. State diagram of the firmware operation. The device is controlled by the Smartphone

Initially, a preliminary configuration establishes the default settings and mute the device, which continues to wait for a serial communication coming from the smartphone. Once connected, the device enters a state of "Waiting for commands", which finishes when a command sent from the smartphone is received.

Table 1. Command list

ID	Command	Arguments
0	Air-left channel	Frequency: 125–8000 Hz Intensity: 0–125 dB
1	Air-right channel	
2	Bone-left channel	
3	Bone-right channel	
4	Settings	Air mode offset (0–128) Bone mode offset (0–128) Air mode steep (0–128) Bone mode steep (0–128)

Then, the command is parsed and analysed to determine the action to take. All possible commands are described in Table 1. There are 5 possible commands that the firmware can read as shown in Table 1.

3.3 Mechanical Part

We have designed an adapter that integrates both the headphones and a bone conductor, making its use easier and more user-friendly. As you can see in Fig. 3, there are two hinges on each side that adapt the bone conductor to the back of the user's skull.

Fig. 3. Mechanical part design and integration with headphones. 3D rendering (left and centre) and real picture (right).

Both the headphones and the bone conductor have their own male 3.5 mm jack connectors, which are connected to the designed electronic device. The position of each connector is indicated in the device case, as shown in Fig. 4.

Fig. 4. Electronic device connected to the headphones and bone conductor.

4 The APP

The APP includes the functionalities that are needed for the clinical evaluation described in Subsect. 2.2. Therefore, the APP takes advantage of the device described in Sect. 3 to implement the automated audiometry (Subsect. 4.1) and acufenometry (Subsect. 4.2). Furthermore, the APP proposes and automatically scores the questionnaires for sleep quality, hyperacusis and the impact of tinnitus in life (Subsect. 4.3). The APP is available for smartphones and tablets running Android 5.0 and above. It is written in Java using Android Studio, and is freely available for download[1].

4.1 Automated Audiometry with Reporting

The APP implements the process described in 2.3, for both air and bone conduction audiometry, with the following two exceptions: (i) the patient touches a button placed in the centre of the smartphone when he/she hears the sound; (ii) the decrement/increment of intensity is not performed. It is worth remarking that such a step is present in process so to ensure that the intensity level reported by a patient was actual and that the patient was not "cheating" to the physician. In our case, since the APP is autonomously used by a patient, such a step was considered unnecessary. The process returns a matrix of intensities, i.e., when the patient heard the sound, for both ears, for both ways (i.e., air and bone), for all investigated frequencies, that is given in input to an automated audiometric reporting procedure. Then, the automated audiometric reporting procedure works as follows: initially, for both ears and all investigated frequencies, recalls the intensities; then, deduces the type of problem and its severity; hence, sums up all such information in terms of frequencies ranges, i.e., low frequencies

[1] http://vittorini.univaq.it/tinnitus/.

(125 Hz, 250 Hz, 500 Hz), medium frequencies (1 KHz, 2 KHz), and high frequencies (3 KHz, 4 KHz, 6 KHz, 8 KHz); finally decides the location of the problem. Figure 5-(a) shows the results of the automated audiometry and reporting.

4.2 Automated Acufenometry

The APP implements the acufenometry described in Subsect. 2.4, without detecting the "threshold of perception" level. Figure 5-(b) shows the interface used to perform the acufenometry: the switches placed on the top can be used to select which ear has the tinnitus, the horizontal/vertical arrows change the frequency/intensity of the tinnitus, while the central button can be tapped to confirm that the emitted sound actually resembles the tinnitus.

4.3 Questionnaires

The PSQI, Khalfa and THI questionnaires are implemented and automatically scored in the APP. A simple ad-hoc XML document defines and enable the APP to show the questionnaires. The document allows to define:

1. the possible variable types used in the questionnaire, as a specialization of numeric, time and categoric types;
2. the list of questions placed in the questionnaire, their types and if required or optional.

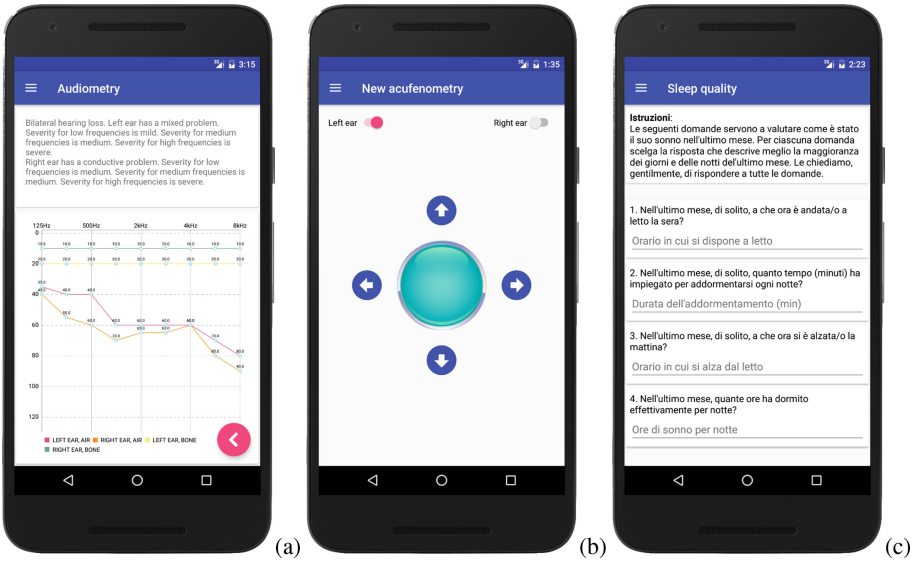

Fig. 5. Snapshots of (a) an audiogram with the automated reporting, (b) an acufenometry in progress, (c) the PSQI

The APP automatically scores the questionnaires and returns in a simple format the results. Figure 5-(c) shows the case of the PSQI questionnaire.

5 Preliminary Results

As preliminary results, we started investigating the APP usability [12]. Since our project was in its first release, coherently with the state of the art, we decided to ask to one usability expert for an heuristic evaluation to generate the initial number of potential usability problems. The expert used a check-list specifically designed to evaluate mobile interfaces, that reuses 69% of literature heuristics, the rest deriving from best-practices and recommendations for mobile

Table 2. Expert-based evaluation result

Item	Score
Visibility of system status	
System status feedback	2
Location information	*NA*
Response times	2
Selection/input of data	1
Presentation adaptation	*NA*
Match between system and the real world	
Metaphors/mental models	1
Navigational structure	2
Menus	2
Simplicity	2
Output of numeric information	*NA*
User control and freedom	
Explorable interfaces	0
Some level of personalization	*NA*
Process confirmation	1
Undo/cancellation	0
Menus control	2
Consistency and standards	
Orientation	1
Design consistency	2
Menus	2
Input fields	2
Naming convention consistency	2
Menu/task consistency	2
Functional goals consistency	1
System response consistency	2
Error prevention	
Error prevention	1
Fat-finger syndrome	1

Item	Score
Recognition rather than recall	
Memory load reduction	2
General visual cues	1
Input/output data	2
Menus	2
Navigation	2
Flexibility and efficiency of use	
Search	1
Navigation	2
Aesthetic and minimalist design	
Aesthetic and minimalist design	1
Multimedia content	1
Icons	2
Menus	2
Orientation	2
Navigation	2
Help and documentation	
Help and documentation	1
Help users recognize, diagnose and recover from errors	0
Skills	
Skills	0
Pleasurable and Respectful interaction	
Pleasurable and respectful interaction	1
Input data	1
Shopping	*NA*
Banking and transaction	*NA*
Privacy	
Privacy	*NA*

interfaces [6]. Such a check-list requires, for each heuristic, to give a score ranging from 0 to 2, where the higher the score, the better the usability (in terms of that heuristic). Table 2 reports the results.

In summary, the median value is 2, i.e., a good usability, with an average of 1.4. We also collected verbose suggestions from the expert, that proposed us to (i) add a clear back/undo button, (ii) more clearly show the goals of each functionality (i.e., audiometry, acufenometry and questionnaires), (iii) implement a font scaling feature[2], (iv) add a search facility, even if it may be not necessary given the shallow navigational structure. These suggestions will be taken into account in the next release of the APP.

6 Conclusions

The proposed usage model, where the device is connected to the users smartphone, has allowed to obtain a low-cost device that includes really powerful functionalities. Although the presented device is only the first prototype, it has been used to evaluate all the parts of the system. It has successfully helped to determine the final configuration to use in an integrated board, with the same electronic components but with smaller size.

As for APP, besides the usability investigation, we also started evaluating also the quality of the automated audiometric reporting procedure, by comparing its results with human reporting. In our preliminary investigation, all the automated audiometric reporting were correct, few of them were even more detailed than the human ones. Beside that, a possible improvement in the automated reporting came out: an audiometry showing a problem only for one frequency is usually reported as an "acoustic hole". Since such a wording is not provided by the APP, it will be added in the next release.

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