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RESEARCH ARTICLE - ENGINEERING (MISCELLANEOUS)

A Low-Resource Hearing Testing Device: An Arduino-Based Audiometer

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Abstract

This paper describes the development and testing of an Arduino-based audiometer for measuring ten levels of sound generated by a speaker. The device uses an Arduino UNO platform and includes an OLED display, a MAX7219 matrix LED, and a push-button for the person being tested to indicate when they hear a sound level. The results showed that the device could accurately measure sound levels and provide a reliable measure of hearing sensitivity. Arduino-based audiometers have several advantages over traditional audiometers, including low cost, portability, and customizability. However, the accuracy of these devices compared to traditional audiometers is still an area of concern, and further research is needed to validate their use in clinical settings. This paper contributes to the growing body of literature on the development and validation of Arduino-based audiometers and demonstrates the potential of these devices to provide an affordable and accessible way to diagnose hearing loss.

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Keywords: Arduino; Portable Audiometer; Hearing Testing; Healthcare Technology; Electronic Medical Devices.

1. Introduction

Hearing loss is a widespread problem, affecting over 5% of the world's population, and the numbers are expected to increase in the coming years due to an aging population and increased exposure to noise pollution [1]. Early detection and intervention can significantly improve outcomes for individuals with hearing loss, making hearing testing an essential part of healthcare. However, traditional audiometers can be expensive, bulky, and not readily accessible in many areas, especially in low-income countries or rural regions. Therefore, there is a need for affordable and accessible hearing testing devices.

One possible solution to this problem is using Arduino-based devices for hearing testing. Arduino is a popular open-source platform that allows for the creation of inexpensive and customizable electronic devices [2, 3]. Arduino-based audiometers developed in recent years are low-cost, portable, and easy to use. These devices use various sensors to measure sound levels and are often coupled with software to analyze and display the results.

This paper presents an Arduino-based audiometer that measures ten levels of sound generated by a speaker and uses a 0.96" OLED 4 pins display [4], and MAX7219 matrix LED [5, 6] to show these levels. A push button records the person's response to each level of sound. When the test is complete, the device shows the person's results on the display. The device is low-cost and easy to use, making it an accessible alternative to traditional audiometers. This study contributes significantly to the field of low-cost, easy-to-use audiometers, which can be used in remote and underserved areas through the following points:

- It has successfully developed a low-resource audiometer using the versatile Arduino platform. This design significantly reduces the cost associated with traditional audiometers, making it accessible for low-resource settings and developing countries.
- The architecture of our device is laid out with an eye on future enhancements, including the integration of advanced noise-cancellation techniques and the conceptualization of an associated Android application. Furthermore, the open-source nature of the Arduino platform invites the global research community to collaborate, refine, and enhance our design.
- The proposed device underwent rigorous testing to ensure its effectiveness and accuracy, making it a reliable tool for hearing assessments.
- It's provided a comprehensive review of existing Arduino-based audiometers, highlighting the advantages and potential shortcomings, thus setting the context for our work.

1.1. The auditory system

The auditory system is responsible for detecting, processing, and interpreting sound. It is a complex system that involves multiple structures and processes, from the external ear to the brain. Sound waves enter the ear canal and are then amplified by the middle ear. The amplified sound waves vibrate the eardrum and the three small bones in the middle ear, the malleus, incus, and stapes.

Nomenclature & Symbols

ANSI	American National Standards Institute	LED	Light-Emitting Diode
ENT	Ear, Nose, and Throat	MCU	Microcontroller Unit
I2C	Inter-Integrated Circuit	OLED	Organic Light-Emitting Diode
IDE	Integrated Development Environment	OAE	Otoacoustic Emissions
LCD	Liquid Crystal Display	USB	Universal Serial Bus

These vibrations are then transmitted to the inner ear, stimulating hair cells in the cochlea, a spiral-shaped structure filled with fluid. The hair cells convert the sound vibrations into electrical signals, which are then transmitted to the brain through the auditory nerve [7]. Fig. 1 shows a simple diagram of the human auditory system.

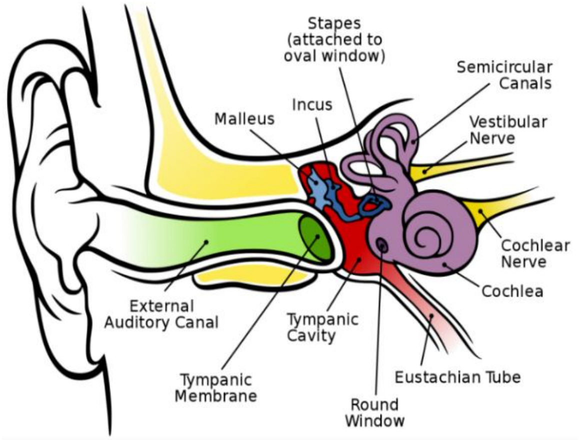


Fig. 1. Human Auditory System [8]

Hearing loss can be classified into two main types: conductive hearing loss and sensorineural hearing loss. Conductive hearing loss is attributed to abnormalities in the outer or middle ear, such as a blockage in the ear canal or malfunctions in the eardrum or bones in the middle ear. On the other hand, sensorineural hearing loss results from injury to the hair cells or the auditory nerve in the inner ear or damage to the auditory processing centers in the brain. Both conductive and sensorineural hearing loss can be detected through hearing tests [9].

1.2. The types of hearing tests

Hearing tests are used to measure the ability to hear and identify sounds. There are several types of hearing tests, including pure-tone audiometry, speech audiometry, and Otoacoustic Emissions (OAE) testing. Pure-tone audiometry is the most common type of hearing test and involves measuring the ability to hear different sound frequencies. The tested person wears headphones and listens to a series of beeps at different frequencies and volumes. The person responds by pressing a button or raising a hand when they hear the sound. Speech audiometry measures the ability to hear and understand speech. The tested person listens to words or sentences at different volumes and repeats them back. This test can help determine how well a person can understand speech in noisy environments. OAE testing measures the sounds produced by the inner ear's hair cells in response to a sound stimulus. This test can help determine the presence of hearing loss and can also be used to screen for hearing loss in infants [10]. Fig. 2 illustrates various types of medical audiometer devices.

(a) (b) (c)

Fig. 1. Human Audiometer devices

Fig. 2 (a) represents the pure tone audiometer device named "Grason Stadler GSI 61 Diagnostic Clinical Audiometer" [11], Fig. 2 (b) illustrates the screening audiometer "MAICO MA 25 Screening Audiometer" [12], and Fig. 2 (c) shows the Otoacoustic Emissions (OAE) audiometer device "39500 Series OAE Hearing Screener" [13]. Although this topic is infrequently addressed, most of the extant literature on the proposed system concept has been thoroughly examined.

According to N. H. Wijaya, et al. in [14], the ear is an important organ for sound detection and the body's balance, but is susceptible to two common forms of hearing loss: decreased hearing conduction and sensorineural hearing loss. However, regular hearing function testing by an ENT doctor at a hospital can be costly and time-consuming. To address this issue, the authors designed a portable hearing loss tool with an Arduino UNO R3 control and IC XR2206 frequency generator, enabling independent testing and data storage of results for consultation by a doctor. The tool has an LCD, portability, and data storage capabilities. The highest frequency error was 0.52% at 8000 Hz, but overall, all systems on the device functioned correctly with an error still within the tolerance of 10%. This audiometer is a suitable option for early diagnosis of hearing function.

R. Rani. in [15] presents the development and evaluation of a portable audiometer designed to detect and monitor hearing loss in patients undergoing cancer treatment or those at risk of hearing damage from exposure to high sound pressure levels. The system consists of a hardware unit, earphones, and a patient response switch to record and transmit responses to the healthcare unit. The audiometer covers a range of testing frequencies from 20 Hz to 20 kHz and stores patient data for remote healthcare applications. The system was tested in various settings, including the home, clinic, and hospital, and proved to be accurate and reliable for detecting hearing changes. Future work could incorporate additional features to enhance the ease and accuracy of hearing sensitivity monitoring. The portable audiometer provides a powerful tool for detecting hearing disorders in patients, enabling frequent and regular monitoring of hearing sensitivity to protect against further damage.

O. Access in [16] describes the importance of early identification of hearing impairment in neonates and developing a prototype device to measure hearing capability in newborns. The device utilizes non-invasive assessments based on otoacoustic emissions (OAEs) to evaluate the biological response to acoustic stimuli and identify hearing impairment. The compact, affordable, and easy-to-use device can be used by trained personnel in hospitals to screen neonates and reduce the incidence of hearing disability and deafness by birth. While the device only considers ambient noise for analysis, future work may involve canceling the noise created within the ear for more accurate results. An Android application may also be developed for easier access to familiar people. The device's development and use represent a significant step toward improving the early identification of hearing impairment and its effect on neonates' speech, language, and educational, economic, and social capabilities.

In [17], A. Rahmawati, et al. present a design and implementation of a pure tone audiometer that uses Arduino microcontrollers to automate hearing loss testing and an Audiogram application that is compatible with Android smartphones. The audiometer uses the Hughson Westlake method and the CD4066 digital switch to regulate frequency and intensity, and patients interrupt the test by pressing a button when they hear a sound. The results are then displayed on the Audiogram on Android. The system uses the XR2206 oscillator series, a frequency switching circuit, and intensity to conduct automatic testing. The study found that the highest error was 3.95% at 1000Hz, while the smallest error was 0.05% at 250Hz. This system can be integrated into conventional audiometer systems to improve the efficiency and effectiveness of hearing testing. However, further experimental investigation is necessary to evaluate the accuracy and precision of variable resistors and replace the amplifier circuit to achieve maximum intensity.

V. M. Raja Sankari, et al. in [18] highlight the advantages of using Arduino-based audiometers, such as their low cost and customizability. The device measures hearing loss by testing the patient's ability to detect pure-tone stimuli at different frequencies and amplitudes. The paper describes the design and construction of the audiometer, including the hardware and software components. The device is made up of an Arduino UNO R3 microcontroller, a digital-to-analog converter, an audio amplifier, and a pair of headphones. The software is programmed to generate pure-tone stimuli at different frequencies and amplitudes and to record the patient's responses. The authors present the results of preliminary audiometer testing on a small sample of patients. The results show that the device can measure hearing loss and are consistent with those obtained from conventional audiometers. The authors suggest that the audiometer can be used in low-resource settings where traditional audiometers may not be available or affordable.

C. Druga, et al. in [19] propose a prototype audiometer to enhance telemedicine practices by improving data transmission between medical devices and practitioners. This system employs an Arduino Mega 2560 development board for wireless data communication to various devices. The audiometer features an LM386 audio amplifier, a headphone jack, a compatible TFT display for visualizing data, and storage modules for pure sounds at specific frequencies. The compact and lightweight design of the device, powered by an external 9V battery, offers a real-time display of test results on an LCD screen, enabling the construction of audiograms and result transmission to computers or smartphones. The system can store and integrate results into a patient database, facilitating diverse testing approaches. Currently used for educational purposes, the low-cost prototype promises easy maintenance and potential for future improvements. This development signifies a valuable contribution to integrating modern technology in medical devices, particularly for telemedicine.

Section 1 delves into the general introduction, provides an overview of the auditory system, and explores various types of hearing assessments, supplemented by a comprehensive literature review. The subsequent sections of this paper are structured as follows: The experimental design and methodology are delineated in Section 2. Section 3 elucidates the findings derived from the experiments. Section 4 is dedicated to discussions on Arduino-based audiometers. Finally, Section 5 encapsulates the conclusions drawn from this study.

2. The Experiment Configuration

The primary objective of our study was to design and evaluate an audiometer powered by Arduino. This distinctive device is programmed to assess and categorize hearing levels across ten distinct gradients. These levels range from excellent hearing (Level 1) to significant hearing impairment (Level 10). The audiometer displays these classifications via a 0.96-inch OLED 4-pin display and a MAX7219 matrix LED for enhanced readability. The device also includes a push button for the tested person to indicate when they hear a sound level. The materials used in our study include an Arduino UNO, a speaker, an OLED display, a MAX7219 matrix LED, a push button, and various electronic components. The development of our device involved several steps. First, we connected the speaker to the Arduino UNO and programmed the Arduino to generate ten different sound levels. Next, we connected the OLED display and the MAX7219 matrix LED to the Arduino and programmed them to display the sound levels. We also programmed the Arduino to respond to the push button input and to record the person's response to each sound level.

2.1. The hardware design of the proposed system

Our device is based on the Arduino UNO platform and includes several components, including a speaker, an OLED display, a MAX7219 matrix LED, a push button, and other electronic components such as Breadboard and jumper wires. The Arduino UNO is a popular MCU board based on the ATmega328P microcontroller. It has 14 digital input/output pins, six analog inputs, a 16 MHz quartz crystal, a USB connection, and a power jack. It is easy to program and can control various electronic devices and sensors, making it a popular choice for hobbyists and professionals [20]. The 0.96" OLED display is a small, low-power display with a resolution of 128x64 pixels. It uses OLEDs to produce bright, high-contrast images, making it ideal for small electronic devices such as smartwatches and portable gaming consoles. It is also easy to interface with microcontrollers such as Arduino, allowing data and graphics display [21]. The MAX7219 is a versatile display driver chip that can control up to 64 individual LEDs arranged in an 8x8 matrix. It uses a simple serial interface to communicate with a microcontroller such as Arduino and can be used to display a wide range of characters, symbols, and animations. It is commonly used in LED displays, scoreboards, and other applications requiring information in a compact and easy-to-read format [22]. A speaker is an electroacoustic device that converts electrical signals into sound. It can be used to play music, sounds, or alerts. A push-button is a mechanical switch that is activated by pressing a button. It is commonly used as a user input device in electronic projects. It can be used to trigger an action, such as turning on an LED or playing a sound. The block diagram of the proposed system is illustrated in Fig. 3. Also, the hardware design of the device is shown in Fig. 4.

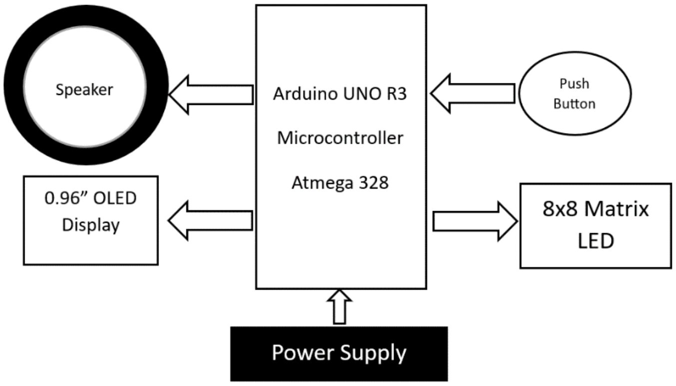


Fig. 3. The Block Diagram of the Experimental Device

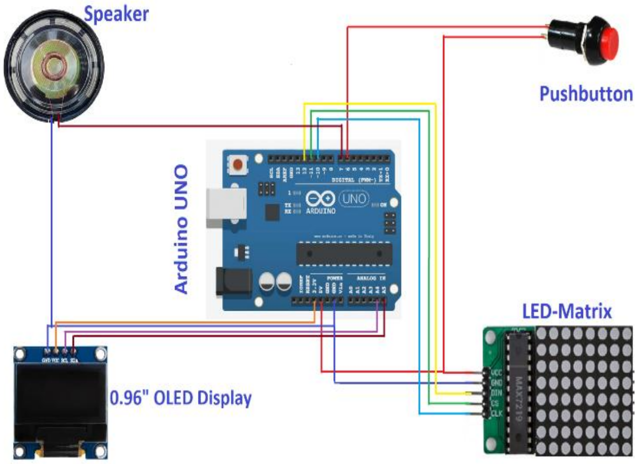


Fig. 4. The Hardware Design of the Proposed System

The speaker is used to generate sound levels, and it is connected to the digital output pins of the Arduino UNO. The sound levels are generated using a tone function in the Arduino programming language. The OLED display is used to show the sound levels and is connected to the I2C pins of the Arduino UNO. The display is a 0.96" OLED 4 pins display, and it is controlled using the Adafruit_SSD1306 library in the Arduino programming language. The library provides functions to display text, draw shapes, and display images on the OLED display. The MAX7219 matrix LED is used to display the sound levels and is connected to the digital output pins of the Arduino UNO. The LED display is an 8x8 matrix, and it is controlled using the LedControl library in the Arduino programming language. The library provides functions to control the individual LEDs in the matrix and display patterns and text. The push button indicates when the person being tested hears a sound level. The button is connected to a digital input pin of the Arduino UNO and is read using the digitalRead function in the Arduino programming language.

Our device is designed to be low-cost, portable, and customizable. The use of Arduino UNO as a platform for the device allows for easy programming and customization of the device. Fig. 5 shows the proposed device.

Consequently, the second phase of the process was devoted to creating functions to visualize the sound levels on two distinct display mediums, namely an OLED display and a MAX7219 matrix LED. For the OLED display, we deployed the Adafruit_SSD1306 library. This library is acclaimed for its convenience, offering a range of built-in functions to display text, draw shapes, and exhibit images. The depiction of sound levels on the OLED display was therefore made significantly easier.

On the other hand, the Led Control library was employed to handle the visualization of sound levels on the MAX7219 matrix LED. Known for its robustness, this library offers control over individual LEDs in the matrix, allowing one to exhibit custom patterns and text on the matrix. The software also provides an interface to interact with the user through a simple push-button interface, enabling the recording of user responses in real-time.

Further details regarding the proposed system software can be found in Appendix A, which provides the pseudo-code of the developed program. A representative flowchart of the system operation has also been illustrated in Fig. 6. For a deeper understanding of our programming approach, Appendix B presents a portion of the utilized Arduino C code, giving insight into our coding and implementation strategies.

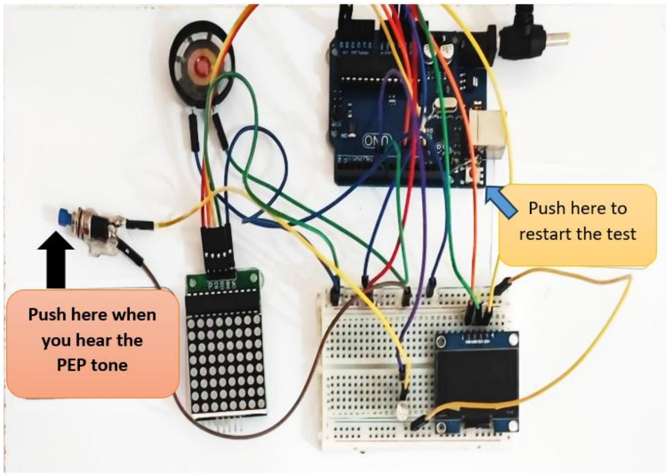


Fig. 5. The proposed system's hardware

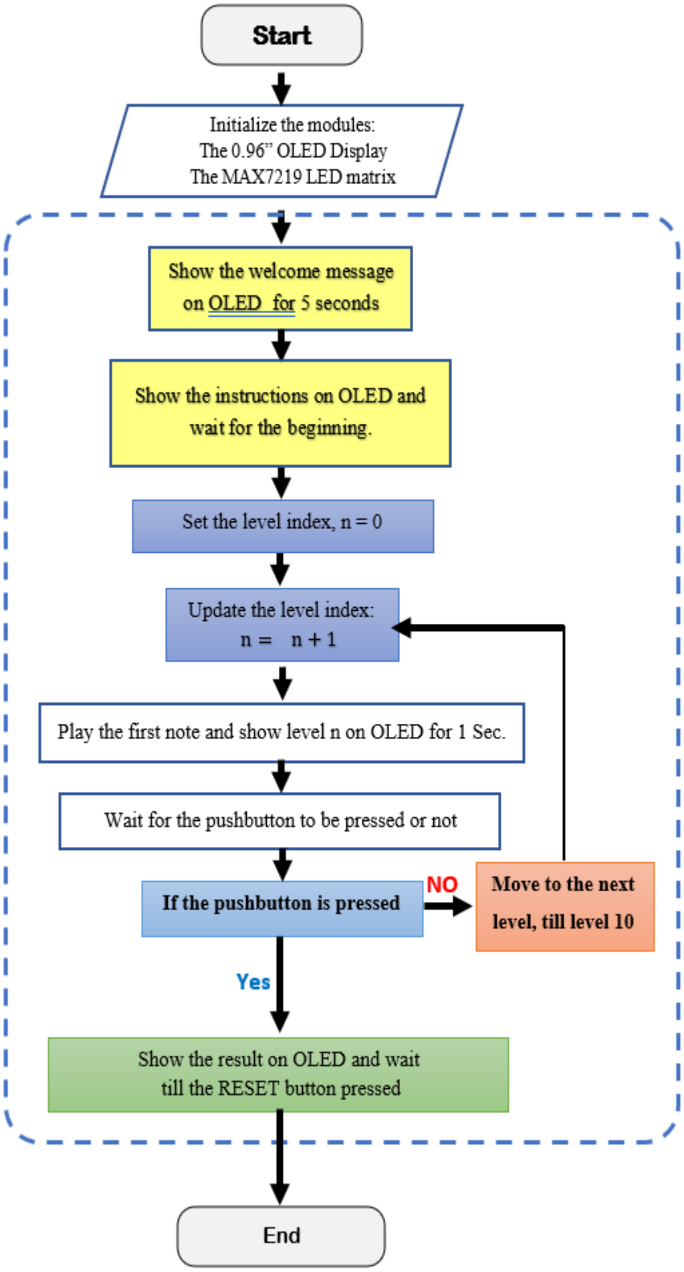


Fig. 6. Flowchart of the proposed system's operation

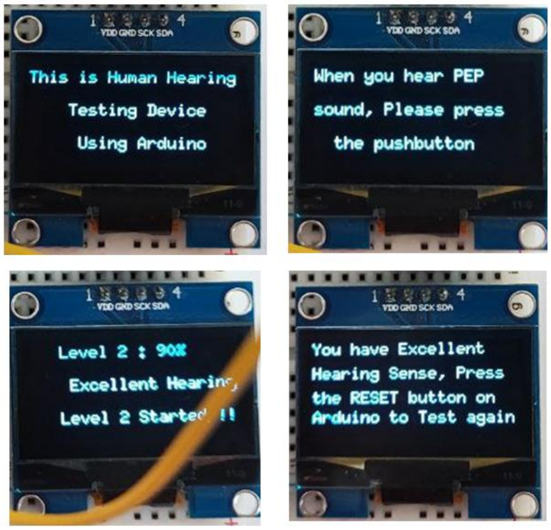
3. The Experimental Results

The test includes ten levels of hearing ability, starting from perfect hearing to a big problem in hearing. A specific sound frequency accompanies each level, which the user needs to hear and then press the push button. The tests were carried out on fifteen people, with each person being tested ten times. The test results showed that the proposed device works well and reliably when considering the ease of use and the construction price, with a small error rate in the used frequency range (30-500 Hz). Among the group, there were three people who had poor hearing. The proposed device diagnosed them with an estimated error rate of approximately 20-30%. Table 1 presents the average of 10 times tests for each of the 15 participants.

Table 1. Summary of Device Testing Procedure: Average Testing Duration, Accuracy, and Hearing Condition of Participants

Test Subject ID	Gender	Age	Average Testing Duration (Minutes)	Average accuracy (%)	Frequency Range (Hz)	Average Estimated Error Rate (%)	Average Hearing Condition
1	Male	28 years	1 Minute	76.4	30-500	23.6	Very Good
2	Female	29 years	1 Minute	75.6	30-500	24.4	Very Good
3	Female	32 years	1 Minute	76.3	30-500	23.7	Excellent
4	Male	26 years	1 Minute	76.2	30-500	23.8	Excellent
5	Male	22 years	1 Minute	75.9	30-500	24.1	Excellent
6	Male	19 years	2 Minutes	76.0	30-500	24	Very Good
7	Male	41 years	2 Minutes	76.1	30-500	23.9	Good
8	Male	67 years	3 Minutes	76.5	30-500	23.5	Poor Hearing
9	Male	38 years	2 Minutes	76.4	30-500	23.6	Very Good
10	Female	31 years	1 Minute	76.2	30-500	23.8	Excellent
11	Male	52 years	3 Minutes	71.0	30-500	29	Moderate Hearing
12	Male	57 years	3 Minutes	80.2	30-500	19.8	Moderate Hearing
13	Female	39 years	1 Minute	79.0	30-500	21	Excellent
14	Female	37 years	1 Minute	72.0	30-500	28	Excellent
15	Male	28 years	1 Minute	70.8	30-500	29.2	Very Good

Overall, the device provides a simple, portable, and cost-effective method for assessing an individual's hearing ability and could potentially be used for screening purposes in clinical settings. Fig. 7 shows a sample of the testing results on the OLED display.



```
This is Human Hearing
Testing Device
Using Arduino
```

```
When you hear PEP
sound, Please press
the pushbutton
```

```
Level 2 : 90%
Excellent Hearin
Level 2 Starte !!
```

```
You have Excellent
Hearing Sense, Press
the RESET button on
Arduino to Test again
```

Fig. 7. Various testing results on the OLED display

4. Arduino-Based Audiometers

Arduino-based audiometers have gained popularity recently due to their low cost, portability, and customizability. Arduino is an open-source platform that provides an affordable and accessible way to create electronic devices. Arduino-based audiometers use various sensors to measure sound levels and are often coupled with software to analyze and display the results.

4.1. Advantages of Arduino-based audiometers

One of the main advantages of using Arduino-based audiometers is their low cost. Traditional audiometers can be expensive and require a dedicated testing room, making them inaccessible in many areas, especially in low-income countries or rural regions. Arduino-based audiometers can be assembled for a fraction of the cost and are often portable, making them easier to transport and use in different locations.

Another advantage of Arduino-based audiometers is their customizability. With Arduino, users can create audiometers tailored to their specific needs and add or remove features as necessary [14]. For example, our device uses an OLED display and a MAX7219 matrix LED to show sound levels for those with sufficient knowledge of English and medical-technical terminology, and for general people with poor learning, respectively. Other audiometers may use different types of displays or additional sensors to measure other aspects of hearing.

4.2. Disadvantages of Arduino-based audiometers

One potential disadvantage of using Arduino-based audiometers is their accuracy compared to traditional audiometers. Traditional audiometers are highly precise and have been extensively validated through research studies. While some studies have found Arduino-based audiometers to be reliable and accurate, others have found them to have lower accuracy than traditional audiometers, and this may be due to differences in the types of sensors used or the calibration of the device [18].

Another potential disadvantage of using Arduino-based audiometers is their lack of standardized protocols. Traditional audiometers use standardized protocols for testing, such as the American National Standards Institute (ANSI) standards, to ensure consistency in testing procedures and results. Arduino-based audiometers may lack a standardized protocol, which could lead to inconsistent results or difficulty in comparing results across different devices.

5. Conclusion

In this paper, it has described the development and testing of an Arduino-based audiometer for measuring ten levels of sound generated by a speaker. The device uses an Arduino UNO platform and includes an OLED display, a MAX7219 matrix LED, and a push-button for the person being tested to indicate when they hear a sound level. Arduino-based audiometers have several advantages over traditional audiometers, including low cost, portability, and customizability. However, the accuracy of these devices compared to traditional audiometers is still an area of concern, and further research is needed to validate their use in clinical settings. Our study contributes to the growing body of literature on developing and validating Arduino-based audiometers. The results of our study demonstrate the potential of these devices to provide an affordable and accessible way to diagnose hearing loss. We hope that our device will be useful in various settings, including schools, community health centers, and remote areas.

The authors suggest that further research and development of these devices will be crucial for ensuring their accuracy and validity in clinical settings, especially if artificial intelligence and machine learning algorithms are used to improve the accuracy and quality of clinical readings for patients, which can be used with Arduino, such as Decision Trees, Naive Bayes Classifier, and Logistic Regression. Eventually, we recognize the value of comparing our results with those from commercial devices and plan to conduct such comparative studies in our future work to further validate the efficacy of our system.

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Appendix A

The pseudo-code of the proposed system is presented here.

Initialize the required libraries and pins.

Setup:

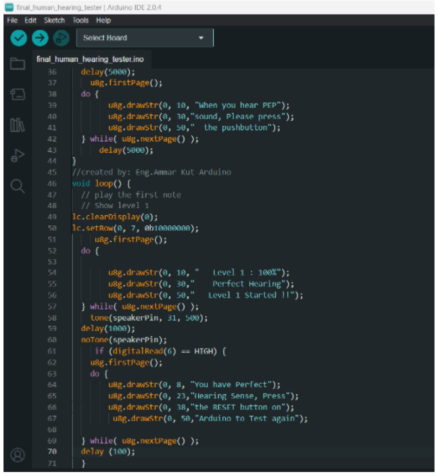
- Start serial communication
- Initialize the matrix set its intensity to 8, and initialize the OLED display and clear it.
- Set speaker Pin as output
- Set the font for the OLED display.
- Display the welcome message for 5 seconds
- Display the instructions for the test for 5 seconds.

Loop:

- Set and display the level of the test.
- Play a tone related to each level.
- If the user presses a push-button during the tone, display a message indicating his hearing level.
- Wait for 5 seconds before moving to the next level.

Appendix B

A snippet of the Arduino C script using the Arduino IDE 2.0 is illustrated in Fig. 8.



```
  delay(5000);
    u8g.firstPage();
  do {
        u8g.drawStr(0, 10, "When you hear PEP");
        u8g.drawStr(0, 30,"sound, Please press");
        u8g.drawStr(0, 50,"  the pushbutton");
  } while( u8g.nextPage() );
      delay(5000);
}
//created by: Eng.Ammar Kut Arduino
void loop() {
  // play the first note
  // Show level 1
lc.clearDisplay(0);
lc.setRow(0, 7, 0b10000000);
     u8g.firstPage();
  do {

        u8g.drawStr(0, 10, "   Level 1 : 100%");
        u8g.drawStr(0, 30,"    Perfect Hearing");
        u8g.drawStr(0, 50,"   Level 1 Started !!");
  } while( u8g.nextPage() );
    tone(speakerPin, 31, 500);
  delay(1000);
  noTone(speakerPin);
     if (digitalRead(6) == HIGH) {
    u8g.firstPage();
    do {
        u8g.drawStr(0, 8, "You have Perfect");
        u8g.drawStr(0, 23,"Hearing Sense, Press");
        u8g.drawStr(0, 38,"the RESET button on");
         u8g.drawStr(0, 50,"Arduino to Test again");

  } while( u8g.nextPage() );
  delay (100);
  }
```

Fig. 8. Code snippet of the used script