<u>The Auditory Range</u>

Final report for a laboratory project

Course JEB1447H F

Sensory Communication

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Abstract

During the Coronavirus Disease 2019 (COVID-19) global pandemic, telemedicine has gradually become a preferable choice to many patients because of its easy-accessible and contactless characteristics. Furthermore, a computer-based at-home self-hearing screening kit has become practical with the rapid development of information technology. This report presents a prototype of MATLAB-based audiometer software, which can be operated on a Windows operating system with a soundcard and provide basic hearing tests. Moreover, experiments on exploring the varying hearing thresholds among different age groups have been performed using this prototype. A variant application for finding the minimum noticeable level of decibel change is also developed.

1. Introduction

1.1 Background & Literature

In 1993, Harvey Fletcher and W. A. Munson indicated in their paper, "Loudness, Its Definition, Measurement and Calculation", that the human ears' sensitivity varies with different frequencies. As illustrated in Figure 1, the Fletcher Munson Curves or the equal-loudness contours measures the sound pressure level over the frequency spectrum, in which it illustrates that the ear is the most sensitive to pure tones in the frequency region from 500 to 2000 Hertz, also commonly known as the mid-range frequencies. The intensity level of lower or higher frequencies must be raised for the ear to perceive the same level of loudness [1].

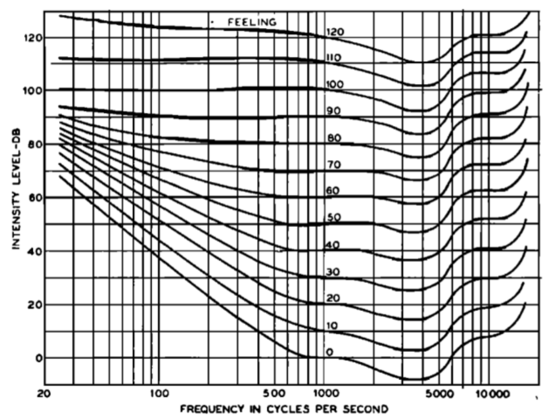

Figure 1 Equal-Loudness Contour [1]

While the human hearing sensitivity is a function of frequency, it also degrades by age. Jungmee Lee et al. demonstrated in their paper, "Behavioral Hearing Thresholds Between 0.125 and 20 kHz Using Depth-Compensated Ear Simulator Calibration", that the average hearing threshold varies by age groups. Generally, among subjects of 10 to 65 years, older age groups show a higher hearing threshold than younger age groups. As shown in Figure 2, hearing loss related to aging is especially prominent at large frequencies [2]. Furthermore, in 1834, Weber made a conjecture on the sensitivity of our sensory system to stimulus changes. Weber believed that, given a reference stimulus, the minimum noticeable change in the intensity of the stimulus is linearly proportional to the intensity of its reference, which is as known as Weber's law:

$$\frac{\Delta I}{I} = K \tag{1}$$

where I denotes the intensity of the stimulus, ΔI is the minimum difference between the reference and a second stimulus, and K is a constant [3]. However, data from a study conducted by Edward H. Adelson shows that Weber's law is disobeyed for both very low and very high intensities [4].

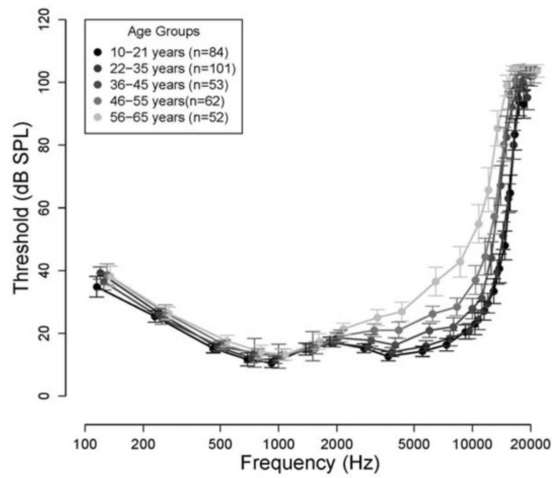

Figure 2 Hearing Thresholds by Age [2]

1.2 Rationale

Under the COVID-19 pandemic, while most social activities can be replaced by online meetings, medical services are harder to be offered remotely. A study conducted by Dr. Jennifer Taber et al. investigated the reasons for medical care avoidance from a patients' perspective, 15.6% of participants reported time constraints [5]. Therefore, the development of telemedicine technologies, such as a remote hearing test system, is in urgent need to reduce social contacts and waiting time in health care delivery. This research project aims to design a hearing test system that allows unsupervised testing through a personal device remotely. The testing results can present a report for doctors' preliminary diagnosis or be used by patients to self-monitor their hearing. From the perspective of the Canadian health delivery system, this application can increase health care efficiency by eliminating patients' travel time as well as reducing wait time in clinics; it also eases the workload of audiologists by offering an alternative for in-person examinations.

2. Objective

The general goal is to design a remotely deployable computer-based auditory diagnosis software that produces pure tones of varying intensities and frequencies for basic hearing tests. This software is expected to interact with users during the test to collect feedbacks and report hearing threshold results. After calibrating this application, experiments will be performed on individuals in various age groups to investigate age-related hearing degradation. Testing results will be analyzed and compared with hearing thresholds in the equal-loudness contour. Furthermore, a variant application will be developed to investigate the minimum step size in the Sound Pressure Level (SPL) that human ears can discriminate.

3. Methodology

Based on the powerful functionality and developable versatility, MATLAB has been selected as the integrated development environment for signal programming. The audiometer, as well as the application for step size tests will be developed in MATLAB App Designer as it provides efficient Graphical User Interface (GUI) design tools and comprehensive application deployment functions. The first step is to generate the pure tone signals used in the audiometer. The formula for the sinusoidal sound wave signal is given by:

$$y = A \times \sin(2 \times \pi \times f \times t) \tag{2}$$

where A is the amplitude calculated using the SPL L_p in dB:

$$A = 10^{\frac{L_p}{20}} \tag{3}$$

f is the frequency of the tone being played, and t is a time set generated by:

$$t = \frac{(2 \times \pi \times [1{:}N])}{f_s} \tag{4}$$

N denotes the sample length in seconds, and f_s is the sampling frequency, set to be 44.1 kHz, as being widely adopted for CD audio. The audio signal generated by MATLAB can be played via a sound card installed in a computer using an embedded function. In view of the difficulty of detecting the actual volume at the headphone port, the audio signal generated will be verified and calibrated numerically by measuring the dB level and frequency in MATLAB.

For the second step, the GUI and algorithm for the audiometer application will be developed. A comprehensive flow chart of the logic behind our application is shown in Figure 3 below. For the best of performance, we require the user to wear headphones and complete the test in a quiet environment. After the user has read all instructions and notices, a pure tone at 1 kHz and 40 dB will be generated and played to both ears of the user, and the user will be asked to adjust their device volume. Upon the user is comfortable with the tone, the test will officially begin. A pure

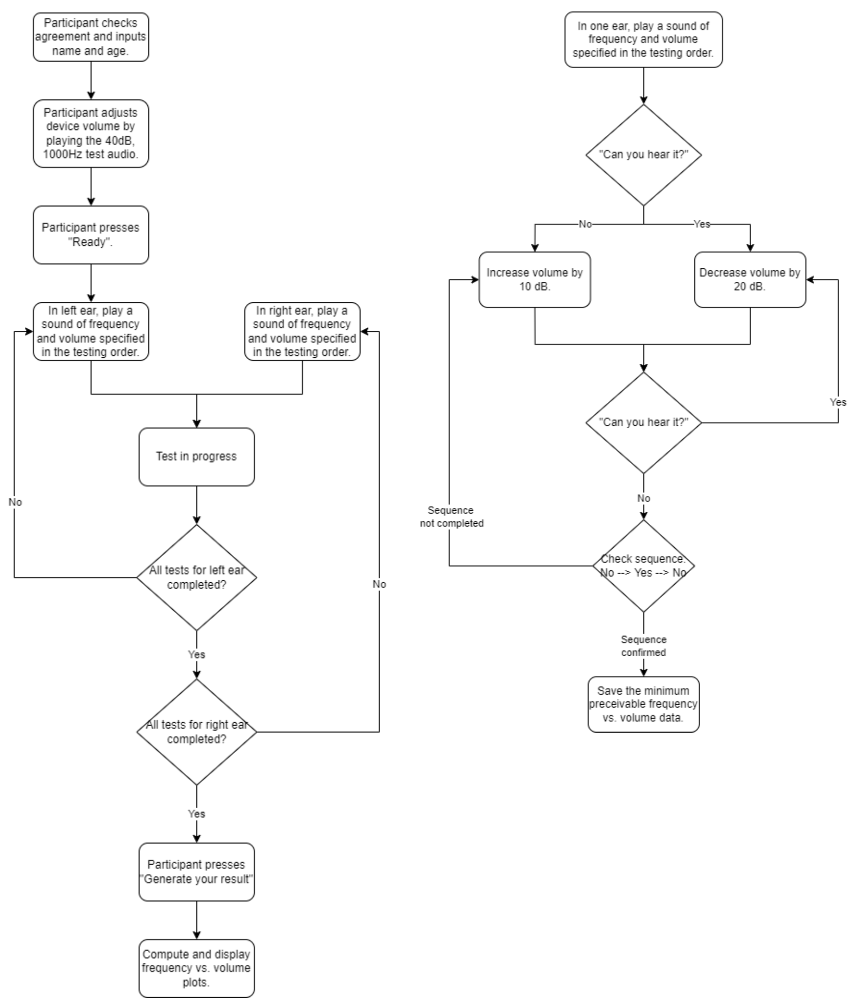

Figure 3 Flow Chart of Audiogram Application Structure

tone at 1 kHz and 40 dB will be played again, but in the left ear only. Moreover, at this point, the user will respond to whether the tone is heard. If 'Yes' is chosen, the SPL will decrease by 20dB, while if 'No' is chosen, the SPL will go up by 10dB. When the program recognizes a response sequence 'No-Yes-No', the frequency played before the user selected 'Yes' will be recorded, and the testing cycle for one frequency is finished. Then a different frequency will be selected randomly among 250 Hz, 500 Hz, 2 kHz, 4 kHz, and 8 kHz, and another testing cycle begins. When the tests for all frequencies have been completed, the same procedure will be repeated at the other ear. After both ears have been tested, an audiogram with SPL recorded versus corresponded frequencies will be plotted. The figure of hearing thresholds by the age shown in Figure 2 will also be displayed side-by-side with the audiogram for the user as a reference. A screenshot of the main page of the audiogram application is shown in Figure 4, and detailed instructions are illustrated in Appendix I. For straightforward distributions, this software is packed into a single installation file. The mathematical analysis between the SPL and the frequency of the signals will confirm the successful development of the application. Then hearing threshold tests will be performed on

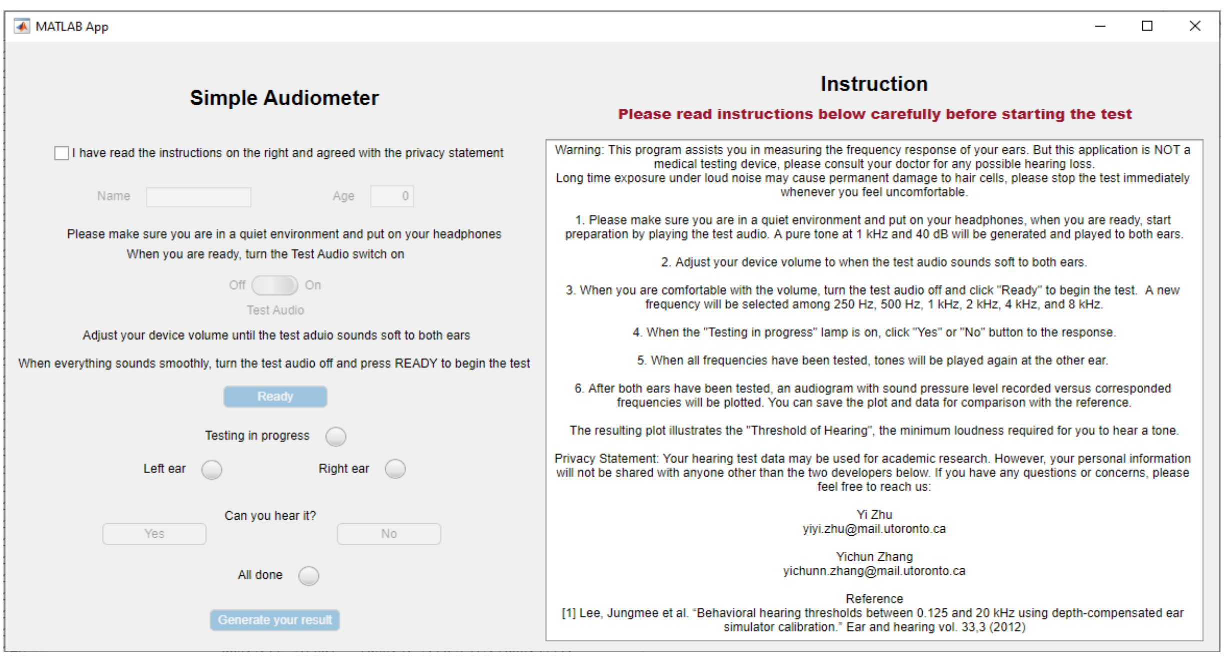

Figure 4 Screenshot of Audiometer Application

subjects of different age groups, 10s, 20s, 30s, 40s, and 50s. All adult participants will be required to consent to any possible risks associated with the test, and all minors will need to acquire permission from their guardians before the start of the tests. The outcomes of the hearing thresholds tests will be discussed in detail in Section 4.

Lastly, derived from the audiometer we already have, a Step Size Testing Application with a manually adjustable ΔSPL is also developed in the MATLAB App Designer, which will be used to explore the minimum noticeable change in SPL of human hearing. In this application, a 1 kHz pure tone of selected decibel will be played for a second, and after a pause of one second, the same pure tone will be played at ΔSPL louder for another second. The user can change the ΔSPL manually using a slider on the application until they recognize a difference. A screenshot of this application is shown in Figure 5, and detailed instructions are discussed in Appendix II. The results collected in decibels will be converted into sound intensities using the formula given by:

$$I = I_0 \times 10^{\frac{L_P}{10}} \tag{5}$$

where I denotes sound intensity in the unit of Watts per square meter, and I_0 is the reference intensity, which is assumed to be $10^{-12}\ W/m^2$ in this study.

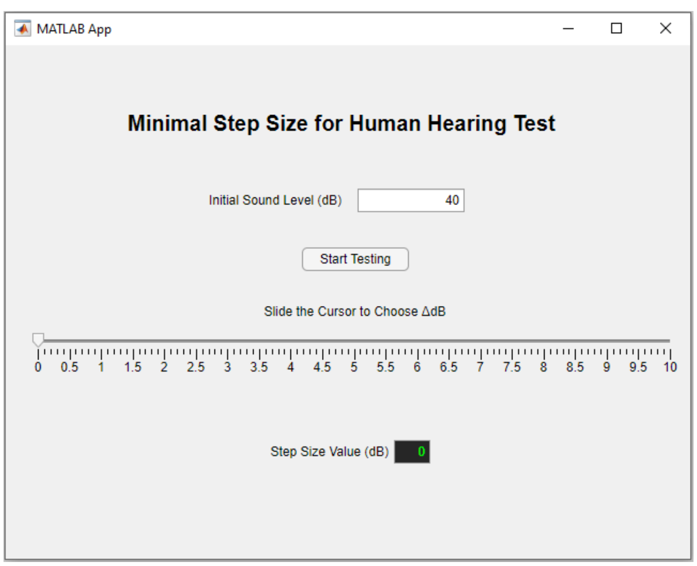

Figure 5 Screenshot of Step Size Testing Application

4. Results and Discussions

Our application has been successfully delivered to and installed on the computers of 18 volunteers using Windows operating systems. The complete feedbacks data is included in Appendix III. All subjects were free of non-age-related hearing impairments when they received the tests. It is worth noting that to protect he privacy of participants, all names have been replaced with ‘first number in age + English letters’. For example, ‘1A’ is used for the first participant in 10s. One sample result dataset from each age group being tested is listed in Figure 6. The general trend of these audiograms approximately follows the equal-loudness contour (Figure 1) that most audiograms illustrate the lowest hearing threshold at about 4 kHz and highest values at 250 Hz and 8 kHz.

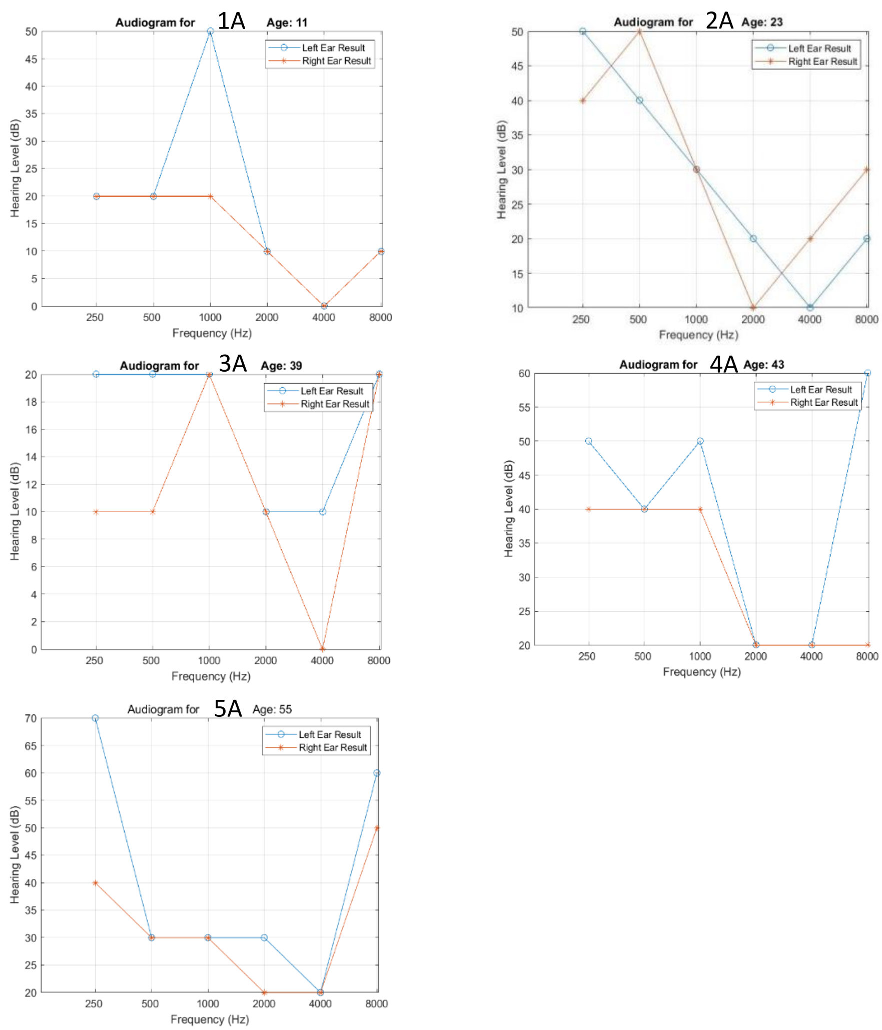

Figure 6 Sample Result Dataset of Hearing Thresholds from Different Age Groups

According to Jungmee Lee et al.'s study in Figure 2, age-related hearing loss is the most prominent at approximately 8kHz. By comparing the hearing threshold obtained at this frequency, hearing loss is insignificant for subjects in the age groups of 10s, 20s, and 30s. Most of these subjects had a hearing threshold of between 20 to 30 dB for an 8 kHz pure tone, which indicates healthy and normal hearing by comparison with Figure 2. However, the audiograms of subjects in their 40s and 50s exhibit minor hearing degradation. At 8 kHz, the subjects in their 40s had an average hearing threshold of 40 dB, and those in their 50s had one of 53 dB, which results are in agreement with Figure 2. These observations also verify the hypothesis that hearing thresholds increase by age and age-related hearing loss is the more prominent for sounds of high frequencies.

Furthermore, the Step Size Testing Application was designed to test a subject's minimum noticeable change in volume given reference sounds at 1 kHz of volumes from 40 to 100 dB. Experimental Data is included in Appendix IV. An analysis of Weber fraction as a function of intensity was performed on three subjects of similar ages. The results collected in dBs are converted into Weber fractions and intensities using Equation 5, and the results are shown in Figure 7. An approximately linear relationship between Weber Fraction and intensity can be observed beyond $3.16 \times 10^{-7}\ W/m^2$, which corresponds to 55 dB. In other words, the linearity is disobeyed at smaller intensities or volumes.

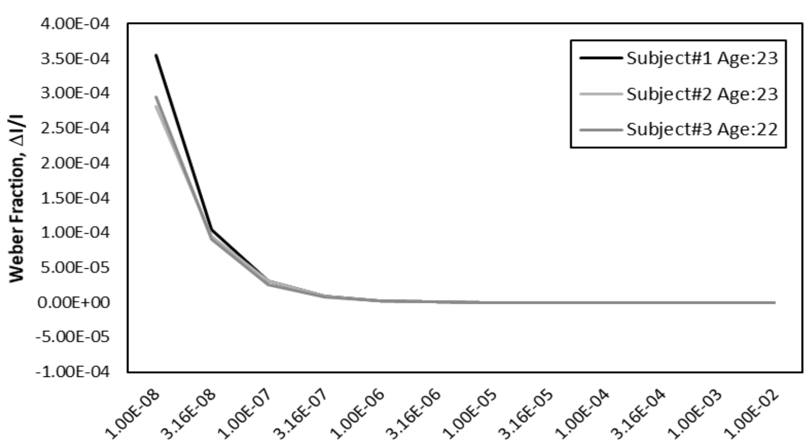

Figure 7 Results of Minimal Step Size for Human Hearing

5. Conclusions

A computer-based self-screening tool for hearing threshold tests was successfully designed and deployed remotely. Audiograms produced by this application agreed with the equal-loudness contour, which verified its accuracy and functionality. After that, hearing threshold tests were performed on subjects of various ages from 10s to 50s, and the results indicated that hearing loss was related to aging. Generally, signs of hearing loss were not evident for subjects between 10 to 40 years, but subjects of 40 years and older showed increasing hearing thresholds, specifically at 8 kHz. Eventually, an experiment was performed on subjects of similar age to test their minimal noticeable change in volume, each time provided with a different reference volume. The results showed that in human hearing, Weber fraction had an approximately linear relationship with sound intensity at medium to high intensities, but linearity was disobeyed for very small intensities.

6. Suggestions for Future Work

Since this study is possibly subject to errors as participants receive their tests in different environments, their test audios can potentially be interfered with by noises due to masking effects. Moreover, participants also used either speakers or headphones with potentially different qualities. Thus, possible software algorithms for noise-reduction, masking correction, and speakers or headphones adaption could be explored. Besides, the accuracy of results may be improved by performing the tests on more subjects, and result comparisons with commercial and professional audiometers could be made. In addition, step changes of 10 dB were adopted to study hearing thresholds. Errors can be further reduced by narrowing down the step size and adding more data points. Lastly, due to the limitation of MATLAB App Designer, current applications can only be operated on Windows systems. To achieve the mobility of telemedical, the audiometer application will be modified to be deployable on macOS, Linux, and further on cloud servers for mobile users.

References

[1] H. Fletcher, W. A. Munson and B. T. Laboratories, "Loudness, Its Definition, Measurement and Calculations," *Journal of the Acoustical Society of America*, vol. 5, pp. 82-108, 1933.

[2] J. Lee, S. Dhar, R. Abel, R. Banakis, E. Grolley, J. Lee, S. Zecker and J. Siegel, "Behavioral Hearing Thresholds Between 0.125 and 20 kHz Using Depth-Compensated Ear Simulator Calibration," *Ear Hear*, vol. 33, no. 3, pp. 315-329, 2013.

[3] E. R. Kandel, J. H. Schwartz, T. M. Jessell, S. A. Siegelbaum and A. J. Hudspeth, "Sensory Coding," in *Principles of Neural Science*, McGraw-Hill, 2012, pp. 450-474.

[4] E. H. Adelson, "Saturation and Adaptation in the Rod System," *Vision Res.*, vol. 22, pp. 1299-1312, 1982.

[5] J. A. Taber, B. Leyva and A. Persoskie, "Why do People Avoid Medical Care? A Qualitative Study Using National Data," *J Gen Intern Med.*, vol. 30, no. 3, pp. 290-297, 2015.

Appendix I

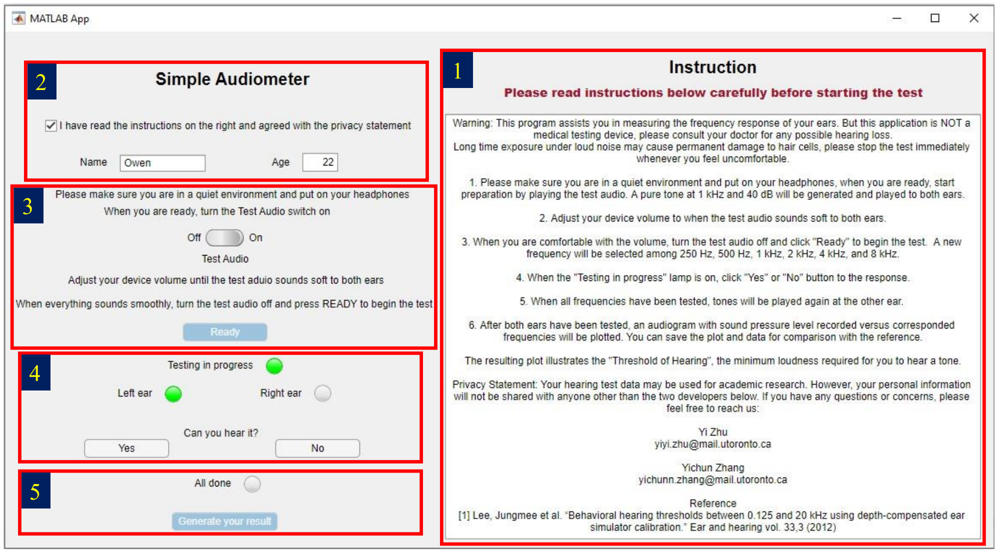

Figure 8 Detailed Divisions of the Audiometer Application

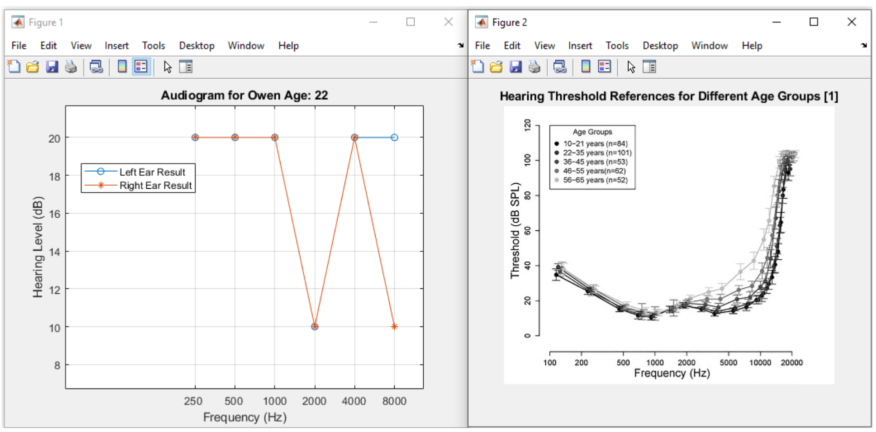

Figure 9 Sample Audiometer Application Test Results

This audiometer is packed into a single installation file and can be run on any computer using Windows operating system even without MATLAB. The GUI of the audiometer is shown in Figure 8. Step by step instructions for using this audiometer application are as follows:

- In section 1, read and understand the instruction carefully.
- When finished with the previous step, click the checkbox in section 2 and enter name and age.
- In section 3, turn the test audio on and adjust the computer volume to a comfortable level. When finished, turn the test audio off and click on the ‘Ready’ button.
- In section 4, the green lamp indicates whether the test is in progress and which ear is being tested. Respond to hear the tone or not by clicking on the ‘Yes’ or ‘On’ button.
- When both ears have been tested, the ‘All done’ lamp in section 5 will be on. Click on the ‘Generate your result’ to get the test result and reference figure. Two figures similar to Figure 9 should be displayed, and the result figure is also saved to the current system path.

Appendix II

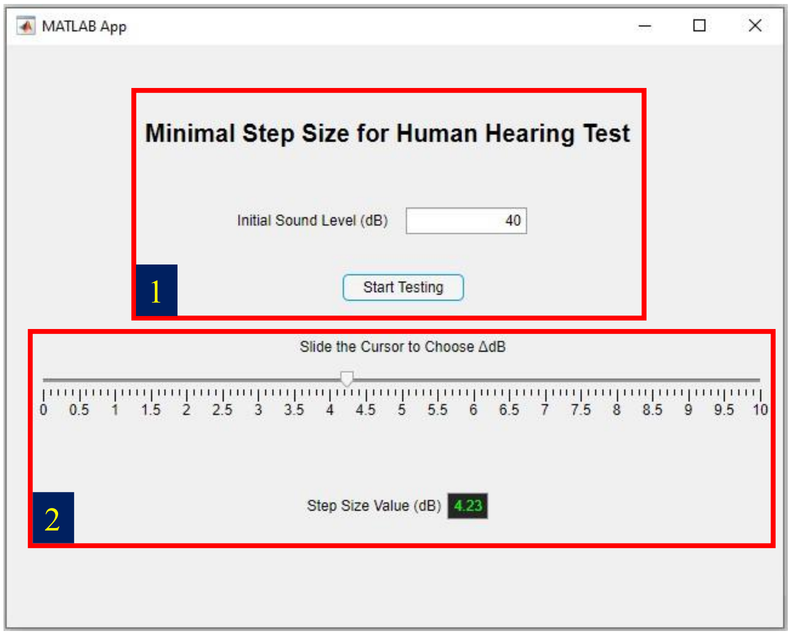

Figure 10 Detailed Divisions of the Step Size Testing Application

As can be seen circled and labeled in Figure 9 and Figure 10, the GUI of this Step Size Testing Application is divided into two sections. Step by step instructions for using this application are as follows:

- In section 1, choose the initial sound pressure level in dB and click on 'Start Testing' when ready. Two one-second-long pure tones with the same amplitude will be played with a one-second pause in the middle.
- In section 2, slide the cursor to choose the ΔSPL to be added to the second pure tone and click on 'Start Testing' in section 1 to re-do the test. Record the value displayed in the 'Step Size Value (dB)' screen when a difference is noticed.

Appendix III

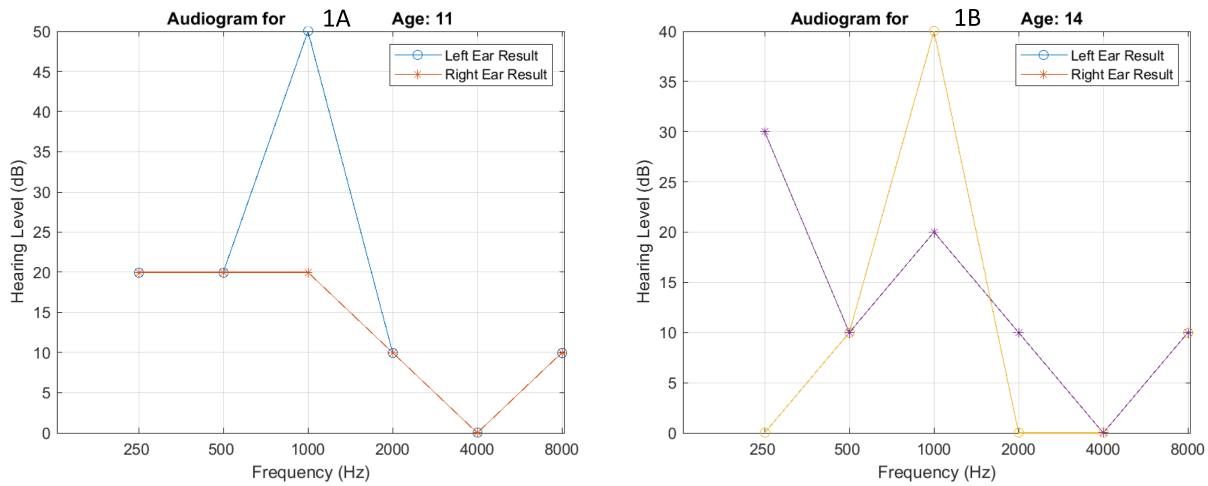

Figure 11 Results of Hearing Thresholds from Participants in 10s

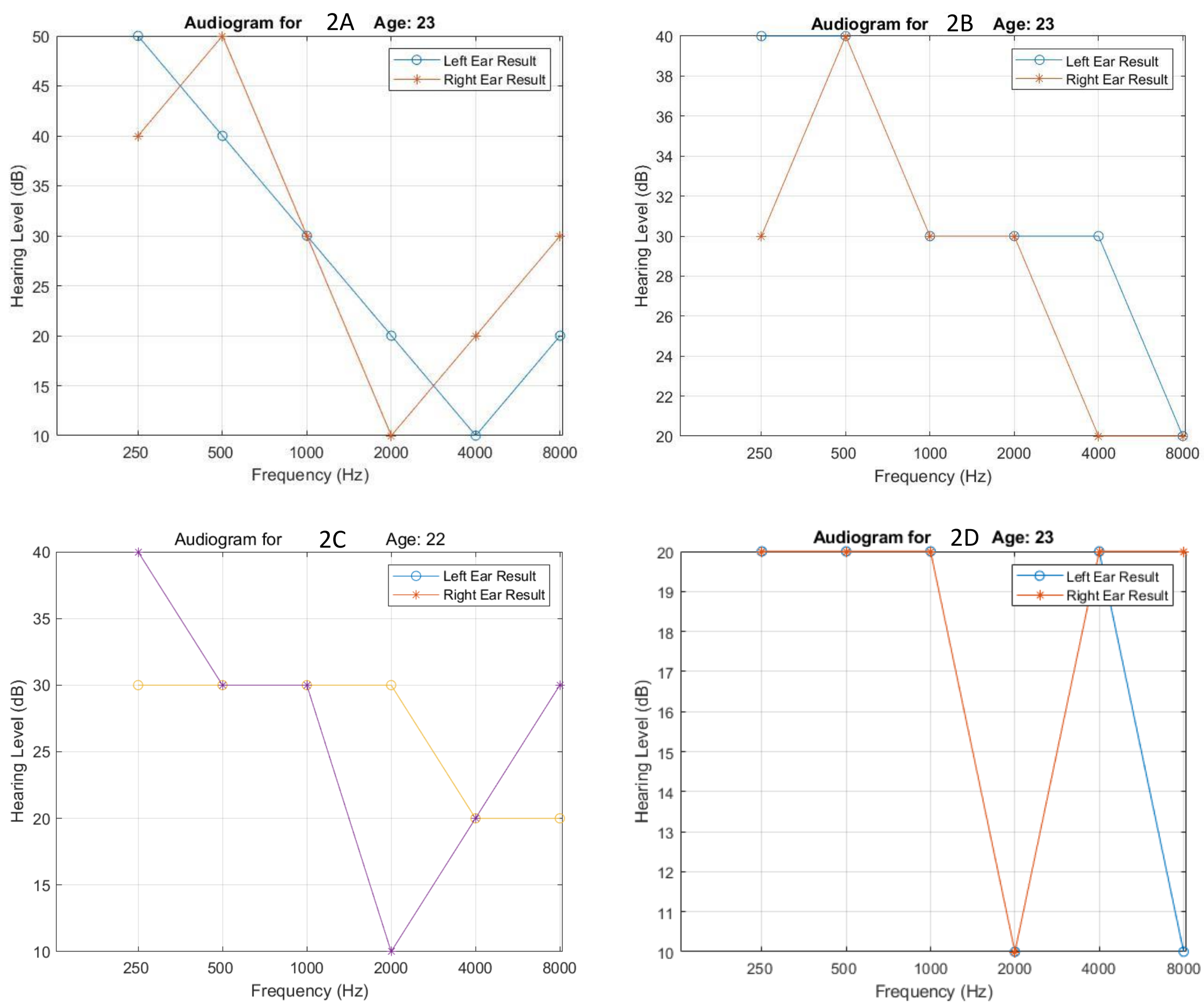

Figure 12 Results of Hearing Thresholds from Participants in 20s

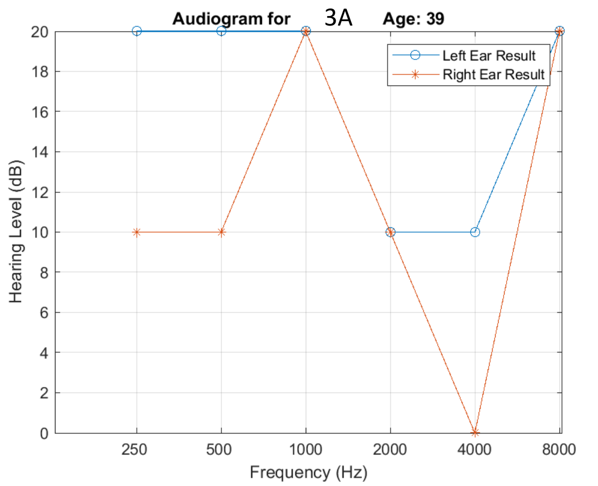

Figure 13 Results of Hearing Thresholds from Participant in 30s

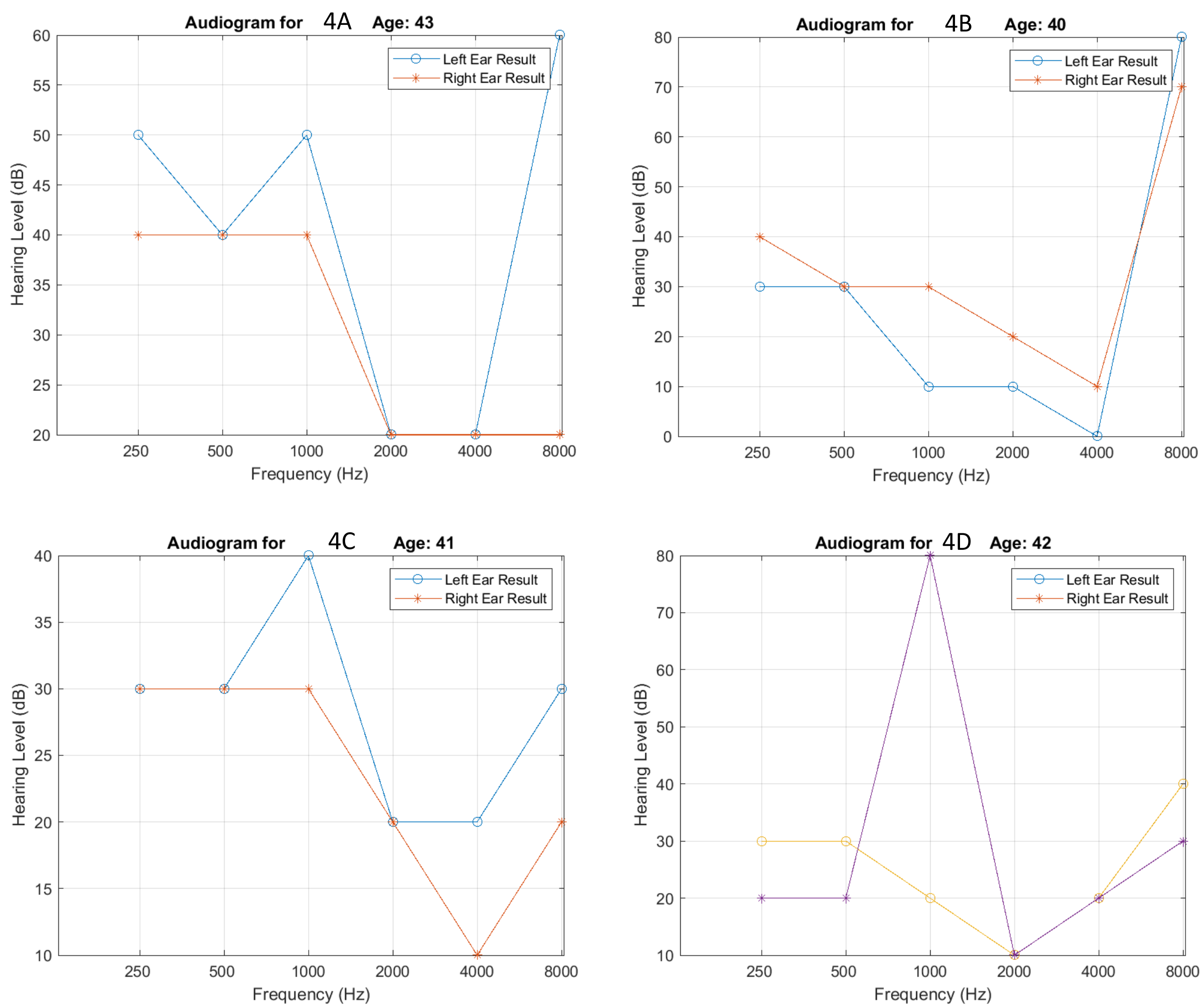

Figure 14 Results of Hearing Thresholds from Participants in 40s (A)

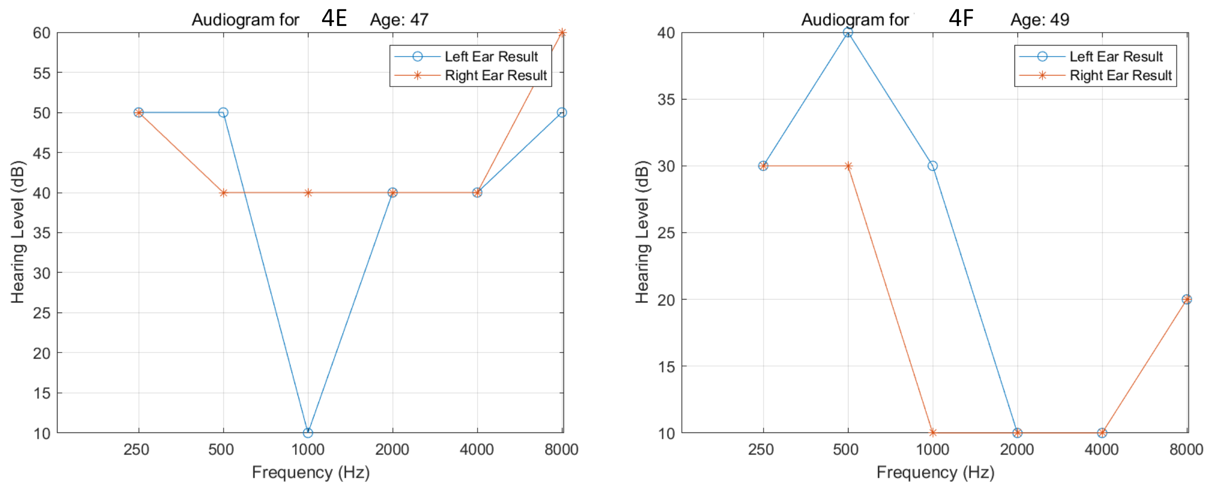

Figure 15 Results of Hearing Thresholds from Participants in 40s (B)

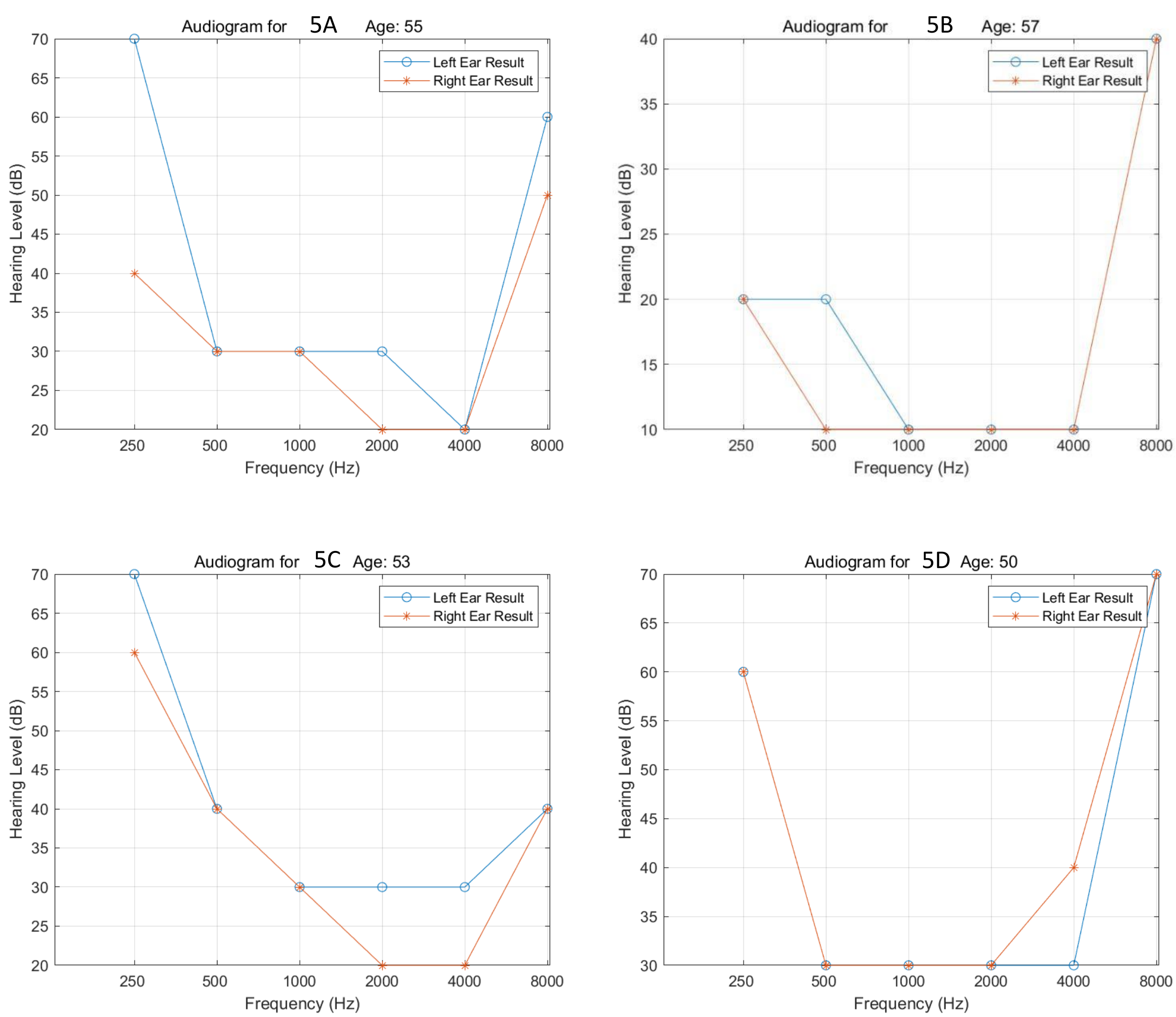

Figure 16 Results of Hearing Thresholds from Participants in 50s (A)

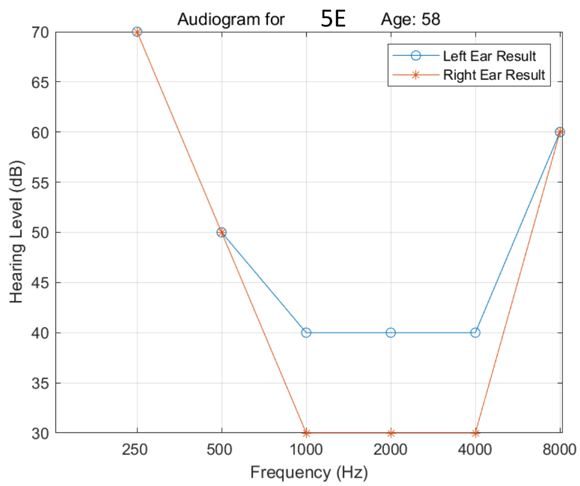

Figure 17 Results of Hearing Thresholds from Participants in 50s (B)

Appendix IV

Table 1 Experimental Data of the Minimal Noticeable Volume Increase Study

Reference dB	ΔdB Subject 1	ΔdB Subject 2	ΔdB Subject 3
40	5.5	4.5	4.7
45	5.2	4.8	4.6
50	4.8	4.8	4
55	4.5	4.5	3.8
60	3.5	4.5	3.2
65	3	3.5	2.6
70	2.5	2.5	2.4
75	1.8	2.5	2.3
80	2	2.4	3.5
85	2.1	3	4.3
90	3.5	2.3	5.3
100	4	2.7	5.5