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Original Research/Review

Analysis of the harmonic structure of the vowel /a/ taking into account the age and gender of the speaker

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Abstract

Sound waves are disturbances propagating through an elastic medium that, upon reaching the ear, elicit auditory sensations. Sounds generated by the surroundings can be captured by a transducer (microphone), which transforms them into an electrical signal. The signal from the microphone is then transmitted to a computer, where software allows for the extraction and analysis of individual tones. This process enables the description of psychoacoustic characteristics of sound as perceived by the human ear, including pitch, loudness, and timbre. Specific sound signals can be transformed into a sound spectrum, facilitating the examination of voice harmonics, which are integer multiples of fundamental tone (lowest voice frequency). Harmonics possess various attributes, including intensity and frequency (loudness and pitch). This article provides an overview of the human voice and related topics, along with insights from studying differences in psychoacoustic features of sound based on gender and age. The objective of the paper is to show harmonic structure of vowels and emphasize the importance of studying the human voice.

Keywords: sound wave, intensity, harmonic frequencies

1. Introduction

The formation of the human voice is an exceedingly complex process that relies on various organs and mechanisms. We can distinguish two stages in the creation of the voice. The first stage is phonation, which occurs in the larynx in conjunction with the respiratory system [3]. This process is responsible for producing the fundamental frequency, which is the primary acoustic signal generated by the vocal cords. The next phenomenon is articulation, where the voice gains resonance and amplification. Articulation takes place through sound-shaping resonators located, among other places, in the nasal and oral cavities. The specific sites responsible for voice production and the corresponding processes are illustrated in Figure 1. The sound produced within the human body is interpreted as a sound wave.

2. Sound wave

A sound wave is a disturbance involving the transfer of mechanical energy due to the vibrations of particles in a medium, such as air. Particles undergo compression and rarefaction. The number of these compressions and rarefactions occurring in one second is referred to as the frequency of the wave. The human ear can detect a wide range of sound frequencies, from 16 Hz to even 20 kHz [5]. Values lower and higher than this range are respectively known as infrasound and ultrasound, with both being inaudible to humans. Another characteristic of a sound wave is its velocity. The physicist who first experimentally determined the speed of sound was M. Mersenne [1]. His measurement in 1636 indicated a speed of approximately 450 m/s, differing by around 120 m/s from modern measurements. Subsequent derivation of the formula for the speed of sound by Newton, and its refinement by Laplace, facilitated further developments in acoustics. Newton's-Laplace formula (1):

$$u = \sqrt{\frac{kp_o}{\varrho}}(1 + at) \tag{1}$$

In this formula:
u – the velocity of sound,
k – a constant,
p_o – the initial pressure of the medium,
ρ – the density of the medium,
a – another constant,
t – the time.

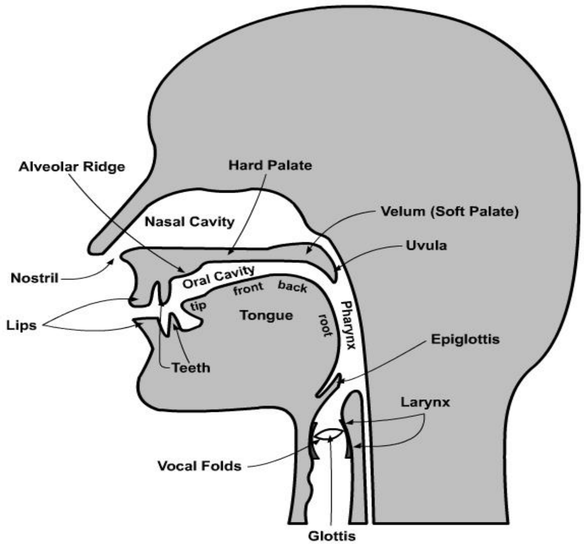

Fig. 1. Speech organs https://alic.sites.unlv.edu/chapter-11-2-speech-organs/ [9]

Measurement methods, including the use of an oscilloscope, have allowed for even more precise measurements of the speed of sound. By knowing the wavelength and frequency of the wave, it was possible to calculate its velocity according to formula (2):

$$u = \upsilon\lambda \tag{2}$$

In this formula:
u – the velocity of sound,
v – the frequency of the sound wave,
λ – the wavelength.

3. Psychoacoustic Characteristics of Sound

3.1. Intensity

Sound is measured as a sound pressure level (SPL), in units of decibels, with a sound level meter (SLM). A decibel is a ratio between a measured level and a reference level [8].

Sound intensity is the power carried by a wave per unit area, as defined by formula (3):

$$I = \frac{P}{S} \tag{3}$$

In this formula:
I – sound intensity,
P – the power of the sound wave,
s – the surface area.

Sound intensity can be defined in various ways, all of which are related to acoustic pressure and the velocity of the sound wave. The human ear can detect a wide range of sound intensities. To improve understanding and the clarity of results, the concept of sound intensity level, determined by equation (4), was introduced [4]:

$$L = 10lg\frac{I}{I_0} \tag{4}$$

In this equation:
L – the sound intensity level,
I – the sound intensity being measured,
I_0 – the reference intensity (the threshold of hearing, typically 10^{-12} watts per square meter).

3.2. Pitch

Pitch is dependent on the frequency of vibrations. In music, sequences of pitch define melody, and simultaneous combinations of pitch define harmony [7]. Lower frequencies result in lower pitch, while higher frequencies lead to higher pitch. Frequency is expressed in hertz, which corresponds to one vibration per second. The name of this unit originates from the discoverer of electromagnetic waves, the German physicist Heinrich Hertz (1857-1894).

The human ear is sensitive to a wide range of sound frequencies [2]. Different individuals can hear different frequency ranges, and this can depend on age and lifestyle. To assess one's hearing ability, audiometric tests can be conducted to determine the values of sound intensity and pitch at which one stops hearing.

3.3. Timbre

This is an individual characteristic of each person, setting us apart from others in society. It allows us to distinguish between voices with the same intensity, frequency, and duration. The timbre of a human sound is variable and can be modulated, among other methods, through adjustments in the larynx and the activation of specific resonant spaces. Physically, timbre refers to the number of harmonic tones and their amplitudes. In other words, timbre is dependent on the structure of the acoustic spectrum (the chart of component tones of the sound based on their pitch).

4. Psychoacoustic Characteristics of Sound

The experiment involved 100 teenagers in the age range of 14 to 17 years. Each participant was tasked with reading aloud the appearing vowels displayed on a computer screen, continuously, for about 3 seconds. After collecting the data, individual vowels were isolated from all the audio files. Subsequently, using the Sound Laboratory program at the Gdańsk University of Technology, sound spectra were created for these vowels, from which harmonic frequencies were extracted for further analysis. For certain groups, the sound intensity level (volume) was also recorded. All the collected data was used to generate tables, charts, and formulate conclusions.

5. Men - Conclusions

The collected data was grouped and presented in tables. Subsequently, for each vowel, the average harmonic frequency at the point of spectrum energy increase was determined, labelled as H[N]. In the next step, the ratio of the average frequency and a given N (representing the sequential number of the harmonic in the spectrum) was calculated. This provided the value H[N]/N, which is crucial for data interpretation and further analysis. Some of the results are presented in Tables 1-3.

Table 1. Average of the harmonic frequencies for vowel /a/ for the 2007-2008 cohort

Gender	Year of birth	Vowel	N	H[N]	H[N]/N
M	2007/2008	A	1	111.583	111.583
M	2007/2008	A	2	224.750	112.375
M	2007/2008	/a/	3	337.000	112.333
M	2007/2008	/a/	4	448.916	112.229
M	2007/2008	/a/	5	562.166	112.433

Table 2. Average harmonic values for vowel /a/ for the 2006-2007 cohort

Gender	Year of birth	Vowel	N	H[N]	H[N]/N
M	2006/2007	/a/	1	101.666	101.666
M	2006/2007	/a/	2	202.777	101.388
M	2006/2007	/a/	3	304.000	101.333
M	2006/2007	/a/	4	405.666	101.416
M	2006/2007	/a/	5	509.222	101.844

Table 3. Average harmonic values for vowel /a/ for the 2005-2006 cohort

Gender	Year of birth	Vowel	N	H[N]	H[N]/N
M	2005/2006	/a/	1	109.111	109.111
M	2005/2006	/a/	2	215.666	107.833
M	2005/2006	/a/	3	332.777	110.925
M	2005/2006	/a/	4	441.222	110.305
M	2005/2006	/a/	5	548.111	109.622

The obtained values of H[N]/N indicate that the study group consisted of males, as there are regular increments in energy around every 101-112 Hz. Values of fundamental frequency (H[1], also in the literature written as F0) are very similar as those in the article [11]. D. R. Feinberg, B. C. Jones, A. C. Little, D. M. Burt & D. I. Perrett received values of H[1] for men aged 20-22 equal 124.6 ± 20.5 Hz. In the research conducted within the age range of 2005-2008, there don't appear to be significant differences in the average harmonic values. For instance, the data in Table 2 is approximately 11 Hz lower than the data in Chart 1.

To provide a clearer illustration of the results, a graph (Fig. 2) was created to show the relationship between the average sound intensity level and the average harmonic frequencies for male participants for vowel /a/ (2007-2008 cohort). Figure 2 also maintains an increasing trend, although it doesn't increase uniformly.

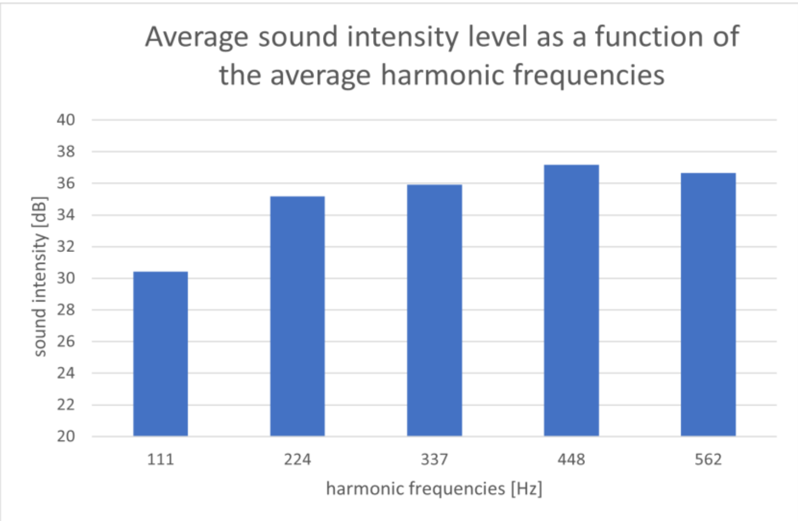

Fig. 2. Average sound intensity level as a function of the average harmonic frequencies for male participants for vowel /a/, 2007-2008 cohort.

6. Women - Conclusions

The next group of participants examined were women. The study was conducted in the same manner as for men. The data was collected and organized into tables. Sample results for vowel /a/ are presented in Tables 4-6.

Table 4. Average harmonic values for vowel /a/ for the 2007-2008 cohort

Gender	Year of birth	Vowel	N	H[N]	H[N]/N
W	2007/2008	/a/	1	219.857	219.857
W	2007/2008	/a/	2	439.071	219.535
W	2007/2008	/a/	3	662.607	220.086
W	2007/2008	/a/	4	884.035	221.008
W	2007/2008	/a/	5	1102.786	220.557

Table 5. Average harmonic values for vowel /a/ for the 2006-2007 cohort

Gender	Year of birth	Vowel	N	H[N]	H[N]/N
W	2006/2007	/a/	1	208.500	208.500
W	2006/2007	/a/	2	416.500	208.250
W	2006/2007	/a/	3	625.500	208.500
W	2006/2007	/a/	4	829.500	207.375
W	2006/2007	/a/	5	1038.250	207.650

Table 6. Average harmonic values for vowel /a/ for the 2005-2006 cohort

Gender	Year of birth	Vowel	N	H[N]	H[N]/N
W	2005/2006	/a/	1	199.000	199.000
W	2005/2006	/a/	2	400.500	200.250
W	2005/2006	/a/	3	602.312	200.770
W	2005/2006	/a/	4	801.625	200.406
W	2005/2006	/a/	5	1003.313	200.662

For women, the ratio H[N]/N ranges from 199 Hz to even 221 Hz, which is nearly twice as high as the values for male harmonics. The presented results demonstrate that human voices differ based on gender. The energy clusters in the female voice spectrum are shifted towards higher frequencies significantly more than in male voices. Another noticeable difference in male and female voices is the varying relationship between the sound intensity level and frequency. The graph of female data shown in Fig. 3 significantly differs from the male graph (Fig. 2). A female voice is characterized by a higher sound intensity level than a male voice, and the sound intensity level graph does not exhibit an increasing trend.

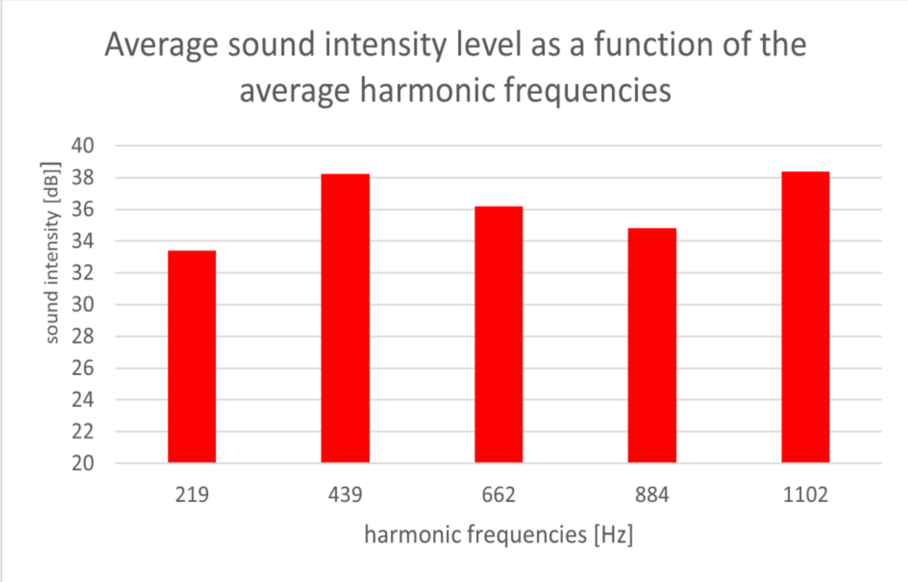

Fig. 3. Average sound intensity level as a function of the average harmonic frequencies for female participants for vowel /a/ in the 2007-2008 cohort.

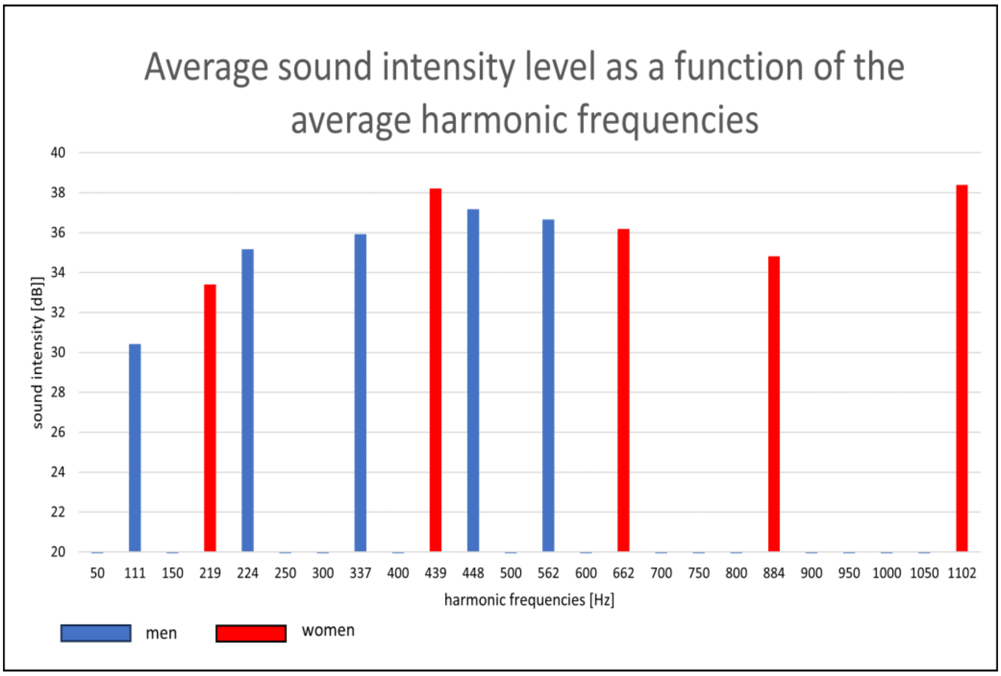

Fig. 4. Average sound intensity level as a function of the average harmonic frequencies for both male and female participants together for vowel /a/ in the 2007-2008 cohort.

Fig. 4 shows the average harmonic frequencies for both male and female participants together in one graph. Male harmonic frequencies are marked in blue whereas female are marked in red. As mentioned in the article, the harmonics of women are shifted towards higher frequencies compared to men. To illustrate these differences more effectively, a graph (Fig. 4) was created, where it's clear that there is a larger concentration of blue bars (male harmonics) and a smaller concentration with a shift of up to 1100 Hz in the red bars (female harmonics).

7. Comparison

To verify the conclusion that human voices differ based on gender, the presented study was compared to the work of a student from the Lodz University of Technology titled [6]. In this study, the author also examined two groups, namely men and women. The results of this experiment were presented in graphs, namely Fig. 5 and Fig. 6. Graphs come from work [6] and were obtained using computer program.

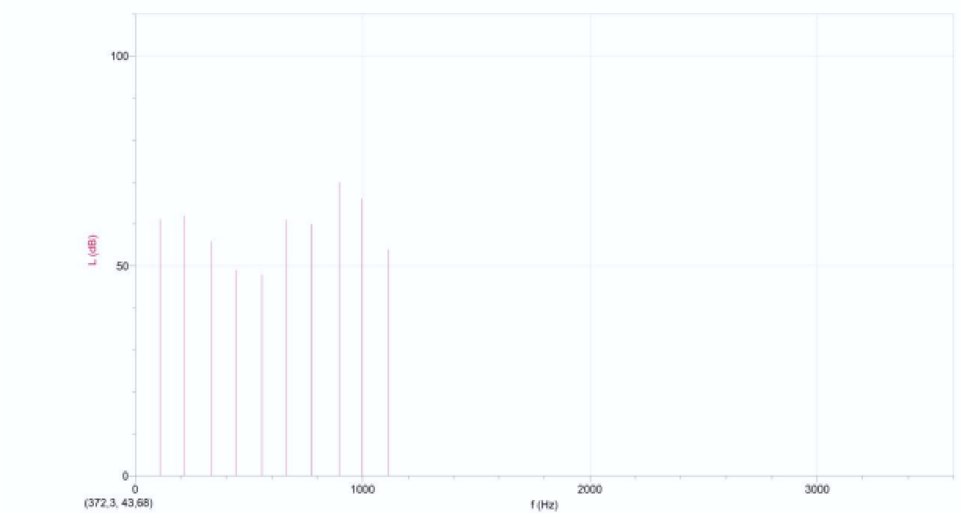

Fig. 5. Average sound intensity level as a function of the average harmonic frequencies for male participants.

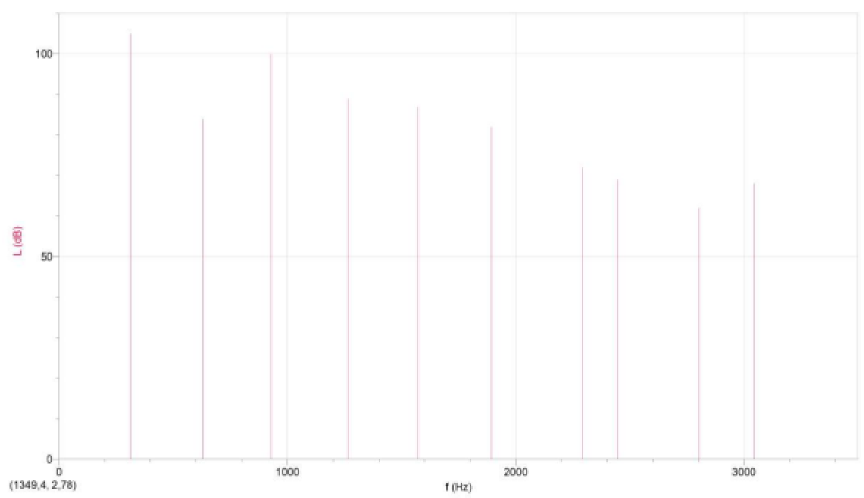

Fig. 6. Average sound intensity level depending on the average harmonic frequencies for women.

In Fig. 5, it can be observed that male harmonics are closely clustered and occur regularly at approximately every 100 Hz, while in Fig. 6 depicting female harmonics, the frequency values are almost three times higher than those of males. The sound intensity level is also different, with higher values for females.

The results presented in the paper [6] confirm that the voice differs depending on gender. Women's harmonics are shifted towards higher frequencies, occur less frequently, and achieve a higher sound intensity level compared to male harmonics.

Human voice is very complicated but at the same time inspiring. Conducting research about psychoacoustic features could contribute to the development of science and technology. Research may also be conducted for other age groups in future. It will show voice differences over the years just like in the [10] paper where authors studied differences of fundamental tone depending on the age of responders.

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