Study of the Distribution of Harmonics in the Complex Sound

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ABSTRACT: *The sound of an instrument is often described as a "complex" sound. A complex sound can be broken down into pure (simple) sounds. In many cases, a sound can be thought of as consisting of fundamental and harmonics that provide its characteristic characteristics, depending on the number of harmonics, their distribution, their amplitude and their envelope. The human auditory system's ability to perceive pitch is related to the harmonics in a complex sound. In this paper, we will look at how the distribution of harmonics within a complex sound influences pitch perception. We will use spectral analysis and listening tests to do this. Particular attention will be paid to the phenomenon of "missing fundamentals."*

Keywords: Complex Sound, Harmonics, Auditory System, Pitch Perception

Received: 3 May 2023, Revised 20 June 2023, Accepted 4 July 2023

DOI: 10.6025/jio/2023/13/3/85-93

1. Introduction

Ability that a human auditory system perceives pitch in a complex sound is of extreme importance for understanding music and speech, and for analysing sound images [1]. Many instruments generate specific sounds, whose main attribute to create a melody is pitch. In verbal communication, pitch carries prosodic information in languages such as English and semantic information in tonal languages such as Mandarin and Chinese. On the basis of differences in fundamental frequencies, we can differentiate sounds and order them in appropriate music scales [1].

From an acoustical point of view, music instruments represent sources that generate sounds of specific characteristics including spectral content. Majority of instrument sounds consist of a fundamental (the lowest partial) and upper partials that can be harmonically related to fundamental or not [2]. Factors affecting perception of such sounds are related to the number, distribution, amplitude and envelope of the partials. Very interesting feature that has attracted attention during the previous decades is pitch perception, and especially a phenomenon known as “missing fundamental”. This has been a motive to investigate the pitch perception in complex sounds and the mentioned phenomenon in more detail here.

For the purpose of investigating pitch perception, various complex sounds are first generated and then analyzed. The pitch perception in such complex sounds is examined through the listening tests. The impact of harmonics distribution on the pitch perception is observed. Emphasis is placed on studying the perceptual consequences of the phenomenon “missing fundamental”.

2. Sound and Perception

The simplest possible sound is a pure sound representing a sinusoidal signal (sound). When a sound consists of two or more pure sounds (partials), it represents a complex sound that can be given by:

$$s(t) = \sum_{n\geq 1} A_n \cos(2\pi f_n t + \theta_n), \tag{1}$$

where A_n is the amplitude, f_n is the frequency and θ_n is the phase. The sound with the lowest frequency is called fundamental, while other sounds whose frequencies are higher are called overtones. An interesting example of sound is obtained when all of the frequencies are integer multiples of a given (fundamental) frequency f, $f_n = nf$. The sound signal is then periodic with period $T = 1/f$. The fundamental (caused by the first mode of vibration) determines the pitch of the corresponding complex sound (tone). The frequency f_n (sound at that frequency) is called the n-th harmonic. Accordingly, the fundamental is the first harmonic. Perceptually, a sound containing only few harmonics is perceived as “poor”, while a sound containing a number of harmonics is perceived as “rich”.

Sounds of all music instruments consist of many partials. Some of them are harmonically related to fundamental and some are not [2]. According to Hornbostel-Sachs system, all music instruments can be classified into five groups depending on what actually makes the sound [3]. These groups are: ideophones, membranophones, chordophones, aerophones and electrophones. In both aerophones and chordophones, there is something long and thin that basically vibrates in one dimension: a vibrating string or column of air. This produces strong resonances, and sound tends to be pure with a specific pitch. In membranophones, the membrane can basically vibrates in two dimensions, while in idiophones, the body of the instrument can vibrate in three dimensions. As the number of dimensions goes up, the resonances become more complex and weaker, and therefore, the sounds become more complex and with more diffuse pitch [3].

Generally, pitch represents an auditory sensation defined in various ways. The most common one given by American National Standards Institute (ANSI) in 1994 describes pitch as an “*attribute according to which the sounds can be arranged in a musical scale, from lowest to highest”* [1]. Pitch is closely related to frequency, but there is no absolute equivalency between those two since the frequency is an objective concept, while pitch is a subjective.

With modern methods for measuring brain activity (fMRI, EEG, MEG), it becomes possible to locate the area of auditory cortex that corresponds to pitch perception called *Heschl’s gyris,* and it is positioned in the right cerebral hemisphere [1,4]. In the auditory cortex, there are two types of neurons:multi-peak and single-peak neurons [1,4]. Multi-peak neuron can be excited with multiple frequencies that are harmonically related. A frequency required to have minimum energy to excite a multi-peak neuron is called the central frequency and it is equal to frequency of the first harmonic (fundamental). The other frequencies are required to have more energy to make the same excitation [1,4]. Single-peak neuron is excited only by a single frequency [1]. In the auditory cortex, about 20 % of neurons represent multi-peak neurons (30 Hz-5 kHz), whereas 80 % are single-peak neurons (5 kHz-20 kHz) [1,4].

Important frequencies for understanding human speech are ranged up to about 4 kHz [1]. On the other hand, the highest frequency of a fundamental tone of symphony orchestra has a piccolo flute, and it is about 4.5 kHz [1]. The tests have shown that people best understand the melody up to 5 kHz; beyond this frequency understanding of melody is difficult or impossible [1].

When the first harmonic (fundamental) is excluded from a complex sound whose partials are harmonically related, we still can perceive the pitch equal to the frequency of missing fundamental. This phenomenon is known as “missing fundamental” [1].

3. Methods of Investigation

For the purpose of spectral analysis of various instrument sounds, the samples from Steinberg’s sounds library called *Hypersonic II* were used. Sample rate of all samples was 44.1 kHz while 16 bits were used for quantization.

Sounds of some instruments belonging to the groups chordophones (acoustic guitar, harp, piano and violin), aerophones (oboa and flute), membranophones (timpani, kick, snare and tambourine) and ideophones (closed hi-hat, open hihat, crash cymbal, finger snap, rattle and effects of wind) are spectrally analyzed. Instruments from the group electrophones are excluded from the analysis because they generate sounds identical to those of instruments from other groups.

Since pitch perception is a subjective attribute, it is investigated here through the listening tests. They were carried out in a typical listening situation (in a typical living room). In the listening tests, different complex sounds were presented to the subjects over the headphones (*Beyedynamic DT-770 Pro*), while the subjects’ response was recorded by the condenser microphone (*AKG C444*) and stored in the corresponding audio tracks using *HP 110 Mini computer* with *Intel Atom N270* processor and integrated sound board. The task of the subjects was to repeat pitch of the reproduced sound by singing neutral syllable *La* or to give the answers to particular questions.

Ten subjects participated in the listening tests of which 7 were male and 3 were female. The mean age of the subjects was 26. Nine subjects have graduated from the Faculty of Arts (Music Arts) and one subject is a student of the secondary music school. In that regard, they can be considered to be expert listeners.

The listening tests are divided in five groups – test 1 to test 5. In the listening test 1, the complex sounds of duration of 2 seconds consisting of fundamental and 4 harmonics were presented to the subject by the headphones. The frequency of fundamental is 440 Hz, while the frequencies of harmonics are: 880 Hz, 1320 Hz, 1760 Hz and 2200 Hz. The spectrum of such a complex sound is given in Figure 1. The task of the subjects was to repeat the pitch of the reproduced sound by singing neutral syllable *La*.

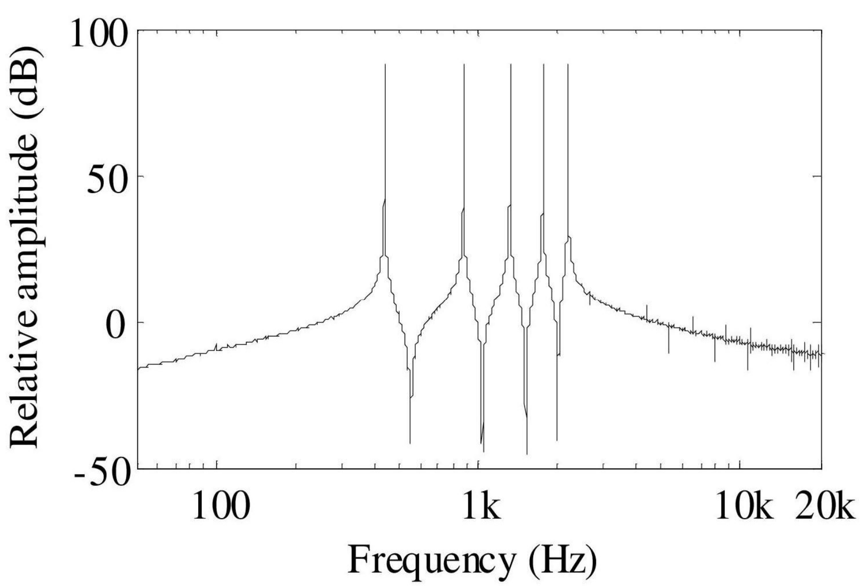


Figure 1. Spectrum of generated complex sound used in the listening test 1

In the listening test 2, the complex sound used in the listening test 1, but without fundamental was presented to the subjects in the same manner as in the test 1. The task of the subjects was also to repeat the pitch of the reproduced sound by singing the neutral syllable *La*. The purpose of this test is to study the phenomenon “missing fundamental”.

Two complex sounds separated by silence of 1 second were presented to the subjects in the listening test 3. The first sound is the same as in the test 1, while the second one is the same as in the test 2. The spectrogram of complex sound applied in the test 3 is given in Figure 2. This time, the task of the subjects was to answer a question: “Is the difference between two reproduced sounds in pitch or in timbre”?

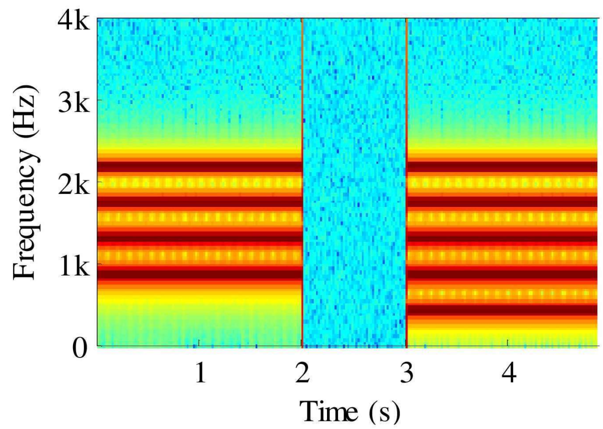


Figure 2. Spectrogram of generated complex sound used in the listening test 3

In the listening test 4, the complex sound of duration of 2 seconds consisting of 5 harmonics with random distribution was presented to the subjects in the same manner as in other tests. The frequencies of harmonics are: 440 Hz, 475 Hz, 483 Hz, 502 Hz, 543 Hz. The spectrum of this complex sound is given in Figure 3. The task of the subjects was the same as in the tests 1 and 2 - to repeat the pitch of the reproduced sound by singing the neutral syllable *La*.

Similarly as in the test 2, the first partial (with frequency of 440 Hz) of the signal from test 4 was removed, and such a complex signal was presented to the subjects in the listening test 5. The task of the subjects was the same - to repeat the pitch of the reproduced sound on the neutral syllable *La*. The purpose of this test is to compare the results with those from the tests 1, 2 and 4 in studying the phenomenon “missing fundamental”.

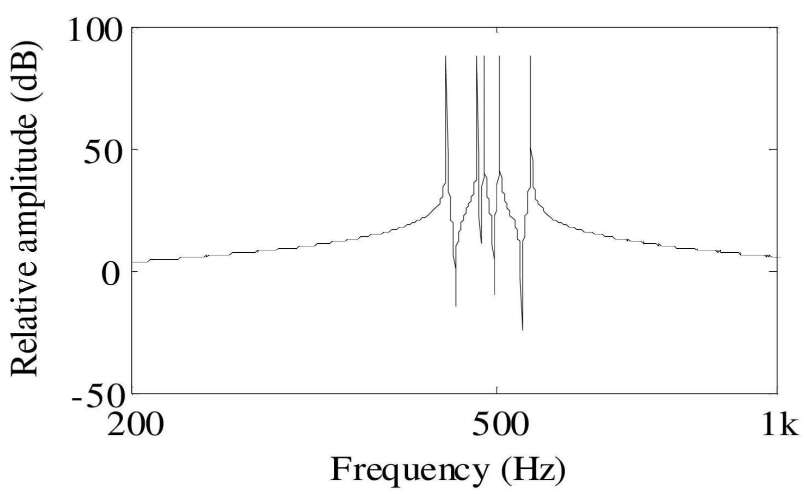


Figure 3. Spectrum of complex sound consisting of 5 partials in nonharmonic distribution used in the listening test 4

4. Results

Performed spectral analysis shows that chordophones and aerophones instruments have harmonically related partials, while membranophones and ideophones instruments do not have a harmonic distribution of partials. Representative examples of instrument sound spectra are given in Figure 4.

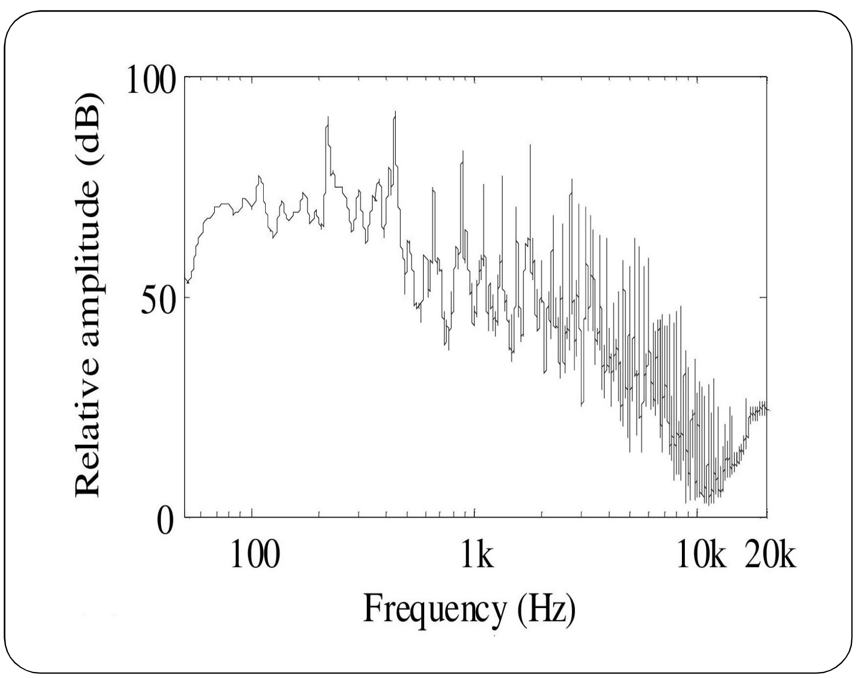
The spectrum of piano (Fig. 4(a)) has harmonically related partials. The frequency of the first harmonic (fundamental) is 215 Hz and frequencies of overtones are: 430 Hz, 645 Hz, 860 Hz, 1075 Hz, 1290 Hz, etc. The spectrum of oboa also has harmonically related partials (see Fig. 4(b)). The frequency of the fundamental is 656 Hz and the frequencies of overtones are: 1312 Hz, 1968 Hz, 2624 Hz, etc. On the other hand, snare and crash chinel do not generate harmonically related partials (see Fig. 4(c) and (d)).

In the listening test 1, all 10 subjects were able to successfully repeat the pitch of the reproduced complex sound containing fundamental and 4 harmonics. A representative example of a subject's response is given in Fig. 5. From presented spectrum and spectrogram, it can be seen that frequency positions of fundamental and harmonics are close to those from the test sound.

The results of the listening test 2 are similar to those of the test 1. So, all 10 subjects were able to successfully repeat the pitch of the reproduced complex sound without fundamental (but with harmonically related partials), that is, they were able to reproduce the pitch of missing fundamental. A representative example of the response of a subject is given in Figure 6.

In the listening test 3, where the subjects compared two complex sounds (with and without fundamental) separated by silence of 1 second, 9 subjects responded that there was a difference in timbre, and 1 subject responded that there was a difference in pitch of compared sounds.

The results of the listening test 4 are different than those from the tests 1 and 2. Since the partials of the presented complex sound are not in harmonic relation, the subjects were not able to perceive and reproduce (sing) the same pitch. The distribution of answers, that is, distribution of the frequencies of fundamental of sang neutral syllable *La* is shown in Figure 7.



(a)

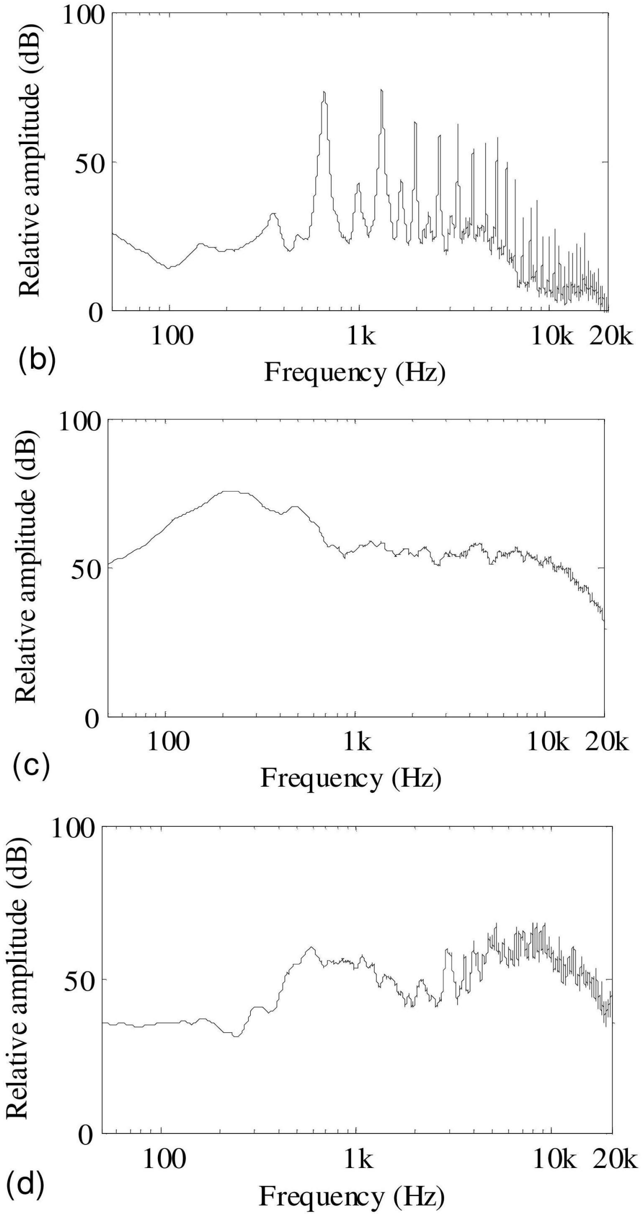


Figure 4. Spectra of sounds of representative instruments: (a) Piano, (b) oboa, (c) Snare and (d) crash cymbal

Similarly to the results of the test 4, the perceived and reproduced pitch of complex sound without first partial presented in the listening test 5 is not the same for all subjects. The distribution of the fundamental frequency of the subjects' responses (sang neutral syllable *La*) is shown in Figure 8.

5. Conclusion

From the previously mentioned results, it can be concluded that the distribution of partials (harmonics) in complex sound plays a key role in the pitch perception. In the case of harmonically distributed partials in a complex sound, the most energy excites the multi-peak neuron(s), so that the impression of pitch is unambiguously clear to the listener. In absence of fundamental frequency, other harmonics excite multi-peak neuron whose central frequency corresponds to the fundamental, and the listener's impression of pitch corresponds to that of the fundamental frequency. This principle can explain the phenomenon "missing fundamental".

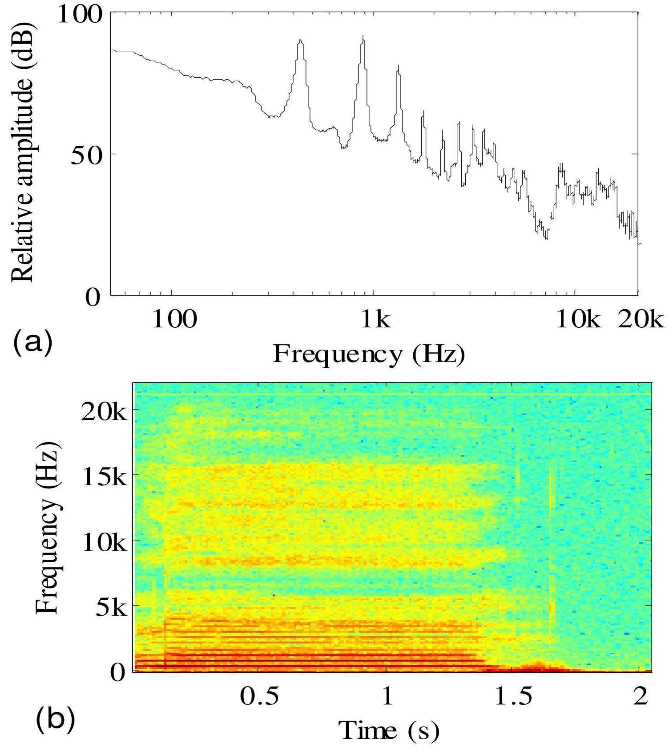


Figure 5. Representative response of a subject in the listening test 1:spectrum (a) and spectrogram (b) of the sang neutral syllable *La*

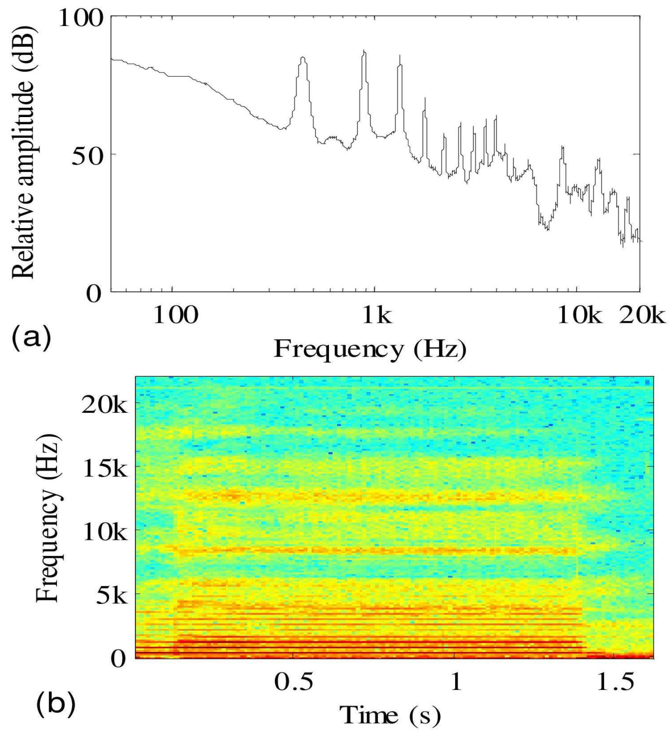


Figure 6. Representative response of a subject in the listening test 2:spectrum (a) and spectrogram (b) of the sang neutral syllable *La*

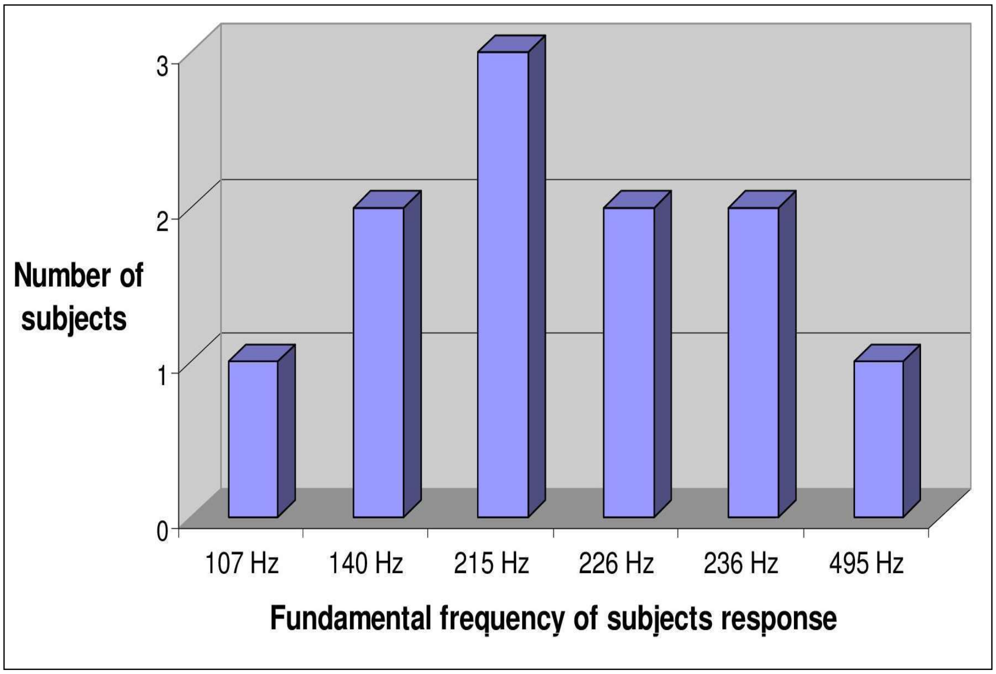


Figure 7. Distribution of fundamental frequency of subjects' responses (sang neutral syllable *La*) from the test 4

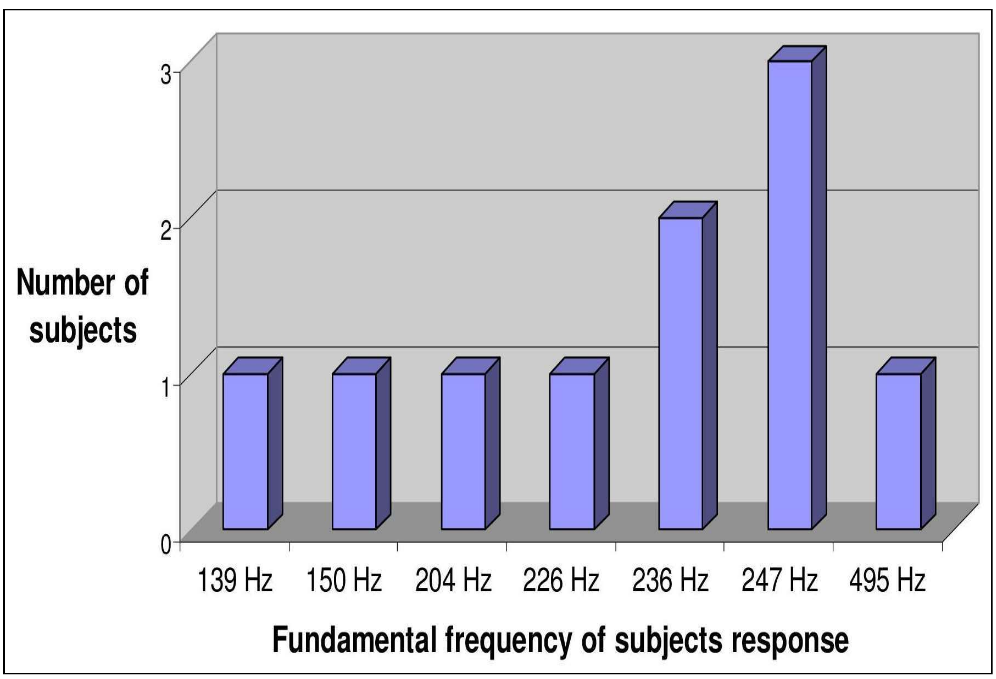


Figure 9. Distribution of fundamental frequency of subjects' responses (sang neutral syllable *La*) from the test 5

Acknowledgement

This research is partially supported by the Ministry of Science and Technological Development of Serbia through the project No. 44009.

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