STANDARD FRENCH VOWEL FORMANTS VS. CHARACTERISTIC TONES OF ROUSSELOT: TUNING FORKS TECHNIQUE RECONSIDERED

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Abstract: In the current study the historical instrumental method of speech analysis using tuning forks is considered from a new point of view. The set of tuning forks for French oral vowels with the engraved frequency values described by Rousselot in the early 20th century is used in a number of experiments. Firstly, the frequencies of the tuning forks were measured with the use of modern methods of acoustic analysis. The accuracy of their values was proved, which allowed their comparison with modern data on French vowel formant frequencies. Eventually, the perception experiment was conducted to find out modern native speakers’ perception strategies.

1 Introduction
The Department of Phonetics of the Saint Petersberg State University houses a wide collection of tuning forks and resonators. The head and founder of the department Lev Scherba studied in Paris and worked in the laboratory of Jean Pierre Rousselot (l’abbé Rousselot) in 1908 [3]. Thus Scherba was acquainted with the newest instrumental methods and techniques of that time. As he noted himself [28], he measured Russian vowels using Rousselot’s tuning forks. In this relation a set of thirteen tuning forks adjusted to the French oral vowels from the Department collection deserves a special mention (see Fig.1). It was seemingly produced by E. Zimmermann, since the manufacturer’s mark “E Z” is inscribed on the yoke of these forks. It means that the set could hardly be commissioned by Rousselot, as long as this scientist generally commissioned his instruments to R. Koenig [25, 31]. At the same time the values engraved on the tuning forks correspond precisely to the numerous descriptions of the French vowel characteristic tones by Rousselot [22, 25]. It makes us suppose that Scherba commissioned to Zimmermann this set composed according to Rousselot’s data. The engraved values are in v.d., i.e. vibrations doubles, a French term which equals to the modern unit of Hertz. The set also includes a wooden hammer and a board with the inscribed symbols corresponding to the thirteen tuning forks.

Figure 1. The set of 13 tuning forks adjusted to the French oral vowels, Phonetic Department collection, Saint Petersburg State University, Russia (photo by the authors)

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2 Background of the current study

Tuning forks are mostly known today for their use in music and in medicine. The fact of this dual usage can be observed from the beginning of their existence. A good example is a tuning fork invented and elaborated by English trumpet and lute player John Shore. When Shore played in Handel’s orchestra, he gave one of his tuning forks to the composer. Then Handel gave it to the Foundling Hospital in 1751 [2]. Another field in which tuning forks traditionally serve as tools has always been physics and notably acoustics [1, 7, 31]. Therefore the tuning fork became one of the first devices of acoustic phonetics at the very beginning of the speech instrumental research [17, 18, 25].

2.1 Pitch tuning standards

In acoustics and, particularly, in experimental phonetics in 19th and in the early 20th century pitch was described by means of musical notation and/or physical terms. Musical notation was appropriate in cases when the tone was defined solely by ear. In numerous works of this period both notations are used [17, 18, 24]. However, the musical notation is sometimes misinterpreted because a variety of pitch tuning standards or systems existed at that time. It still exists today, although on a much smaller scale.

According to J. P. Rousselot [26], at the beginning of the 18th century the note “la” (or “A” in Latin nomenclature) consisted with 405 vibrations per second. Nevertheless, the orchestra tuned their instruments higher and higher in order to obtain brighter sound. Thus, there was a diversity of pitch tuning in Europe with maximum at 452.5 or even 455.5 vibrations per second. In Great Britain, as indicated in [2], 452 vibrations per second became a Philharmonic Pitch in 19th century. Another value, 435 vibrations per second at 18° C, was suggested by J. Lissajous. He was one of a group of French scientists and composers developing new pitch standard. This standard was adopted in France in 1859 [1] and announced as the International Pitch in 1885 [32]. In some sources this standard is also cited as the New Philharmonic Pitch [2]. The pitch which is most commonly applied nowadays to the so-called middle “la” is that of 440 vibrations per second known as the Stuttgart standard [1]. The initiator of its use is German amateur scientist J. H. Scheibler, who is also known as the tonometre inventor [31]. The advantage of this pitch standard is that it enables obtaining the whole number of vibrations for most of the notes [1, 26]. This pitch was used by Helmholtz in his “Physiological Theory of Music” [17]. This fact caused a misinterpretation of cited values when this work was translated into French and the musical notation was referred to physical terms [26]. The pitch adopted by J. P. Rousselot in his studies differs from those mentioned above. It differs even from the French standard of his time because the investigator followed the system of Rudolf Koenig, whose instruments Rousselot employed [25, 31]. Koenig tuned his devices into the middle “ut” (i.e. “do” or “C”) at 256 vibrations per second at 20° C. Therefore the “la” was supposed to be at 426.6 [24]. This standard, only one octave higher, i.e. C at 512 Hz, is also known today for its clinical use and is named “scientific” or “philosophical” pitch [2]. This very pitch was applied by the tuning fork’s inventor John Shore [2].

2.2 Physical terms diversity

There is a diversity of terms in most of relevant literature of the 19th century. Sometimes a number of them occur within the same work. As mentioned above, J. P. Rousselot calculates the values in vibrations doubles, i.e. “double” vibrations, the French term for vibrations per second. He sometimes translates them in a number of vibrations simples or demi-vibrations, i.e. a half of the “double” or “complete” vibration. The term vibrations simples was traditionally used in France [24, 25, 26, 27]. Outside France the widespread term was cycles per second (c.p.s. or c.s.) [1]. The unit of Hertz officially replaced it only in 1960 [6], although the name of Hertz was given to the unit in 1930. This discordance in terminology leads from time
to time to some confusions even today. Thus the following equation shows the correspondence of various terms indicating the number of vibrations per second:

\[
1 \text{ vibration per second} = 1 \text{ v.d. (vibration double)} = 2 \text{ v.s. (vibrations simples)} = 2 \text{ d.v. (demi-vibrations)} = 1 \text{ c.p.s. (cycle per second)} = 1 \text{ Hz.}
\]

2.3 Measuring pitch with tuning forks: techniques used by J. P. Rousselot

Many different techniques to measure vowel pitch by means of tuning forks or resonators existed. One of them supposed setting the vocal tract as resonator for the tuning fork’s sound. When the correct articulation for a concrete vowel was formed, the tuning fork should be placed nearby the mouth. Then it was struck not too strong in order to avoid too much additional noise. If the articulation was correct and the tuning fork’s pitch was well found, the tuning fork’s sound was reinforced [25]. Another technique intended the use of the weighted adjustable tuning fork (i.e. with sliders on its prongs). Once the sound enhancement was found, as in the previous case, it was possible to check the value through the lips position repetitive change. Rousselot gives an example of the sequence “à – ô – â – û” etc. [26]. If the suggested value was correct, the last heard sound would be the target tone [26]. Rousselot also describes other two methods when a vowel was whispered or sung at a given note and then reinforced by a sounding tuning fork or a resonator [24, 25]. Although the last techniques were familiar to Rousselot, the suggested values of the French vowel characteristic tones (in v.d. or v.s.) apparently consisted with the first methods’ result [22, 25]. Rousselot himself indicated in this relation that his whispered vowels differed from the silently articulated vowels and that a singing vowels changed their characteristics [26].

2.4 French oral vowel system described by J. P. Rousselot

Rousselot gives a detailed description of the French vowel system including nasal vowels [22, 23, 25]. His definition of the front unrounded and back oral vowels is of special interest, since the characteristic tones of these vowels are represented in the set of the tuning forks. In the current study, Rousselot’s terms and symbols are accompanied by the modern IPA notation.

![Figure 2. Characteristic tones frequency of the French oral vowels except [y], [ɔ], [œ] given by Rousselot in v.d. [22, 25] (values included in the set of tuning forks are given in dark grey; additional values are in white; 1v.d. = 1 Hz)](image)

The description of French oral vowel system by Rousselot is more detailed than the modern classification (see Figure 2). He suggests two variants of the close vowels [i] and [u] (i fermé [i], i moyen [j]; ou fermé [u], ou moyen [u]) [22, 23]. Instead of the division into close-mid and open-mid vowels he gives three variants of the “mid” vowels for both rows. These are e fermé [ɛ], e moyen [ɛ/ɛ] and e ouvert [ɛ] of the first row and o fermé [o], o moyen [ɔ/ɔ], o ouvert [ɔ] of the back row. He defines three variants of "a" in the same way. A ouvert corre-
sponds to the front vowel \[ a \], a fermé to the back vowel \[ a \] and a moyen \[ a'/a \] to the modern term a médiane. The terms fermé ("close") and ouvert ("open") seemingly correspond to the modern standard French vowel nomenclature. Exceptions are the two “\[ a \]” which are described in terms of aperture/ closeness by Rousselot. Nowadays traditional phonological descriptions use the terms of anteriority/ posteriority to define the corresponding vowels. It should also be noted that the term fermé, i.e. "close" (except the a fermé), is referred by Rousselot to the vowels in the word-final position or a stress-group-final position. The term ouvert, i.e. "open", indicates vowels mostly in a stressed syllable before \[ r \] (the cases of e, a, o), as well as in other combinations with consonants [22]. The term moyen (i.e. "middle") corresponds mostly to unstressed allophones. In the latter case no difference is made by Rousselot between close-mid and open-mid vowels. Thus the unstressed variants of the \[ e \] (e fermé) and \[ e \] (e ouvert) are considered together as \[ e'/e \] (e moyen). In Rousselot’s description, the term “middle” also represents the vowels in a stressed syllable before a certain consonant or a group of consonants. The number and quality of consonants is individual in each case [22, 23].

In some of his works [25] Rousselot gives additional values for several vowels (see white columns in the diagram, Fig.2). Three values represent e moyen and are indicated as \[ e \], \[ e'/e \], \[ e \]. Rounded “\[ a' \]” \[ n \] corresponds to some regional variants of the back \[ a \]. The sound “\[ a' \]” \[ a'/a \] corresponds to the front vowel \[ a \] in Parisian pronunciation. Thus, Rousselot tries to give a comprehensive and subtitle description of French vowels’ pronunciation which covers various regions. At the same time these additions are due to the author’s ambition to elaborate a balanced vowel system. In his “Principles of Experimental Phonetics” [27] Rousselot assumes the existence of scales of vowel characteristic tones similar to those in music, although they differ in the number of elements and relationship within the scale. The main assumption of Rousselot [25, 27] is the existence of an equal intervallic span between two neighboring vowels (or their variants) which, ideally, should form a sort of scale. This idea can be in some way compared to the recent psychoacoustic scales of barks and ERBs. Nonetheless not all of the vowels fit in such a system correctly. Therefore some supplementary variants are suggested by Rousselot supposedly in order to help fill in the lacking cells of the assumed structure.

As it has already been mentioned, J. P. Rousselot gives precise values of the French vowel characteristic tones [22, 25]. As well as many of his predecessors [7, 17, 18], Rousselot tries to find one tone that gives the brightest resonance perceivable by ear. At the same time the author recognizes the existence of other characteristic frequencies, although they are weaker and seem to be less important for the vowel resonance perception [22, 25, 31]. Thus, Figure 2 represents only one characteristic tone value suggested by Rousselot [22, 25] in vibrations doubles (i.e. vibrations per second) for each oral vowel. Thirteen values correspond precisely to those engraved on the tuning forks in the collection. The four other meanings represent additional regional variants which are not included in the set of the tuning forks.

A comment has to be made in reference to individual pronunciation of the investigator and its relation to the cited values. Rousselot analyzes his students’ and colleagues’ pronunciation in relation to their geographical provenance and compares it to his own pronunciation [27]. Besides, when Rousselot presents the acoustic vowel description, he notes that “the mouth is adjusted to various vowels in the Haut-Angoumois region with the following notes” (translated by the authors) [22: 48]. It should be mentioned that the Haut-Angoumois region and notably Cellefrouin, the town Rousselot was from, is situated in the department of Charente in the south-west of France. The comparison of the characteristic tones of all the described variants allows us to conclude that Rousselot’s main description of the French vowel system is based mostly on his own pronunciation [27]. Thus the set of the tuning forks from the Phonetic Department collection seemingly represents characteristics of Rousselot’s own vowels. Consequently, it shows the Haut-Angoumois accent of the early 20th century.
2.5 Front rounded oral vowels as “composite” sounds

The absence of the front rounded vowels in the set of the tuning forks may be due to their "compound" (or "composite") nature, according to Rousselot [22, 25]. As shown in Table 1, the author gives two characteristic tones for these vowels. The first value corresponds to the front non-rounded vowel, the second value to the back vowel. Rousselot describes only the front rounded vowels and their variants by the two characteristic tones. Both tones belong to the more open vowels than the targets. Therefore \( [\ddot{u}] \) (\( \ddot{u} \) fermé) in Rousselot’s system is composed by \( i \) moyen and \( ou \) moyen and not by \( i \) fermé and \( ou \) fermé, the same relation is observed for other vowels as well [22, 25].

Table 1. Characteristic tones of the French front rounded oral vowels according to Rousselot [22] (in v.d.; 1 v.d. = 1 Hz)

<table>
<thead>
<tr>
<th>Rousselot's terms</th>
<th>IPA symbols</th>
<th>Rousselot's description</th>
<th>IPA symbols</th>
<th>Tone 1 (v.d.)</th>
<th>Tone 2 (v.d.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ü fermé</td>
<td>[\ddot{y}]</td>
<td>( i ) moyen + ( ou ) moyen</td>
<td>( [\ddot{u}] + [i] )</td>
<td>342</td>
<td>2736</td>
</tr>
<tr>
<td>ü moyen</td>
<td>[\ddot{y}]</td>
<td>( e ) fermé + ( o ) fermé</td>
<td>( [o] + [e] )</td>
<td>456</td>
<td>1824</td>
</tr>
<tr>
<td>oe fermé</td>
<td>[\ddot{o}]</td>
<td>( e ) moyen + ( o ) moyen</td>
<td>( [\ddot{o}] + [e] )</td>
<td>684</td>
<td>1710</td>
</tr>
<tr>
<td>oe moyen</td>
<td>[\ddot{\varnothing}]</td>
<td>( e ) moyen + ( o ) ouvert</td>
<td>( [\ddot{\varnothing}] + [\ddot{\varepsilon}] )</td>
<td>798</td>
<td>1596</td>
</tr>
<tr>
<td>oe ouvert</td>
<td>[\ddot{\varnothing}]</td>
<td>( e ) ouvert + ( a ) fermé</td>
<td>( [\ddot{\varnothing}] + [\ddot{\varepsilon}] )</td>
<td>912</td>
<td>1368</td>
</tr>
</tbody>
</table>

3 Modern instrumental analysis data vs. Rousselot’s measurements

3.1 Evaluation of the tuning forks with modern methods of acoustic analysis

All 13 tuning forks of the described collection were recorded in the soundproof cabin. They were struck one by one by a special wooden hammer from the same set (see photo in Fig. 1). The instrumental analysis revealed the main fundamental frequency which in all cases was prevalent. A various number of additional frequencies were observed as well. Most of these frequencies had no correspondence to the main tuning fork’s tone. The appearance of such non-harmonic frequencies is commonly observed in otologists’ practice when tuning forks are struck off a metal or a wood [29].

The dominant tone emerges and can be heard in general after a short span of time after the beginning of the signal. A strong aperiodic noise appears when a tuning fork is struck. Then it gives place to the periodic dominant tone that lasts over 5 or even 7 seconds. The upper harmonic or non-harmonic periodic tones last as long as the fundamental tone or may fade 2 or 3 seconds after the initiation of the tuning fork. It corresponds to the data described in [19]. The middle of the dominant tone frequency band is calculated by means of the spectral analysis. The results show that the values engraved on the tuning forks are quite close to the frequencies calculated by modern methods of instrumental analysis. The difference from Rousselot’s values never overpasses one semitone. This fact allows us to appreciate the sophisticated ear technique used by Rousselot and to apply these values at the later stages of the study.

3.2 Formant value measurements using modern instrumental analysis

A comparison between modern and earlier data is of particular interest to the speech investigation history. Thus, the values engraved on the tuning forks which correspond to Rousselot’s description (see Figure 2) are put in parallel with a wide range of later instrumental data. These data contain formant characteristics of the French oral vowels measured from 1948 until
The juxtaposition (see Fig. 3) shows that the observations made by Rousselot in the early 20\textsuperscript{th} century correspond to the F1 values quite rarely. This is the case of the back vowels [u], [o] or of their variants [u̞], [o̞/ɔ̝], [ɔ]. Such correspondence is less characteristic for [a] and [a̙/ɑ̘].

![Figure 3](image3.png)

\textbf{Figure 3.} F1 of the French oral vowels except [y], [ø], [œ], data from 1948 until 2012, in Hz (isolated hyphen markers) vs. Rousselot’s characteristic tones engraved on the tuning forks, in v.d. (continuous dotted line)

The last variant [a̙/ɑ̘] can be related to the so-called “a” \textit{médiane} measured by modern phoneticians. In our data this variant replaces the front [a] and the back [ɑ] from 1986 [4] onwards. Herewith formant characteristics of all vowels except [u] and [o] are lower than the corresponding characteristic tones calculated by Rousselot. It has to be mentioned that in modern pronunciation [u] and [o] appear to be more open than the corresponding vowels examined by Rousselot in the early 20\textsuperscript{th} century. Among all vowel formants the most crucial mismatch with Rousselot’s results is observed for the close vowel [i].

![Figure 4](image4.png)

\textbf{Figure 4.} F2 of the French oral vowels except [y], [ø], [œ], data from 1948 until 2012, in Hz (isolated hyphen markers) vs. Rousselot’s characteristic tones engraved on the tuning forks, in v.d. (continuous dotted line)

Contrary to the F1 data, F2 characteristics (see Figure 4) have greater data scattering. Nevertheless only [i] has a much higher value than the corresponding vowel second formant.
The tones of other vowels suggested by Rousselot are lower, especially those of [u] and [o]. Sometimes they coincide, as in cases of [e], [a], [æ], [ɔ]. The mismatches depend on the concrete corpus of the modern data. We can suppose that Rousselot perceived the second formant of the oral front unrounded and back vowels. The exception is provided by [o] and [u] (see above) and the characteristic tone of [i]. The latter value is close to the modern F3 frequency. Such closeness of the vowel characteristic tones evaluated by ear to the F2 values measured with modern instrumental analysis can be noticed from 1679 onwards [15]. This fact may be due to the psychoacoustic phenomenon of the better sensitivity of the human ear to high frequencies.

Figures 5 and 6 show conformity between the first characteristic tone given by Rousselot and the first formant value of [y]. The same relation is sometimes observed between the second formant of [ø] or [œ] and the corresponding tuning forks’ tones. Although a variety of meaning is obvious, the difference between the modern and earlier data clearly appears in cases of the [œ] F1 value and the [y] F2 value. Only one individual meaning [14] is quite close to the F2 of [y]. The interesting fact is that the first characteristic tone of this vowel corresponds almost completely to the actual data while the second tone given by Rousselot remains beyond the modern pronunciation characteristics. Meanwhile its variant [y] described by this scientist as an open variant (ū moyen) almost entirely coincides with the modern [y] F2 characteristics. This observation leads us to check the characteristic tones of the both variants of this vowel suggested by Rousselot with modern listener’s perception.

**Figure 5.** F1 of the French front rounded oral vowels, data from 1948 until 2012, in Hz (isolated hyphen markers) vs. 1st characteristic tone given by Rousselot in v.d. [22] (continuous dotted line)

**Figure 6.** F2 of the French front rounded oral vowels, data from 1948 until 2012, in Hz (isolated hyphen markers) vs. 2nd characteristic tone given by Rousselot in v.d. [22] (continuous dotted line)
4 Auditory perception experiment

4.1 Materials and methods
Two synthesized sounds were obtained through digital signal processing. These sounds corresponded to Rousselot’s description of the two characteristic tones of [y] (ü fermé) and [y] (ü moyen). For this purpose the intervals with the duration of one second were extracted from the middle of the corresponding tuning fork recordings. It allowed to avoid additional noise and non-fundamental frequencies. Then these two extracts were juxtaposed and normalized in such a way that the upper tone to be about half of the lower tone amplitude. Obtained compound sounds were presented to the two native French speakers. The subjects are a man from Provence region and a woman from Lorraine region. Both of them are teachers of the FLE (Français Langue Étrangère) with different levels of musical education. These subjects were asked to answer if the sound they heard was similar to any vowel of their language, and if so, to indicate the vowel. Besides these two synthesized sounds, two more series were demonstrated. One of them consisted of four extracts from the recordings of the tuning forks with engraved values of 1228, 342, 1824 and 2736 v.d.. The length of these four stimuli was the same as in the previous series, i.e. one second. The last series comprised three different sounds produced by the sets of the tuning forks from the collection. Firstly, the tuning forks with values of 342 and 2736 v.d. were activated by a wooden hammer in the presence of the subjects. The tuning forks of 456 and 1824 v.d., then those of 798 and 1596 v.d. were presented in the same way. The last stimulus was the sound produced by the smallest tuning fork from the collection (of 3648 v.d.) activated likewise the previous sets. All stimuli were repeated three times. The both subjects listened to the sound material at the same time.

4.2 Results
The interesting fact is that the listeners were able to accomplish the suggested task and tried to associate such non-natural sounds with certain vowels. Nevertheless among ten demonstrated sounds only three were recognized unanimously. Such conformity was observed for the synthesized sound which included transformed recordings of the tuning forks of 456 and 1824 v.d.. Thus, the sound which corresponded to an unstressed “middle” [y] in Rousselot’s description was perceived as the “close” [y]. One of the subjects explained that he perceived this sound as the [y] in a stressed open syllable. However, such suggestion may be explained as the result of the sound sample length. The crucial fact is that listeners can hardly put in parallel a sound with a length of one second with a short vowel in an unstressed position. At the same time the sound which corresponded to the description of the stressed “close” [y] in the early 20th century was not recognized by any subject. The answers were [i] and [ê]. The extraction from the recording of the tuning fork of 2736 v.d. defined by Rousselot as “middle” [i] was unanimously perceived as [i]. The same answers were observed for the sound of the activated isolated tuning fork of 3648 v.d. which represented the “close” [i]. These results only partially correlate with observations made by Rousselot and may witness of a change of the French vowel system.

5 Conclusion
The results of the current study show that the experimental technique of vowel identification by one or two characteristic tones which uses recorded tuning fork sounds is still valid. This may be achieved not only by a well-trained phonetician, but also by a modern naïve native speaker. Furthermore, the comparison of Rousselot’s description with the modern instrumental data leads us to several conclusions. Firstly, F1 and, especially, F2 values of some vowels are approximate to the characteristic tones given by Rousselot. At the same time, the modern formant measurements of [i] described in the early 20th century as the “close i” still crucially
differ from the values suggested by J. P. Rousselot. The same relation is observed for the second formant of \([y]\) (the “close \(\ddot{u}\”)”. However, compared to the recent data [14, 20], characteristic tone of \([i]\) is apparently very close to its F3 meaning. It allows us to suppose that Rousselot perceived the F3 as the dominant tone of \([i]\). Such inference also correlates with the data of another recent formant characteristics’ study [13]. Auditory experiment’s results demonstrate that the modern \([y]\) corresponds more to its open variant in Rousselot’s description. As it can be seen from the modern data (mentioned above), the close vowels \([u]\), \([i]\) and \([y]\) became more open during the last century. This fact may be caused by entirely linguistic reasons as well as by anthropological changes, such as the increasing height of the human race in general. Thus, in the accomplished study one century old acoustic devices and methods are applied along with the new instrumental analysis and signal processing procedure. That allows us to suggest that the experimental technique used in the earlier days of acoustic phonetics, instead of being a museum issue, remains useful today. It enables reconstructing some old methodologies and investigating the pronunciation of earlier times. Therefore, it gives an insight into the sound system functioning and evolution.

6 References

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