Prethodno priopćenje
Rukopis primljen 13. 4. 2018.
Prihvaćen za tisak 21. 12. 2018.
https://doi.org/10.22210/govor.2018.35.11

Maksym O. Vakulenko
maxvakul@yahoo.com
Ukrainian Lingua-Information Fund of NAS of Ukraine, Kyjiv
Ukraine
Lionbridge Technologies, Inc., Tampere
Finland

Ukrainian vowel phones in the IPA context

Summary

Acoustic and articulatory properties of Ukrainian vowels are investigated in this study and a full set of relevant IPA notations are proposed. The notations are shown in the vowel diagram and the table. The results of the earlier acoustic invariant speech analysis based on special software, auditory and spectrum analysis were used and the results are discussed in the context of general and Ukrainian phonetic laws governing language evolution and acoustic properties of non-stressed vowels in relation to their stressed cognates. Such combined approach resulted in a more detailed vowel inventory than proposed heretofore. The findings of this research contribute to better understanding of Ukrainian language and its special features in comparison with other world languages that may have substantial practical use in various phonetic and translation studies, as well as in modern linguistic technologies aimed at artificial intelligence development, machine translation incorporating text-to-speech conversion, automatic speech analysis, recognition and synthesis, and in other areas of applied linguistics.

Key words: Ukrainian vowel phones, International Phonetic Alphabet, vowel diagram, acoustic properties of vowels

1. INTRODUCTION

Rapid development of modern linguistic tools, offering unprecedented perspectives for modern linguistics (see Shyrokov, 2011, p. 3), imposes a need for more thorough and detailed investigation of the special features of the world languages. Recent advances in automatic speaking systems, translation and text-to-speech technologies (realized in such tools as Google Translate, Microsoft Cortana, Apple Siri, SAPI Phone Converter, etc.) are provided by elaboration of relevant phone sets and lexicons of the English, Spanish, Portuguese, Italian, Chinese, German, and other technologically supported languages. However, not many world languages take advantage of modern linguistic technologies to their full extent (Scannell, 2007, p. 1; Vakulenko, 2015, p. 9). Given this, the under-resourced languages such as Ukrainian need more detailed investigation, particularly in the field of speech processing that has experienced significant progress in the past decade (Besacier, Barnard, Karpov, & Schultz, 2014, p. 85). In addition, European perspectives of Ukraine result in intensification and diversification of its trade, political, economic, scientific and cultural relations with the world countries that give rise to further interest in its linguistic issues.

The first difficulty in incorporating Ukrainian into modern speaking tools is that the relevant phonetic studies are scarce and not widely known in the world. The lack of reliable and sufficient experimental data on the Ukrainian phones motivates researchers to draw analogies with the more explored world languages or to make conjectures that are not duly justified (see Bilodid, 1969; Buk, Maczutek, & Rovenchak, 2008; Pompino-Marschall, Steriopolo, & Żygis, 2017; Tocjka, 1981; Zhovtobrjukh & Kulyk, 1965). Correct comparison with other languages accounting for the special features of the Ukrainian phonetic system is necessary for phone mapping rules needed in various phonetic studies and for speech recognition purposes.

The most famous works in the Ukrainian phonetics are the *Contemporary standard Ukrainian. Phonetics* (Bilodid, 1969), and *Contemporary standard Ukrainian: Phonetics, orthoepics, graphemics, orthography* (Tocjka, 1981), both written in Ukrainian decades ago. It is noteworthy that the section 'Vowels' in Bilodid (1969) was written by Tocjka, who based her assumptions on her own observations and measurements, as well as on observations and conclusions of Broch (1910), Synjavsjkyj (1929), Zilynsjkyj (1932) whose work was also translated from

Polish into English in 1979, and of Kalynovych (1947), Brovchenko (1954), Zhovtobrjukh and Kulyk (1965), and others. Previous studies were used with minor changes (and without up-to-date experimental evidence) in a number of the later Ukrainian textbooks.

Thus, the second problem is that the mentioned studies are grounded on outdated phonetic data collected with old-fashioned apparatus.

Third, the results on speech sound production in Bilodid (1969) and Tocjka (1981) are obviously based on the experimental data received from but one speaker that is far from being sufficient.

An attempt to describe the Ukrainian vowels in terms of the IPA notations was made by Bilous based on acoustic and auditory analysis of the speech of one female native Ukrainian speaker (see Dudnyk, 2004, pp. 20–23) that provides a somewhat different picture from that described in Bilodid (1969) and Tocjka (1981). Bilous assigns IPA symbols to vowels according to absolute values of their first and second formants. It is necessary to note that this approach has two intrinsic issues that should be accounted for to avoid possible errors, which was not demonstrated in her study.

First, it is a well-known fact that formant frequencies vary from speaker to speaker, being higher for children and women and also for raised pitch. So, reliable conclusions on average absolute formant values may be drawn only on the basis of statistically significant measurements or normalized (to the fundamental or any other formant) frequency quantities which were not done. Second, there are two different kinds of resonance in the human vocal tract: (1) a **tube resonance**, where the formant frequencies correlate with the tube length, or tongue position along the vocal tract, and (2) a **low-frequency Helmholtz resonance** appearing in a relatively large volume with a narrow constriction, where the formant frequencies depend on the cross-sectional area and the length of the constriction and a large tube volume (see details in Stevens, 1998, pp. 138–142). Most of the formants are caused by tube resonance and, therefore, well correlate with the back-front tongue position. However, the lowest formants in 'high' vowels, such as Ukrainian /i/, /и/, and /y/, arise due to the Helmholtz resonance and, therefore, are not inversely proportional to the tongue height (actually, in the Ukrainian [y], like in the English [u], two first formants are caused by the Helmholtz resonance). Accordingly, the vowel location on the Jones diagram determined by its articulation cannot be straightforwardly inferred from its formant frequencies: in high vowels like an /и/, the first formants

are caused by the Helmholtz resonance, so there is no simple correlation between formant frequencies and the tongue position as for the low ones. Unfortunately, this fact was not duly commented and accounted for in Dudnyk (2004) throwing some doubt on reliability of relevant conclusions. As emphasized in Vakulenko (2000, 2007, 2010, 2011a, 2011b, 2015), the only acoustic invariant characteristic of a speech sound is its formant ratio, i.e. relation between permanent formant frequencies. So, when relating phone articulation with its acoustic characteristics, it is necessary to carry out the relevant **normalization** of the latter ones.

Buk et al. (2008) try to describe Ukrainian phones in terms of IPA notations based on their own interpretation of the conventional literature on Ukrainian phonetics. The authors do not present their original experimental phonetic data, though a significant number of conjectures and declarations in this work (some of them being fairly novel for the Ukrainian phonetics) are not duly grounded on relevant linguistic facts and necessary references. The issues will be discussed in more detail when relevant.

A draft investigation of the Ukrainian phone system following IPA conventions was proposed in Steriopolo (2012) saying that additional research is needed.

The recent article 'Ukrainian' (Pompino-Marschall et al., 2017) presents alternative results on phonetic properties of Ukrainian speech sounds grounded on recordings of one male talker from Bukovyna (South-Western Ukraine). In particular, a somewhat retracted articulation of a /и/ has been reported. However, in order to represent IPA notations, observation of articulation movements of a speaker are needed, but also their instrumental recording as well as examination and comparison with the data obtained in other phonetic experiments. Besides, there is no explanation why the authors follow the theoretical classification of Buk et al. (2008) which has no references to experimental studies. There is no information on how the articulation data were obtained (automatic processing, filming, palpation, etc.). The formant frequencies were not normalized throwing certain doubt on the description of low vowels /a/ and /e/.

Finally, in order to determine the most relevant International Phonetic Alphabet (IPA) symbol for the given Ukrainian sound is not straightforward and easy since it requires collecting representative experimental data, profound comparative analysis of the multi-lingual phonetic material, and good command of

the IPA notations. In particular, unreasonably large distance between the stressed and unstressed [*и*] and [*и*] (apparently due to inaccurate interpretation of these vowels) in the results of Bilous (Dudnyk, 2004, pp. 20–22) contradicts the general tendency of Ukrainian vocalism to preserve a vowel property in a non-stressed position (see Tocjka, 1981, p. 101).

The invariant acoustic approach to analysis of the Ukrainian vowels (pronounced by six native Ukrainian talkers) was carried out by Vakulenko (2000, 2007, 2010, 2011a, 2011b, 2015) where their absolute and invariant (robust) acoustic characteristics were found. It was demonstrated that the only acoustic invariant characteristic of a speech sound is its formant ratio, i.e. relation between permanent formant frequencies. These results add important information to the description of the Ukrainian speech sounds that should be accounted for in creating an inventory of Ukrainian sounds.

The situation with the Ukrainian phonetics is rather special. On one hand, there is an urgent need to know phonetic characteristics of Ukrainian speech sounds in due detail relevant for modern speech processing tools. On the other, there is no reliable experimental evidence on Ukrainian phones, given that such a task requires not only sufficient time, but also corresponding equipment and a specially trained team. The first urgent task is to propose the most likely candidates for every phone in question that would be involved in neural speech processing tools and are to be automatically adjusted and updated.

So, this article is aimed to analyze phonetic features of the Ukrainian vowels in the IPA notations context, and to present a Ukrainian phone system.

2. RESEARCH METHODS AND MATERIAL

The choice of research methods and approaches is determined by the fact that there is no governmental maintenance of the phonetic field in Ukraine. For example, the experimental phonetic laboratory at the Kyjiv National University after Taras Shevchenko is the last working laboratory of this kind in the capital of Ukraine. The available experimental equipment for the articulation study is totally outdated there and does not meet the requirements of modern research. Therefore, this laboratory is focused only on the tasks associated with the teaching process.

At the same time, recent rapid advance in linguistic tools (see above) requires detailed and immediate knowledge on Ukrainian phones.

This research is based on the combined use of auditory comparative analysis, auditory observation, acoustic invariant speech sound analysis (presented earlier in Vakulenko, 2007, 2015, pp. 162–179 and new one).

The auditory comparative analysis was done by auditory comparison of the CD-quality recorded speech of four native Ukrainian professional actors trained according to the orthoepic norms described in Bilodid (1969), with reference IPA sounds on the page of the Experimental Phonetic Laboratory 'Arturo Genre' (Laboratorio di Fonetica Sperimentale). One of the speakers represented the southwestern dialect group, and three represented the southeastern dialect group which forms the basis of the contemporary standard Ukrainian. Thus, we provided not only the data on the standard Ukrainian, but on its dialectal variations also not included in research for decades (the more detailed comparison with the previous studies will be presented in the Discussion section).

This analysis was applied to the back phonemes /a/, /o/ and /y/ that have clear sound in Ukrainian but may cause difficulties in their classification. Front phonemes that also cause classification problems but are often realized in an unclear or mixed sound were excluded.

The utterances with non-high vowels in the next syllable were chosen thus excluding vowels harmony effects. The central parts of the analyzed vowels (5–10 cycles of the fundamental frequency, depending on the sound quality) were selected and played back in a soundproof room. The total numbers of acoustic realizations of the Ukrainian phonemes /a/, /o/ and /y/ were 40, 60 and 40, respectively. The number of listeners was 5 (three male and two female native speakers of Ukrainian). They were asked to compare the analyzed sound with the reference IPA sounds of [ɑ], [ɐ] and [a] (possible realizations of an /a/), [o] and [ɔ] (possible allophones of an /o/) and [u] and [ʊ] (possible allophones of an /y/), respectively, as pronounced in 'Arturo Genre', and indicate notations corresponding to the most similar sounds. The results are summarized in Table 1, Table 2 and Table 3, where the vowels were separated according to their accent distribution (stressed and non-stressed) and to the presence or absence of palatalizing effect from preceding consonants. The numbers of assessments were averaged for each case and rounded to integer values.

Table 1. Perception of the Ukrainian vowel /a/
Tablica 1. Percepcija ukrajinskog vokala /a/

Listener and classification / Red. br. slušača i klasifikacija	In initial position, after plain consonants (excluding [j]) and vowels, stressed/non-stressed / U inicijalnoj poziciji iza konsonanata (osim [j]) i vokala, naglašeno/nenaglašeno	After [j] and palatalized consonants, stressed/non-stressed / Iza [j] i palataliziranih konsonanata, naglašeno/nenaglašeno
L1: [ɑ]	14/3	1/2
L1: [ɐ]	5/16	19/16
L1: [a]	1/1	0/2
L2: [ɑ]	17/2	3/5
L2: [ɐ]	3/17	17/14
L2: [a]	0/1	0/1
L3: [ɑ]	13/3	2/2
L3: [ɐ]	7/16	15/16
L3: [a]	0/1	3/2
L4: [ɑ]	15/3	0/1
L4: [ɐ]	5/16	20/18
L4: [a]	0/1	0/1
L5: [ɑ]	12/2	1/2
L5: [ɐ]	6/17	18/15
L5: [a]	2/1	1/3
Average / Prosjek: [ɑ]	14/3	1/2
Average / Prosjek: [ɐ]	5/16	18/16
Average / Prosjek: [a]	1/1	1/2

Table 2. Perception of the Ukrainian vowel /o/
Tablica 2. Percepcija ukrajinskog vokala /o/

Listener and classification / Red. br. slušača i klasifikacija	In initial position, after plain consonants (excluding [j]) and vowels, stressed/non-stressed / U inicijalnoj poziciji iza konsonanata (osim [j]) i vokala, naglašeno/nenaglašeno	After [j] and palatalized consonants, stressed/non-stressed / Iza [j] i palataliziranih konsonanata, naglašeno/nenaglašeno
L1: [o]	20/19	5/4
L1: [ɔ]	4/2	4/2
L2: [o]	21/19	4/3
L2: [ɔ]	3/2	5/3
L3: [o]	22/20	7/5
L3: [ɔ]	2/1	2/1
L4: [o]	20/17	6/4
L4: [ɔ]	4/4	3/2
L5: [o]	20/18	5/3
L5: [ɔ]	4/3	4/3
Average / Prosjek: [o]	21/19	5/4
Average / Prosjek: [ɔ]	3/2	4/2

The auditory assessment was used to study the perceptual character of spontaneous Ukrainian speech heard in Kyjiv in 1991–2017.

To adjust acoustic proximity of Ukrainian vowels, we used the results of our phonetic experiments presented in Vakulenko (2000, 2007, 2010, 2011a, 2011b, 2015), where six native Ukrainian and ten native American English talkers in total were involved to produce Ukrainian and American English speech sounds, respectively. They pronounced (in triple repetition) separate sounds, words and given word combinations in a normal tone of voice, in a whisper and in changing tone (rising and falling). Five Ukrainian informants spoke standard Ukrainian based on the southeastern dialect group, and one spoke southwestern. Thus, the obtained invariant (independent of the talker identity and the speech mode) speech sound characteristics, in comparison to those of normal spontaneous speech only, have a higher robustness

degree that is important for various automatic linguistic tools dealing with speech analysis, recognition and synthesis.

Table 3. Perception of the Ukrainian vowel /y/
Tablica 3. Percepcija ukrajinskog vokala /y/

Listener and classification / Red. br. slušača i klasifikacija	In initial position, after plain consonants (excluding [j]) and vowels, stressed/non-stressed / U inicijalnoj poziciji iza konsonanata (osim [j]) i vokala, naglašeno/nenaglašeno	After [j] and palatalized consonants, stressed/non-stressed / Iza [j] i palataliziranih konsonanata, naglašeno/nenaglašeno
L1: [u]	18/3	2/2
L1: [ʊ]	2/17	18/18
L2: [u]	16/5	3/2
L2: [ʊ]	4/15	17/18
L3: [u]	19/3	2/2
L3: [ʊ]	1/17	18/18
L4: [u]	17/2	3/3
L4: [ʊ]	3/18	17/17
L5: [u]	18/4	3/4
L5: [ʊ]	2/16	17/16
Average / Prosjek: [u]	18/3	3/3
Average / Prosjek: [ʊ]	2/17	17/17

Also, an additional spectral analysis was carried out. Within this thread of research, the CD-quality recorded speech of a native Ukrainian professional actor (born in Dnipro, Central Ukraine) trained according to the orthoepic norms described in Bilodid (1969), was also used to examine acoustic realizations of the Ukrainian phoneme /e/.

The used software for the acoustic analysis was Sound Forge 4.0, WaveLab 2.1, and CoolEdit 95. The sound segmentation was performed by selecting specific patterns in oscillograms, with audio control. The selection on the oscillogram with relevant visual outline and sound was used for the frequency analysis giving rise to corresponding spectrograms (two- or three-dimensional).

We did not use the popular program Praat as its formant recognition accuracy does not meet our requirements. Particularly, it was experimentally shown that this software failed to correctly determine the test monochromatic signals. The signal of 100 Hz was interpreted as a sound with a fundamental frequency of 111 Hz and two formants of 2588–2793 Hz and 3933–4002 Hz, the signal of 1000 Hz was interpreted as a sound with a 'double' fundamental frequency of 978 and 1022 Hz and two formants of 1084–1122 Hz and 3490–3754 Hz, and the signal of 5000 Hz was interpreted as a sound with a fundamental frequency of 1068–1081 Hz and three formants of 2344–2352 Hz, 4959 Hz and 4997 Hz (see further details in Vakulenko, 2011, pp. 171–172, 2015, pp. 166–167).

To illustrate our findings, the three-dimentional (waterfall) spectrograms obtained from fast Fourier transform were used. They are highly informative and have a number of advantages. First of all, they include three parameters (time, frequency, amplitude) instead of two parameters in the usual two-dimensional spectrograms (amplitude vs frequency). This makes such spectrograms preferable for tracking temporal changes in spectral composition (for example, formant shifts) or selecting time intervals with quasi-stationary acoustic characteristics, and for general estimations and comparisons. In this sense, just a single waterfall spectrogram may substitute a number of two-dimensional spectrograms covering relatively small time span, usually 10 ms (cf. Stevens, 1998, p. 298, p. 408).

There is also a purely mathematical reason to use a single waterfall spectrogram covering relatively large time period. The spectrograms of the waveform *f(t)* are built on the basis of its temporal Fourier transform (see van Belle, 2014):

$$\hat{f}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(t) e^{-i\omega t} dt ,$$

where ω is the cycle frequency, and the integration over time is taken from minus infinity to plus infinity. Given that infinite boundaries are always an idealization, each spectrogram is just an approximation to the exact function image in the frequency space. If the analyzed time interval t is much larger than the oscillation period T, $t/T >> 1$, the spectrogram inaccuracy is small. The shorter is the time span, the larger are the boundary effects (where the transformed function abruptly jumps to zero) that may significally distort real acoustic data.

A certain drawback of approximate visual frequencies measurements in three-dimentional spectrograms is compensated by strict arithmetic calculations of these

within relevant periods in the oscillograms. So, the formant frequencies were estimated visually through the waterfall spectrograms by projecting on the frequency axis the point of maximum amplitude of the given harmonic at the certain time moment corresponding to the analyzed phone, and then calculated exactly from the oscillogram as inverse periods of corresponding modes.

The compliance of the obtained results with the general and Ukrainian phonetic laws and acoustic properties of unaccented vowels in relation to their accented cognates (Bilodid, 1969, p. 63, pp. 116–118, pp. 378–381; Stevens, 1998, pp. 294–299; Tocjka, 1981, pp. 100–101; Zhovtobrjukh & Kulyk, 1965, pp. 118–119) was checked.

3. UKRAINIAN VOWEL SYSTEM

A stressed Ukrainian vowel /a/ is traditionally described as a low back vowel (Bilodid, 1969, p. 59; Tocjka, 1981, p. 51) or a low back vowel approaching a central one (Zhovtobrjukh & Kulyk, 1965, p. 118), whereas Bilous, as well as Press and Pugh refer it to the central category (Dudnyk, 2004, pp. 20–22; Press & Pugh, 2015, p. 22). Our measurements indicate that this sound has the second permanent formant Fp2 in the range of 1000–1200 Hz, thus being a low back advanced vowel [ɑ⁺] with a formant *ratio r* = Fp2/Fp1 = 4/3 (Vakulenko, 2000, 2007, p. 84, 2010, p. 28, 2011a, p. 173, 2011b, p. 439, 2015, p. 167; cf. Stevens, 1998, p. 286). This conclusion is confirmed also by our auditory comparative analysis (see Table 1), where the majority of utterances (14 of 20) were recognized as [ɑ].

Its unstressed counterpart is characterized as a probably mid central vowel (Bilodid, 1969, p. 113) or a midlow central vowel (Dudnyk, 2004, pp. 20–22; Tocjka, 1981, p. 101). Our auditory comparative analysis (see Table 1) confirms that this is a midlow central vowel [ɐ] (16 of 20 utterances). This phone appears also in the letter <я> readout: after [j] in an iotated vowel [jɐ] and after palatalized consonants (cf. Bilodid, 1969, p. 125). A similar sound is heard in the second syllable of the German *besser*.

The Ukrainian non-stressed vowels have a vowels harmony feature, or, in other words, a property of harmonic, or distant, or vocal assimilation. This is a special type of regressive assimilation of vowels in adjacent syllables when a previous vowel more or less assimilates to the following one (Tocjka, 1981, p. 104). Thus, the quality of an /*a*/ may be modified even further to [a^{e}]([ɜ⁺]) before front vowels as in *яйце* 'egg',

який 'what' (cf. Bilodid, 1969, p. 124; Broch, 1910, p. 115; Pompino-Marschall et al., 2017, p. 7).

A stressed Ukrainian vowel /o/ is characterized as a midback labialized vowel, more closed than the /a/ (Bilodid, 1969, p. 59; Tocjka, 1981, pp. 53–54). It is difficult to place in the classification diagram. Tocjka places this sound nearer to /a/ on the articulation chart and closer to /y/ on the acoustically determined diagram (Tocjka, 1981, pp. 59–60). Press and Pugh propose the symbol [ɔ] stating (without any experimental evidence) that its approximate pronunciation is 'as in English *got*, not as in English *more*' (Press & Pugh, 2015, p. 19), thus unreasonably referring this sound to low back vowels (British English [ɒ] or American English [ɑ]). At the same time, it is admitted that 'unstressed [ɔ] before stressed [u] (and at times even [i]) may narrow to [u] or [ɔw] or, perhaps better, to [o]' (Press & Pugh, 2015, p. 22). Such drastic change of an unstressed vowel articulation from low ([ɒ]/[ɑ]) to high ([u]) is very questionable for the Ukrainian vocalism where stressed and unstressed vowels do not differ sharply (see Tocjka, 1981, p. 101). In turn, Bilous treats this vowel as a midheight back one with an IPA notation /o/.

The location of a Ukrainian /o/ on the vowel chart may be roughly estimated by comparison of its acoustic characteristics with those of the reference central sound [ə]. If the length of the model uniform vocal tract with rigid walls and a uniform cross-sectional area is 15.4–17.7 cm, the formant frequencies lie in the range F1 = 500–600 Hz, F2 = 1500–1800 Hz (see Stevens, 1998, pp. 285–286). With F1 = 530–540 Hz (see Vakulenko, 2000, p. 63, 2007, p. 84, 2010, 2011a, p. 173, 2011b, p. 439, 2015, p. 167), a stressed Ukrainian /o/ is expected to reside near the central line, probably a little higher.

Another argument to support this location comes from regressive assimilation of an unstressed [*u*] before the syllable with an [e] or [a] that in this case approximates an [*e*] more strongly (Zhovtobrjukh & Kulyk, 1965, p. 118). As a vowel [o] does not display such influence, it is most likely higher than a midlow [e].

The question whether a Ukrainian /o/ is midlow (i. e. closer to [ɑ]) or midheight (i.e. closer to [u]), may be ultimately solved by addressing the flatness property of Ukrainian vowels /o/ and /y/ that results in decrease of the first formant frequencies of the preceding consonant (see Tocjka, 1981, p. 60). Figure 1 presents three-dimensional spectrograms of a Ukrainian consonant /k/ before stressed /a/ and /o/.

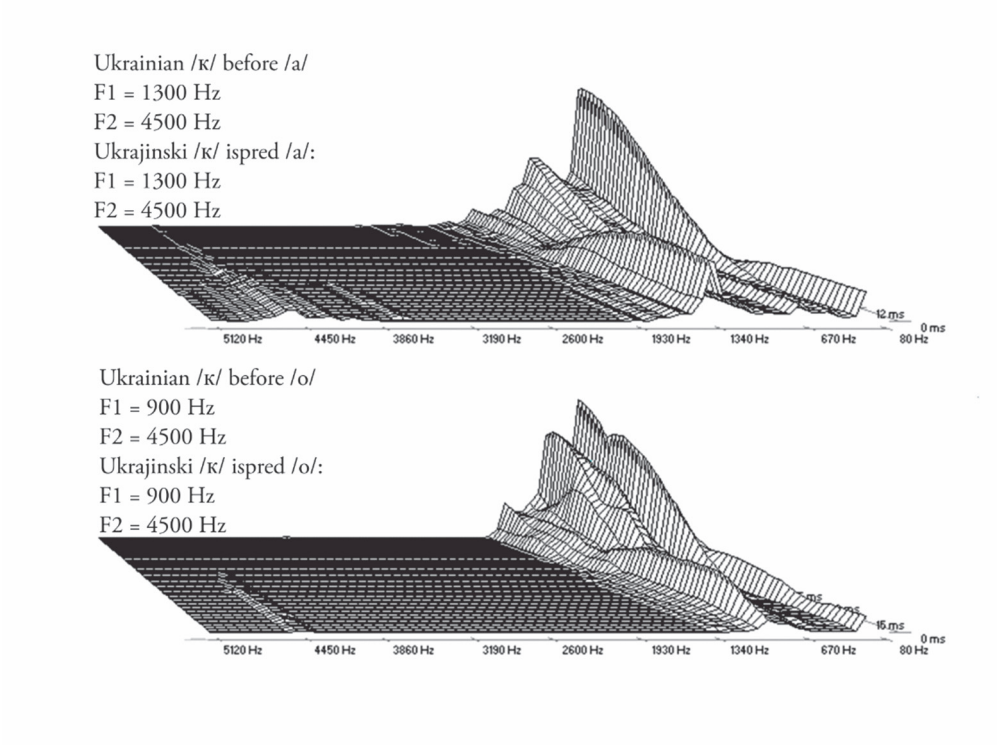

Figure 1. Three-dimensional spectrograms of a Ukrainian consonant /k/ before stressed /a/ (top) and /o/ (bottom), produced by a male speaker. Measurements are made at 12, 18 and 24 ms (top) and at 16, 24 and 32 ms (bottom).

Slika 1. Trodimenzionalni spektrogrami ukrajinskog konsonanta /k/ ispred naglašenog /a/ (gore) i /o/ (dolje), u izgovoru muškoga govornika. Izmjereno u 12., 18. i 24. ms (gore) te u 16., 24. i 32. ms (dolje).

It can be noticed from Figure 1 that the first formant in a /k/ has the frequency of 1300 Hz before an /a/ (taken at the time point of 12 ms) and a decreased value of 900 Hz before an /o/ (the time point of 16 ms), so a Ukrainian phone /o/ has a flatting effect on a preceding consonant. Our experiments showed that this property is not inherent to the sound [ɔ] as in English *boy*, *choice*, *thought*, etc. (see Fig. 2).

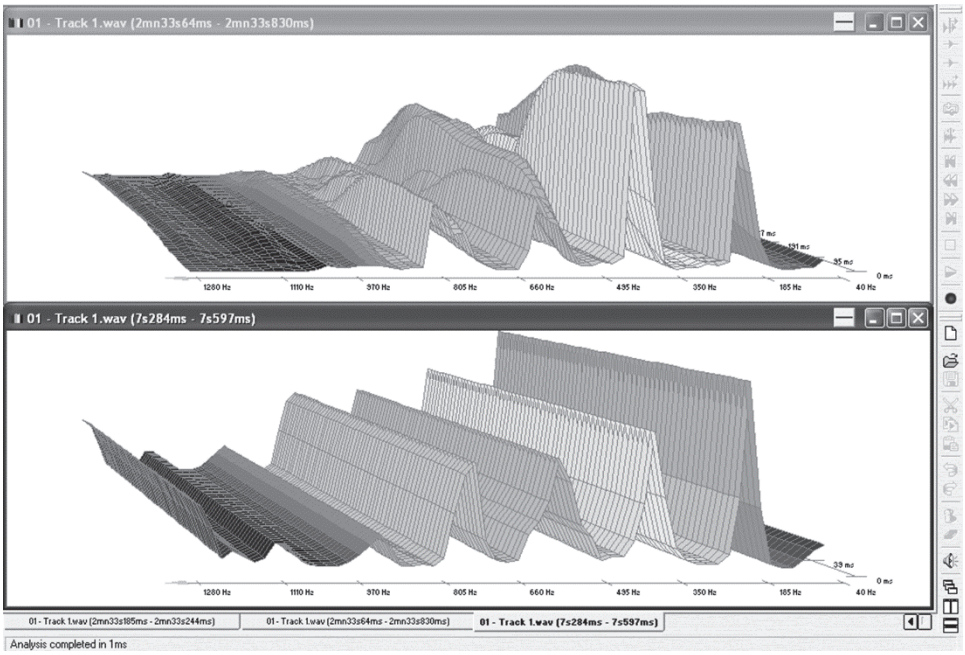

Figure 2. Low-frequency part of three-dimensional spectrograms of the sound /b/ in the English *boy* (top) and *bubble* (bottom), produced by a female speaker. Measurements are made at 40, 60 and 80 ms (top) and at 40, 50 and 60 ms (bottom).

Slika 2. Niske frekvencije prikazane na trodimenzionalnom spektrogramu glasa /b/ u engleskim riječima *boy* (hrv. dječak) (gore) i *bubble* (hrv. balončić) (dolje), u izgovoru ženskoga govornika. Izmjereno u 40., 60. i 80. ms (gore) i u 40., 50. i 60. ms (dolje).

As seen from Figure 2, [ɔ] causes no noticeable change in low-frequency behavior of [b] where the harmonics of 200 Hz, 400 Hz, 600 Hz and 800 Hz (measured at time point of 35 ms in the top and 39 ms in the bottom spectrograms) do not display any trend towards the lower values. This fact strongly supports the classification of Ukrainian /o/ as a midheight lowered back rounded vowel [o̞]. The auditory analysis (see Table 2) also supports this conclusion (21 of 24 utterances).

The information about unstressed allophones of the Ukrainian phoneme /o/ is inconsistent. Broch notes a small difference from its stressed counterpart and a somewhat lower articulation of the unstressed one (Broch, 1910, p. 116), but see also discussion in Bilodid (1969, p. 113). Such downward movement is noticed also in the recent

investigation by Bilous (see Dudnyk, 2004, pp. 20–22). A contrary tendency to its narrower (higher) articulation in comparison to stressed /o/ is reported in Bilodid (1969, p. 112) and Tocjka (1981, p. 101), with a reserving remark about the actual absence of experimental material (Bilodid, 1969, p. 111). Press and Pugh also report more upward position of the unstressed Ukrainian [*o*] (Press & Pugh, 2015, p. 22). It is stated that an unstressed /*o*/ somewhat approaches an unaccented /*y*/ and that they are more akin by the tongue back position than their stressed cognates (Bilodid, 1969, p. 115).

It should be kept in mind that an unstressed vowel moves towards the central (indifferent) position on the Jones chart (cf. Stevens, 1998, pp. 294–299). As far as a stressed /o/ resides above the central line, the only way to approach center is a downward motion. So, a non-stressed /*o*/ must move slightly downwards (thus becoming a bit wider) and to the center, remaining a midheight lowered back but slightly advanced rounded vowel [o̟˖] (an unstressed /*y*/ experiences more pronounced downward wander thus moving closer). This pattern, experimentally observed in Dudnyk (2004, pp. 20–22), correlates with the suggestions of our auditory comparative analysis presented in Table 2 (19 of 21 acoustic events). However, its marking by Bilous by /ɔ/ (as a midlow phone which resides below the central line of the vowel diagram) contradicts the above conclusions and seems not to be correct.

When the next syllable has a stressed or a secondary stressed high vowel /u/ or /i/, the vocal assimilation results in an *и*-like tinge of unstressed /*o*/ that correspondingly transforms into [*o*ʸ]: ***кожух*** [kо̟˗ˈʒux] 'sheepskin coat', ***зозуля*** [zо̟˗ˈʐu-ɬʲɐ] 'cuckoo', ***виловіть*** [ˈvɨ̟˖-ɬoᵘ-vʲiˌtʲ] 'draw out!', ***виволік*** [ˈvɨ̟˖-vо̟ᵘ-lʲiˌk] '(he) dragged out', (see Bilodid, 1969, p. 114, pp. 384–385; Zhovtobrjukh & Kulyk, 1965, p. 119). The variant[*o*ʸ] corresponds to [o˖].

An accented Ukrainian vowel /y/ is determined as a high back strongly labialized (rounded) vowel (Bilodid, 1969, p. 60; Tocjka, 1981, p. 54; Zhovtobrjukh & Kulyk, 1965, p. 119). Its IPA transcription is /u/, like in English *boost*.

It is observed that there is no qualitative difference in pronunciation of a stressed /y/ and an unstressed /*y*/ (Bilodid, 1969, p. 116; Zhovtobrjukh & Kulyk, 1965, p. 119), whereas Zilynsjkyj and Synjavsjkyj state that the latter is a little wider and lower in articulation (Bilodid, 1969, p. 116). An unaccented /*y*/ is regarded as a midheight central vowel shifted backwards (Bilodid, 1969, p. 118; Tocjka, 1981, pp. 100–101) or as a lowered high back (advanced) vowel (Dudnyk, 2004, p. 22). Our auditory comparative analysis (see Table 3) indicates that it is a high (lowered) back (shifted to center) rounded

vowel [ʊ], like in English *oops*. This sound appears also in the letter <ю> readout: after [j] in an iotated vowel [jʊ] and after palatalized consonants (cf. Bilodid, 1969, p. 96).

An accented Ukrainian vowel /і/ is conventionally classified as a high front vowel (Bilodid, 1969, p. 65; Tocjka, 1981, p. 58; Zhovtobrjukh & Kulyk, 1965, p. 118). Its IPA notation is /i/, like in English *valley*. In the Ukrainian language, this vowel usually results in palatalization of the preceding consonant.

An unstressed /і/ does not differ significantly, being a bit lowered and retracted but remaining a high front vowel (see Bilodid, 1969, p. 122; Dudnyk, 2004, p. 22; Tocjka, 1981, p. 100; Zhovtobrjukh & Kulyk, 1965, p. 118). The modified IPA symbol /i̝/ seems to be appropriate here. It was stated also in Pompino-Marschall et al. (2017, p. 6) that a harmonizing tendency may result in the farther shift of an unstressed [*i*] preceding a stressed [ɛ] towards /e/ thus resulting in the sound [*i*^{e}] ([e̞]).

There exists also a more wide allophone [i^{и}] of the phoneme /і/ that does not result in palatalization of a preceding consonant at the morpheme boundary: *безіменний* 'nameless', *передісторія* 'pre-history', *педінститут* 'pedagogical institute' (Bilodid, 1969, p. 183) – and may appear in the initial position in the words *інший* 'different, another', *іноді* 'sometimes', *інколи* 'time by time', *інде* 'somewhere', *інакше* 'in the other way' (Zhovtobrjukh & Kulyk, 1965, p. 161) and sometimes after a Ukrainian /р/ (Kalynovych, 1947, p. 51), but see also Bilodid (1969, p. 106). A nearby high front vowel with a more centralized (a bit lower and more retracted) articulation and the same formant ratio (r = 5/4) is denoted by the IPA symbol [ɪ] (see Vakulenko, 2007, p. 85, 2010, 2011a, p. 172, 2011b, p. 439, 2015, p. 169). The tube resonance formants of an English [ɪ] were found at the frequencies: Fp1 = 2000 Hz (1800–2200 Hz), Fp2 = 2500 Hz (2300–2700 Hz), with a formant ratio r = Fp2/Fp1 = 5/4 (large tertian) that corresponds to a Ukrainian /і/. We remind that the low-frequency (~300 Hz) incidental formant caused by Helmholtz resonance is not involved in the invariant ratio (see Vakulenko, 2007, pp. 80–82, 2010, pp. 22–27, 2011a, pp. 168–170, 2011b, pp. 434–437, 2015, pp. 159–164).

Classification of a Ukrainian /и/ is probably the most unclear, and relevant information is insufficient and contradictory. It is stated that physiological conditions of its production are investigated a little (Bilodid, 1969, p. 63). Broch, having studied the Western-Ukrainian pronunciation, described this sound as a mid-central vowel on a margin with the front row, approximate to a narrow [e] (Broch, 1910, p. 118), see also Bilodid (1969, p. 63). It is emphasized also that a narrow, raised articulation of /и/ does not make the standard norm and that in contrast to a number of Western Ukrainian

dialects where this sound is tenser and front, the typical Central Ukrainian /и/ is more light and relaxed that has to serve as a norm (Bilodid, 1969, p. 378).

Later Brovchenko characterized this sound as a front (shifted backwards) high vowel, wider than a Ukrainian /i/ (Brovchenko, 1954, p. 30), see also Bilodid (1969, p. 63). A stressed /и/ is considered as a front high vowel with lowered and retracted articulation (Bilodid, 1969, p. 378; Zhovtobrjukh & Kulyk, 1965, p. 118). Tocjka qualifies a stressed /и/ as a front midheight vowel (Tocjka, 1981, p. 57). Press and Pugh describe this sound as 'somewhat between English *i* in *sit* and the very beginning of the *a* in *gaze*' (Press & Pugh, 2015, p. 19), but use an inexact designation /ɪ/, as in English *sit*. The same transcription uses Bilous (Dudnyk, 2004, p. 22).

The marking /ɪ/ seems misleading for this sound because of the following:

(1) The notation /ɪ/ should be reserved for a lowered retracted allophone of /i/ with the same formant ratio (r = 5/4) appearing at the morpheme boundary where no palatalization occurs (see above), whereas a Ukrainian /и/ has a different formant ratio of r = 6/5 (Vakulenko, 2000, p. 63, 2007, p. 84, 2010, 2011a, p. 172, 2011b, p. 439, 2015, p. 167).

(2) It is a well-established fact that an unstressed /*и*/ approximates an unaccented [*е*] (see Bilodid, 1969, p. 381; Tocjka, 1981, p. 101; Zhovtobrjukh & Kulyk, 1965, p. 118) that, in turn, should be more central than a stressed /e/. So, the tentative correspondence /и/ → [ɪ] would result in an unreasonably large distance between its stressed and unstressed cognates, as can be seen from Dudnyk (2004, p. 22).

(3) An analogy with the relation between tense and lax vowels, like in English [i:] and [ɪ], is not appropriate here since there is no phonological distinction in Ukrainian based on vowel duration, diphthongization, etc. (see Stevens, 1998, pp. 294–299) and since the Ukrainian phoneme /и/ has no stress limitations.

(4) It is commonly agreed that the phones denoted by the same symbols, may sound differently across languages, so there is no threat to confuse the sound of the Ukrainian [и] with the Russian [ы].

Based on acoustic data obtained in her phonetic experiments, Steriopolo concludes that a Ukrainian /и/ is a front retracted vowel close to [ɨ] (Steriopolo, 2012, p. 55). The essential difference in sound of Ukrainian [и] and [ɪ] as in German *bitte* led Pompino-Marschall (personal communication, 2012) to the conclusion that the first is closer to an [ɨ]. However, later a compromising notation /ɪ̠/ (lying between /ɪ/ and /ɨ/) appeared: 'The vowel [и]… would be more correctly transcribed as [ɪ̠], since in contrast to [i] the tongue is quite retracted and lowered in the production of this vowel. (In the acoustical vowel

space it may seem to shift to [ɪ] due to its articulation with strongly spread lips…)' (Pompino-Marschall et al., 2017, pp. 5–6).

The second formants of /и/ and /е/ were found to lie in the range of 1300–2100 Hz and 1600–2600 Hz, with the central values of 1800 Hz and 2100 Hz, respectively; that is between the relevant formants of /а/ (F2 = 1100 Hz) and /і/ (F2 = Fp1 = 2400 Hz) (Vakulenko, 2000, p. 63, 2007, p. 84, 2010, 2011a, p. 172, 2011b, p. 439, 2015, pp. 167–168). These data indicate that a stressed /и/ resides on the Jones diagram somewhere in the boundary region between central and front vowels, above an accented /е/, being a high lowered central advanced vowel. This description corresponds well to the requirement of its light and relaxed character in the standard Ukrainian (cf. Bilodid, 1969, p. 378). A similar sound is quite intelligibly heard in Polish *ryba* 'fish' and in American English *rose's*. So, an accented Ukrainian /и/ should be accordingly rendered through the symbol [ɨ̟⁺].

An unstressed /*и*/ is reported to have a lowered (wider) articulation as compared to its stressed correlate (Bilodid, 1969, p. 381; Zhovtobrjukh & Kulyk, 1965, p. 118), and classified as a front mid elevated vowel (Bilodid, 1969, p. 121). On the chart obtained by Bilous (Dudnyk, 2004, p. 22), its position is more central. It is noteworthy that the pronunciation of this sound depends on the following vowel resulting from distant assimilation: while next high vowels [i]/[*i*] or [y]/[*y*] do not cause major changes in pronunciation of an unstressed [*и*] – *дити́на* 'child', *живи́* 'live!', *etc.*, – next [e]/[*e*] and [a]/[*a*] give rise to its notable shift down towards an unaccented [*е*] – *живе́* 'lives', *ба́чила* '(she) saw', etc. (Zhovtobrjukh & Kulyk, 1965, p. 118). So, we may determine ′near′ and ′distant′ unstressed allophones of the phoneme /и/: a high more lowered central less advanced vowel [ɨ̟⁺] and a midheight central vowel [ɘ⁺].

An accented Ukrainian /е/ has been considered as a mid (lowered) front (center-approached) vowel (Zhovtobrjukh & Kulyk, 1965, p. 118), or as a mid-front retracted vowel (Bilodid, 1969, p. 61), or as a front vowel on the border with the central row, mid but strongly lowered (Tocjka, 1981, p. 56), or, as follows from the chart given in (Pompino-Marschall et al., 2017, p. 5), a slightly retracted midlow front vowel. Our auditory analysis shows that this vowel is close in sound to [ɛ] as in French *même*, but a bit more relaxed. Its formant frequencies of F1 = 700 Hz; F2 = 2100 Hz (Vakulenko, 2000, p. 63, 2007, p. 84, 2010, p. 28, 2011a, p. 173, 2011b, p. 439, 2015, p. 167) suggest that the position of /e/ is midlow and front but not extreme. Thus, we propose the designation [ɛ̠].

Its unstressed cognate is described as a more raised vowel than a stressed /e/, especially before the syllable with a high vowel /i/, /и/, or /y/due to the vowel harmony effect (Tocjka, 1981, p. 104; Zhovtobrjukh & Kulyk, 1965, p. 118; see also Bilodid, 1969, p. 381), or a front mid vowel being a little more advanced than a stressed /e/ (Bilodid, 1969, pp. 119–120), or, on the contrary, a more retracted and raised as compared to /e/ vowel (Dudnyk, 2004, 20–22). All these descriptions should be adjusted to the fact that, in absence of distant assimilation or other sound interaction effects, an unaccented vowel is closer to the center of the Jones diagram than its accented cognate.

According to Brovchenko and Zilynsjkyj, more narrow and front allophone of /e/ arises between palatalized consonants as in *лєтьcя* 'is flown' and also as in *знаємо* 'we know' (see Bilodid, 1969, p. 96, p. 127). Such a narrow variant does appear after palatalized consonants, as observed in our experiments (see Figure 3) and may result also due to vowel harmony (cf. Pompino-Marschall et al., 2017, p. 6).

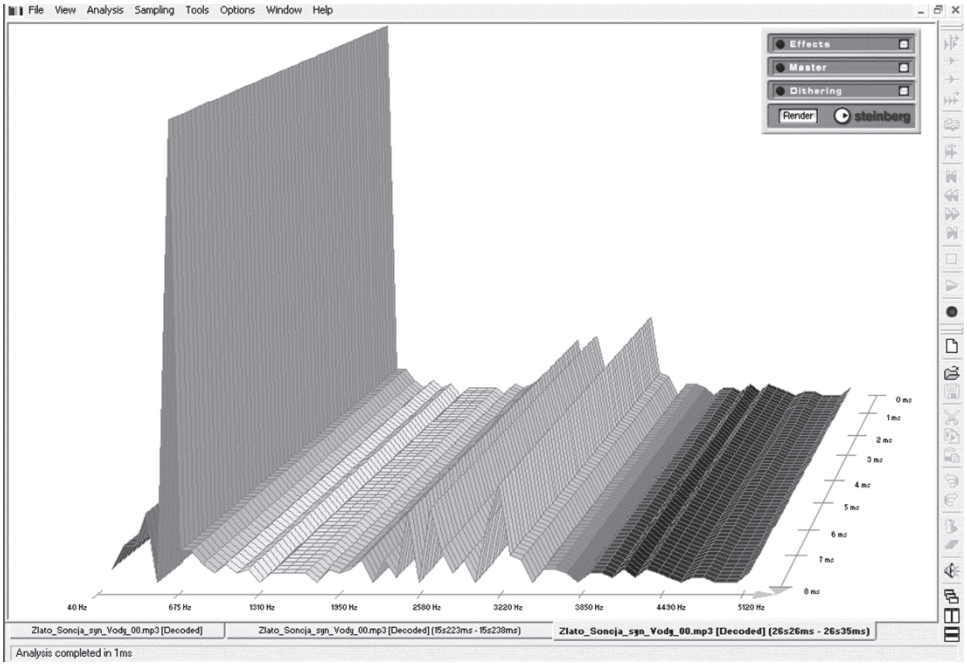

Figure 3. The ending of a Ukrainian sound [*e*] in *спробує* '(he, she) will try', produced by a female speaker. Measurements are made at 4 ms.

Slika 3. Završetak ukrajinskoga glasa [*e*] u riječi *спробує* (hrv. pokušat će), u izgovoru ženskoga govornika. Izmjereno u 4. ms.

Figure 3 presents an informative 8-ms stationary interval with the most clear and characteristic sound.

This is a typical mixed phone with four major formants: F1 = 500 Hz, F2 = 2000 Hz, F3 = 2500 Hz, F4 = 3100 Hz. The first two are characteristic to /e/, where raised tongue position is manifested in the lowered F1, and F3 and F4 are characteristic to [i] with a relevant formant ratio of large tertian: r = F4/F3 ≈ 1.24 ≈ 5/4 (cf. Vakulenko, 2007, pp. 84–85, 2010, pp. 28–29, 2011a, pp. 172–173, 2011b, pp. 439–440, 2015, pp. 167–168).

Thus, two major variants of an unstressed Ukrainian /e/ are possible: a 'regular' central [ɜ̟⁺] (being normally shifted towards a center of the Jones diagram) and strongly raised sound corresponding to [ɐ̟⁺] resulting from vocal assimilation with next high vowels. In addition, an *i*-coloured [e̝⁻] following a palatalized consonant may be both accented and unaccented.

The general diagram of Ukrainian vowels is presented in Figure 4, where the non-stressed allophones are typed in *italic*.

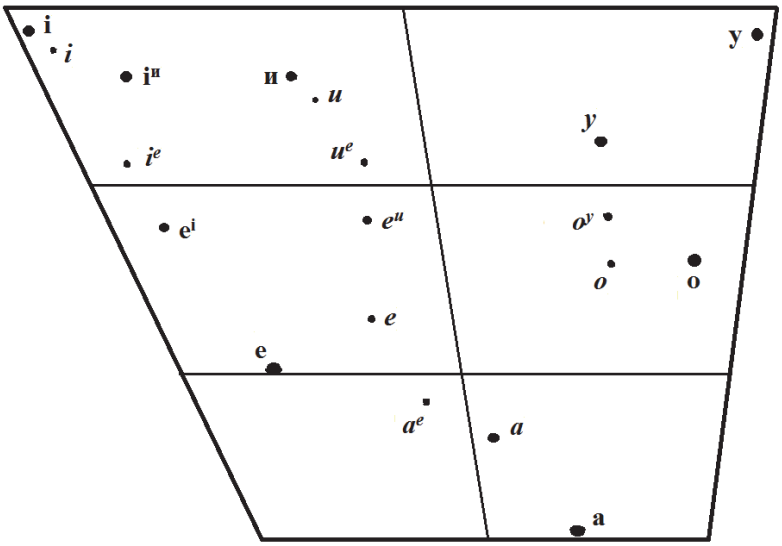

Figure 4. The diagram of Ukrainian vowels (the sounds are denoted in Cyrillic script)

Slika 4. Vokalski dijagram ukrajinskog jezika (glasovi su zabilježeni ćiriličnim pismom)

The correspondence between Cyrillic and IPA phonetic symbols for the Ukrainian vowels is summarized in Table 4.

Table 4. Ukrainian vowel phonemes and their allophonic realizations
Tablica 4. Ukrajinski vokali i njihove alofonske inačice

Ukrainian phoneme / Fonem u ukrajinskom jeziku		Chief allophone / Glavni alofon		Other allophones / Ostali alofoni	
Cyrillic / Ćirilica	Latin / Latinica	Cyrillic / Ćirilica	IPA	Cyrillic / Ćirilica	IPA
/а/	/a/	[а]	[ɑ⁺]	[*а*], [*а*^{е}]	[ɐ], [ɜ⁺]
/о/	/o/	[о]	[o̟]	[*о*], [*о*^{у}]	[o̟⁺], [o⁺]
/у/	/u/	[у]	[u]	[*у*]	[ʊ]
/і/	/i/	[і]	[i]	[*і*], [і^{и}], [*і*^{е}]	[i̞], [ɪ], [e̞]
/и/	/y/	[и]	[ɨ⁺]	[*и*], [*и*^{е}]	[ɨ⁺], [ɔ⁺]
/е/	/e/	[е]	[ɛ⁻]	[*е*], [*е*^{и}], [е^{і}]	[ɜ̝⁺], [ɐ̝⁺], [e̞⁻]

4. DISCUSSION

The lack of experimental equipment in Ukraine imposes certain difficulties in carrying out phonetic research. In this context, new phonetic material and comprehensive interpretation of the data obtained are of high importance. Let us discuss more the central character of an [и] as compared to earlier results of Bilodid (1969) and Tocjka (1981). This is likely due to more detailed and versatile study of this sound in Vakulenko (2000, 2007, 2010, 2011a, 2011b, 2015) including normal speech, changing tone and whisper, involvement of larger number of informants, use of modern software, and application of acoustic invariant speech analysis. Our results are closer to those of Bilous (Dudnyk, 2004, pp. 20–22) regarding unstressed vowel and differ in the part of a stressed [и]. This difference may be caused by incorrect evaluation of this sound as [ɪ] by Bilous that resulted in unreasonably large distance between the stressed and unstressed cognates. The conclusion about placement of [и] on the vowel diagram are similar to those of Steriopolo (2012), Pompino-Marschall (personal communication, 2012), and Pompino-Marschall et al. (2017, pp. 5–6).

5. CONCLUSIONS

Acoustic and articulatory properties of Ukrainian vowels based on earlier studies of Ukrainian have been reported in this study. Specific experimental procedures were described and a full set of relevant IPA notations for the vowel phones of contemporary standard Ukrainian were proposed, including stressed and non-stressed vowel allophones. Auditory comparative analysis, auditory observation, and earlier acoustic invariant speech analysis were applied interpreted in the context of general and Ukrainian phonetic laws governing language evolution and acoustic properties of unaccented vowels in relation to their accented cognates. Such combined approach resulted in a more detailed phone inventory than proposed before.

Vowel chart with a full set of main vowel allophones including the non-stressed ones were proposed. The chief allophone of /и/ is determined as more central than described in Bilodid (1969) and Tocjka (1981) that may result from the more versatile investigation of its acoustic parameters in various pronunciation modes including normal speech, changing tone, and whisper. Such an approach yields invariant, robust characteristics independent on the speaker's individuality and a pronunciation mode. The chief allophone of [e] was found to be more advanced than proposed in Bilodid (1969) and Tocjka (1981), whereas we claim that due to its flatting property, a stressed Ukrainian [o] is a midheight back rounded vowel.

Due to approaches applied, one may expect that the findings of this work offer more precise, comprehensive, grounded and detailed description of the Ukrainian vowels than the previous results of Bilodid (1969), Buk et al. (2008) and Pompino-Marschall et al. (2017).

The findings of this research contribute to better understanding of Ukrainian and its special features in comparison with other world languages that may have substantial practical use in various phonetic and translation studies, as well as in modern linguistic technologies aimed at artificial intelligence development, machine translation incorporating text-to-speech conversion, automatic speech analysis, recognition and synthesis, and in other areas of applied linguistics.

REFERENCES

Besacier, L., Barnard, E., Karpov, A., & Schultz, T. (2014). Automatic speech recognition for under-resourced languages: A survey. *Speech Communication*,

56(1), 85–100. Retrieved January, 28, 2017 from https://www.researchgate.net /publication/259118437

Bilodid, I. K. (Ed.). (1969). *Suchasna ukrajinsjka literaturna mova. Fonetyka [Contemporary standard Ukrainian. Phonetics]*. Kyjiv: Naukova dumka. (in Ukrainian).

Broch, O. (1910). Ocherk fiziologii slavjanskoj rechi [Sketch of Slavic speech physiology]. In *Encyclopedia of Slavic philology* 5/2. Saint Petersburg: Izdanie otdelenija russkogo jazyka i slovesnosti Imperatorskoj Akademii nauk. (in Russian).

Brovchenko, T. A. (1954). Sravniteljnyj analiz glasnykh ukrainskogo i anglijskogo jazykov [Comparative analysis of vowels in Ukrainian and English]. *Uchjonye zapiski I MGPIIJa*, *8*, 24–55. (in Russian).

Buk, S., Maczutek, J., & Rovenchak, A. (2008). Some properties of the Ukrainian writing system. *Glottometrics*, *16*, 63–79.

Dudnyk, Z. (2004). Varianty realizaciji gholosnykh ukrajinsjkogho movlennja v klasyfikaciji MFA [Variants of the Ukrainian speech vowels realization in the IPA classification]. *Ukrajinsjke movoznavstvo [Ukrainian Linguistics]*, *29–30*, 18–23. (in Ukrainian).

Kalynovych, M. (1947). *Vstup do movoznavstva [Introduction to linquistics]*. Part I. Kyjiv – Ljviv.

Laboratorio di Fonetica Sperimentale 'Arturo Genre' (n. d.). Retrieved November, 17, 2018 from http://www.lfsag.unito.it/ipa/

Pompino-Marschall, B., Steriopolo, E., & Żygis, M. (2017). Ukrainian. *Journal of the International Phonetic Association*, *47*(3), 349–357.

Press, I., & Pugh, S. M. (2015). *Ukrainian: A comprehensive grammar*. Routledge Comprehensive Grammars.

Scannell, K. P. (2007). The Crúbadán project: Corpus building for under-resourced languages. *Cahiers du Cental*, *5*, 1–10. Retrieved January, 28, 2018 from https://pdfs.semanticscholar.org/ef9f/81a662aa9618173d033e95d46d74e14aeafc.pdf

Shyrokov, V. A. (2011). *Komp'juterna leksykoghrafija [Computer lexicography]*. Kyjiv: Naukova dumka. (in Ukrainian).

Steriopolo, O. I. (2012). Ukrajinsjka fonetychna systema u paradyghmi mizhnarodnoji fonetychnoji asociaciji (MFA) [Ukrainian phonetic system in the paradigm of International Phonetic Association (IPA)]. *Naukovyj visnyk*

Uzhghorodsjkogho universytetu. Series: Philology. Social communications, *27*, 51–58. (in Ukrainian).

Stevens, K. N. (1998). *Acoustic phonetics*. Cambridge, Mass.: MIT Press.

Synjavsjkyj, O. N. (1929). Sproba zvukovoji kharakterystyky literaturnoji ukrajinsjkoji movy [An attempt of sound characteristic of the literary Ukrainian language]. In *Naukovi zapysky Kharkivsjkoji naukovo-doslidnoji kafedry movoznavstva II* (pp. 5–33). (in Ukrainian).

Tocjka, N. I. (1981). *Suchasna ukrajinsjka literaturna mova: fonetyka, orfoepija, ghrafika, orfoghrafija [Contemporary standard Ukrainian: Phonetics, orthoepics, graphemics, orthography]*. Kyjiv: Vyshha shkola. (in Ukrainian).

Vakulenko, M. O. (2000). Akustychni kharakterystyky ta invarianty zvukiv ukrajinsjkoji movy [Acoustic characteristics and invariants of the Ukrainian sounds]. *Naukovyj visnyk kafedry JUNESKO KDLU [Scholarly News of the KSLU UNESCO Chair]. Filologhija, pedaghoghika, psykhologhija [Philology, Pedagogics, Psychology]*, *1*, 62–66. (in Ukrainian).

Vakulenko, M. O. (2007). Acoustic invariant approach to speech sound analysis for brand new speech recognition systems (Ukrainian and English). *Computing*, *6*(3), 79–86. Retrieved January, 28, 2017 from http://computingonline.net /index.php/computing/article/view/455

Vakulenko, M. O. (2010). Acoustic invariants of Ukrainian vowels. *Visnyk Kyjivsjkogho linghvistychnogho universytetu. Series 'Philology'*, *13*(1), 21–31.

Vakulenko, M. O. (2011a). Invariant acoustic speech analysis and constant characteristics of Ukrainian vowels. *Dialog der Sprachen – Dialog der Kulturen. Die Ukraine aus globaler Sicht. I. Internationale virtuelle Konferenz der Ukrainistik* (pp. 164–177).

Vakulenko, M. O. (2011b). Metod akustychnykh invariantiv u doslidzhenni gholosnykh zvukiv ukrajinsjkoji movy [Acoustic invariant method in the Ukrainian vowels study]. *Slavia*, *4*, 431–442. (in Ukrainian). Retrieved January, 28, 2017 from http://www.ceeol.com/aspx/issuedetails.aspx?issueid=34be1bd3-2cde-4b31-bfe3-1e5a83d1a320&articleId=d713efd8-613a-45bb-b9e3-744f3e36f82f

Vakulenko, M. O. (2015). *Ukrajinsjka terminologhija: kompleksnyj linghvistychnyj analiz [Ukrainian terminology: Complex linguistic analysis]*. Ivano-Frankivsjk: Foliant. (in Ukrainian). Retrieved January, 28, 2017 from http://www.twirpx.com/file/1842764/

van Belle, J.-L. (2014). Reading Feynman. Complex Fourier analysis: An introduction. Retrieved November, 14, 2018 from https://readingfeynman.org /2014/10/06/complex-fourier-analysis-an-introduction/

Zhovtobrjukh, M. A., & Kulyk, B. M. (1965). *Kurs suchasnoji ukrajinsjkoji literaturnoji movy [A course of moderm Ukrainian literary language]*. In 2 parts (3rd ed.). Kyjiv: Rad. shk. Part 1. (in Ukrainian).

Zilynsjkyj, I. (1932). *Opis fonetyczny języka ukraińskiego [Phonetic description of the Ukrainian language]*. Kraków: Gebethner and Wolff. (in Polish).

Maksym O. Vakulenko
maxvakul@yahoo.com
Ukrajinska jezično-informacijska zaklada Ukrajinske akademije znanosti, Kijev
Ukrajina
Lionbridge Technologies, Inc., Tampere
Finska

Vokali ukrajinskog jezika prema Međunarodnoj fonetskoj abecedi

Sažetak

U ovom se radu opisuju akustičke i artikulacijske osobitosti vokala u ukrajinskom jeziku te se daje opis vokalskog sustava u skladu s notacijom IPA. Opis je prikazan u vokalskom dijagramu i tablici. Rezultati ranijih akustičkih istraživanja, kao i istraživanja slušne procjene vokala, interpretiraju se u kontekstu općih zakonitosti u evoluciji jezika i zakonitosti specifičnih za ukrajinski jezik, što se posebno odnosi na akustičke karakteristike nenaglašenih i naglašenih vokala. Time se dobiva detaljniji vokalski sustav. Rezultati ovog rada doprinose boljem razumijevanju ukrajinskog jezika i njegovih osobitosti u odnosu na druge svjetske jezike. Praktična primjena moguća je u fonetskim i komparativnim istraživanjima, kao i u usavršavanju suvremenih jezičnih tehnologija koje doprinose razvoju umjetne inteligencije, strojnom prevođenju koje uključuje prepoznavanje tekstova govorom (engl. *text-to-speech*), automatskom prepoznavanju govora i govornoj sintezi te u drugim područjima primijenjene lingvistike.

Ključne riječi: fonemi ukrajinskog jezika, abeceda Međunarodnog fonetskog udruženja, vokalski dijagram, akustička analiza vokala