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Positions of Polish phonemic vowels in the IPA Vowel Diagram estimated using neural networks trained on Cardinal Vowel Productions

Pozycje polskich samogłosek fonemicznych na czworoboku samogłoskowym IPA uzyskane przy użyciu sieci neuronowych wytrenowanych na artykulacjach samogłosek kardynalnych

Abstract

This article aims to verify and refine the positions of Polish phonemic vowels in the IPA Vowel Diagram as proposed in phonetic literature. To achieve this, neural network models trained on productions of Cardinal Vowels by a representative group of phoneticians were used. This automated approach eliminates potential confounding effects of individual researchers' intuitions, and the locations established this way may be more accurate within the Cardinal Vowel System. The results suggest positions similar to those proposed in articulatory descriptions found in the literature. Nonetheless, the placements tend to be more central. These findings are consistent with the observation that the relatively small inventory of Polish vowels does not require tense phonetic productions. All this points to the conclusion that the positions of Polish phonemic vowels should be placed slightly away from the edges of the Vowel Diagram, indicating more lax articulations.

Keywords: Polish vowels, vowel articulation, vowel production, IPA Vowel Diagram

Streszczenie

Celem niniejszego artykułu jest weryfikacja i doprecyzowanie pozycji polskich samogłosek fonemicznych w czworoboku samogłoskowym IPA, zaproponowanych w literaturze fonetycznej. W tym celu wykorzystano modele sieci neuronowych wytrenowane na nagraniach wymowy samogłosek kardynalnych przez reprezentatywną grupę fonetyków. Takie zautomatyzowane podejście eliminuje potencjalne subiektywne wpływy wynikające z indywidualnej intuicji badaczy, a uzyskane w ten sposób lokalizacje mogą być trafniejsze w ramach systemu samogłosek kardynalnych. Wyniki sugerują pozycje zbliżone do tych proponowanych w literaturze przedmiotu, jednak mają one tendencję do przesunięcia w kierunku centrum czworoboku. Jest to zgodne z obserwacją, że stosunkowo niewielka liczba samogłosek fonemicznych w języku polskim nie wymaga napiętej artykulacji. Wszystko to prowadzi do wniosku, że pozycje polskich samogłosek fonemicznych powinny być umieszczane nieco dalej od krawędzi czworoboku samogłoskowego, co wskazuje na luźniejszą artykulację.

Słowa kluczowe: polskie samogłoski, artykulacja samogłosek, wymowa samogłosek, czworobok samogłoskowy IPA

Aims

The positions of Polish phonemic vowels in the IPA Vowel Diagram, as proposed in phonetic literature, are only approximate and may involve a degree of imprecision. This results from various factors. For example, different dimensions of the Quadrilateral are found across different publications, and the practical use of the Cardinal Vowel system tends to involve a certain amount of phoneticians' intuition (see the discussion in section "Cardinal Vowel System").

The aim of this article is to verify the assumed positions of the Polish phonemic vowels using neural network models trained on productions of Cardinal Vowels by several phoneticians. This approach mitigates several limitations faced in previous studies. The positions established in the present research are not based on individual authors' intuitions; instead, they result from automated comparisons to Cardinal Vowel productions by a group of phoneticians. These productions have been quantified within a uniform coordinate system based on a single version of the IPA Vowel Diagram. The results obtained in this way may be more precise and objective.

Cardinal Vowel System

Throughout the nineteenth century, various transcription systems were proposed, including the "Phonotypic Alphabet" by Pitman and Ellis (1845), the "Standard Alphabet" by Lepsius (1855; 1863), "Visible Speech" by Bell (1867), the "Palaeotype Alphabet" by Ellis (1869), and the "Romic Alphabet" by Sweet (1877, 1906). A major milestone in this development was the founding of the International Phonetic Association in 1886, which led to the creation of the International Phonetic Alphabet (IPA).

The aspect of the IPA most relevant to this study is the system of Cardinal Vowels, as formalised by Jones (1914, 1917a, 1917b). Initially, the system comprised eight Primary and eight Secondary Cardinal Vowels. Over time, additional reference vowels were introduced. In the current version of the IPA Vowel Diagram, their number amounts to 28.

The Cardinal Vowel system is intended to be universal in the sense that "(a) the vowel qualities are unrelated to particular values in languages, though many may occur in various languages, and (b) the set is recorded, so that reference may always be made to a standard, invariable scale" (Gimson, Cruttenden, 2001: 36). Researchers should be able to describe any vowel appearing in a natural language by comparing it to the Cardinal Vowels, which serve as reference points along the articulatory continuum (Jones, Ward, 1969; Ladefoged, 1975; Lisker, 1989).

Nonetheless, the system faces several challenges. Cardinal Vowels have been recorded by numerous phoneticians and are available from various sources. These phonetic productions differ from each other to varying degrees. Even Daniel Jones himself recorded more than one version, and in practice, it is difficult to identify a single set of reference recordings. Moreover, it has been indicated that phoneticians differ in their judgements regarding the placement of individual articulations within the IPA Vowel Diagram (Dioubina, Pfitzinger, 2002). The shape of the Vowel Diagram has also undergone several stages of revision, and in practice, different versions appear across research papers, making cross-publication comparisons difficult. Finally, the Diagram does not precisely reflect the physical articulatory positions of the Cardinal Vowels (Butcher, 1982), and the system has been described as "impressionistic" (Nolan, 1988).

Polish phonemic vowels

The Polish language has six phonemic vowels: the close front /i/, the mid-open front /ɛ/, the central open /a/, the mid-open back /ɔ/, the close back /u/, and the mid-close central /ɨ/. Their exact positions in the IPA Vowel Diagram cannot be accurately determined because the judgements proposed in the literature on Polish phonetics are largely based on different authors' intuitions. The assumed position of a given vowel often varies across publications. This problem is compounded by the differing dimensions of the Vowel Diagram used by various authors and by other issues discussed in "Cardinal Vowel System" regarding the Cardinal Vowel System. Nevertheless, based on descriptions provided by Bartnicka-Dąbrowska (1968), Benni (1959), Biedrzycki (1978), Dłuska (1986), Dukiewicz (1995), Jassem (1974; 1975; 1981), Jaworski (1986), Madelska and Witaszek-Samborska (1988), Pilich (1975), Rocławski (1976), Sawicka (1995), Strutyński (1987), and Wiśniewski (1997), the positions of the vowels are shown in figure 1. It must be stressed that these locations are only rough approximations and represent a synthesis of varied articulatory descriptions.

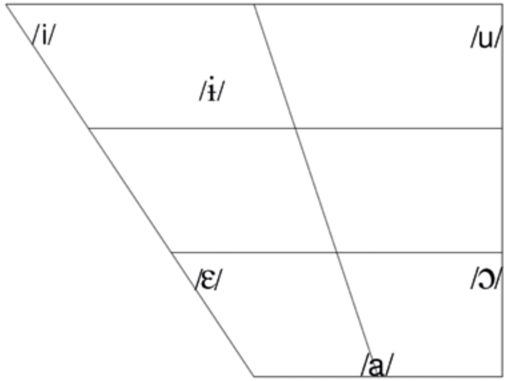

Fig. 1. Assumed positions of the Polish phonemic vowels

Source: based on Benni, 1959; Bartnicka-Dąbrowska, 1968; Jassem, 1974; 1975; 1981; Pilich, 1975; Rocławski, 1976; Biedrzycki, 1978; Dłuska, 1986; Jaworski, 1986; Strutyński, 1987; Madelska, Witaszek-Samborska, 1988; Dukiewicz, 1995; Sawicka, 1995; Wiśniewski, 1997.

Automatic placement of vowel production in the IPA Vowel Diagram

Attempts to automate the placement of vowel productions in the IPA Vowel Diagram include a series of publications by Pfitzinger (1995; 2003; 2005). He proposed various algorithms that use F0, F1, and F2 measurements as inputs and output x – y coordinates within a system he developed for the version of the Vowel Diagram specified at the Kiel Convention in 1989. Initially, the algorithms were relatively complex and relied on Bark-transformed values of F0, F1, and F2 (Pfitzinger, 1995). The data used to develop these formulae were also limited to a single speaker producing vowels in German, which were then placed in Cardinal Vowel Diagrams by a group of trained phoneticians. Later developments included a more extensive sample of German vowels, judged by a larger number of phoneticians. The resulting algorithms were simpler and easier to implement (see: formula 1 below, taken from Pfitzinger, 2005).

$$h = 3.122 \log(F0) - 8.841 \log(F1) + 44.16$$
$$b = 1.782 \log(F1) - 8.617 \log(F2) + 58.29$$

Formula 1. Automatic prediction of the height (h) and backness (b) coordinates in Pfitzinger (2005)

However, the practical use of Pfitzinger's proposals faces several obstacles. First, a model trained solely on decisions made by human participants may be imprecise. As Pfitzinger (2003) reports, phonetically trained subjects are unable to place vowel articulations in the IPA Vowel Diagram at exactly the same location after one year. This suggests a potential error in the resulting data and model. More crucially, Pfitzinger does not specify the type of hardware, software, or measurement parameters that should be used to obtain F0, F1, and F2. Without such specifications, his models are exceedingly difficult to implement in practice. For example, Stolarski (2020) demonstrated that applying different settings in Praat (Boersma, Weenink, 2024) leads to considerable variation in measured values and has a major impact on the placement coordinates generated using the equations in formula 1.

Another attempt to automate the placement of vowel productions in the IPA Vowel Diagram was undertaken by the author, who employed neural network technology and recordings of Cardinal Vowel productions by different phoneticians. A detailed description of the procedures followed in developing the model lies beyond the scope of this publication and may warrant a separate paper. Nevertheless, since this approach serves as the primary automatic method of determining vowel positions in the IPA Vowel Diagram, a brief summary outlining the major stages of the process is provided below.

As a first step, a coordinate system was established based on the 2020 revision of the IPA Vowel Diagram, which is available online (*The International Phonetic Alphabet and the IPA Chart*, n.d.). The dimensions of the quadrilateral were measured in pixels using GIMP (2019), and the values obtained were converted into proportional relationships. The upper horizontal line was assigned a value of 1, and the right vertical line was set to 0.75 (see: fig. 2). Next, the coordinates for the Cardinal Vowels were determined. Cardinal Vowels 1 and 9 were assigned values of 0 on the x-axis and 0.75 on the y-axis. Likewise, the coordinates for Cardinal Vowels 4 and 12 were set to 0.5 and 0; for Cardinal Vowels 5 and 13, to 1 and 0; and for Cardinal Vowels 8 and 16, to 1 and 0.75. All other positions were calculated mathematically, assuming that the slanted vertical line denoting the central region is positioned in the centre of the diagram, and that the two horizontal middle lines are evenly spaced.

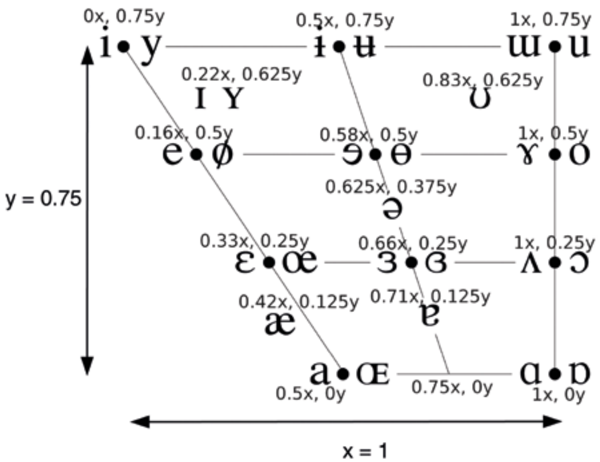

Fig. 2. IPA Vowel Diagram with the x and y coordinate values used in the training of "Vowelmeter"

Source: The International Phonetic Alphabet and the IPA Chart (n.d.). The coordinate values are based on the author's own research.

Next, sets of Cardinal Vowel recordings by fourteen different phoneticians – freely available on the Internet – were collected. Each production of a Cardinal Vowel was measured in terms of F0 and the first two formants, utilising the Parselmouth library (Jadoul, Thompson, De Boer, 2018), a Python interface for Praat (Boersma, Weenink, 2024). These measurements were then normalised using Miller's method (1989), which has been found to be among the most effective approaches tested in Adank, Smits and van Hout (2004).

All of these data were used to train two separate neural networks. One was designed to predict vowel backness, and another to predict vowel height. Each network consists of three input neurons (representing the outputs of Miller's normalisation), two hidden layers (each containing eight neurons), and a single output neuron that provides either the backness or height value within the coordinate system described above. The testing accuracy, measured on a test set comprising 10% of the acoustic measurements, was found to be 0.1278 for the backness model and 0.0968 for the height model.

Both models have been implemented in a prototype of a free web application, available at vowelmeter.pythonanywhere.com. The site allows users to upload recordings of prolonged vowel articulations in wav or mp3 format and extract measurements of F0 and the first three formants. Once the user accepts these measurements as sufficiently accurate, they may be submitted to the models to predict vowel backness and height. The final results are displayed graphically in the IPA Vowel Diagram and also presented as numeric coordinates indicating the predicted placement within the defined coordinate system.

Test materials and measurements

An elongated pronunciation of the basic allophone of each Polish phonemic vowel was recorded by 42 native speakers of Polish. 24 of the respondents were female, and 18 were male. Their ages ranged from 21 to 25. The recordings were made at home using various hardware and software setups. This is consistent with how the software accessible at vowelmeter.pythonanywhere.com was intended to be used. There are no specific technical requirements, as the Cardinal Vowel recordings used to train the neural network models were themselves produced using a variety of hardware and software components.

The values of F0, F1, F2, and F3 for each recording were automatically measured at vowelmeter.pythonanywhere.com. This process included a qualitative verification step, in which the extracted values were compared with the corresponding spectrograms. In a few cases, the values were adjusted slightly. Finally, the coordinates for the position in the IPA Vowel Diagram for each articulation, as predicted by the models, were obtained.

Results

Figure 3 summarises all of the predictions. A quick visual inspection suggests that the scatter of articulations for the high front vowel /i/ tends to be greater along the horizontal axis than the vertical one. Conversely, the dispersion of articulations for the back vowels /u/

and /ɔ/ appears greater in the vertical dimension than in the horizontal. In other cases, the scatter is relatively similar across both dimensions.

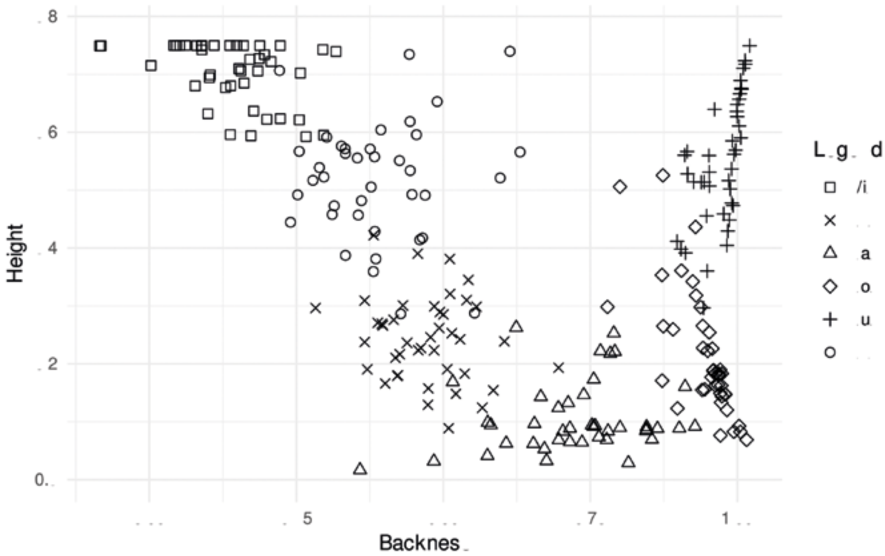

Fig. 3. Automatic placement of Polish vowels articulated by 42 participants

Source: Author's own research.

One way to quantify the overall dispersion of individual productions within a vowel category is to calculate the mean Euclidean distance from the category's centroid (see: formula 2). The centroids for each vowel were computed by averaging the x and y coordinates; they are indicated as unfilled shapes in figure 5. Lower values of this metric indicate less scatter in the automatic placements. The results are summarised in the first column of table 1. These values are generally similar across vowels, with the exception of the mid-close central /ɨ/, which shows relatively greater dispersion (0.1239).

$$d(a,b)=\sqrt{(a_1-b_1)^2+(a_2-b_2)^2}$$

Formula 2. Euclidean distance for two-dimensional data: a and b are two points in a plane; a1 and a2 are coordinates for a, while b1 and b2 are coordinates for b

The dispersion of articulations for different vowel categories was further evaluated using the R package Dynamic Range Boxes (dynRB) (Junker et al., 2016). This package estimates the "hypervolume" for a given category based on two or more numerical predictors. The mathematical foundations of the approach are discussed in Junker et al. (2016). Among the available aggregation methods, product was selected, meaning that the size of each dimension is first calculated separately and then multiplied. Final values range from 0 to 1, with those near 0 indicating a small size and those near 1 indicating a large one. The results obtained are provided in the second column of table 1. In relative terms, they closely resemble the previously discussed dispersion values based on the mean Euclidean distances.

Tab. 1. Dispersion of articulations for each vowel quantified as the average Euclidean distance from the corresponding centroid and as the "hypervolume size"

Vowel	Mean Euclidean distance	Hypervolume size
i	0.0882	0.0529
ɛ	0.0923	0.0631
a	0.1094	0.0701
ɔ	0.0941	0.0511
u	0.0984	0.0470
ɪ	0.1239	0.1154

Source: Author's own research.

It is also important to examine the distribution of individual automatic placements according to speaker gender. This analysis helps evaluate whether the overall approach effectively accounts for gender-related variation. The results depicted in figure 4 clearly demonstrate that the placements are randomly distributed within each vowel category, which is marked by an oval outline. Female and male articulations are freely intermixed, and no consistent gender-based patterns are observable.0

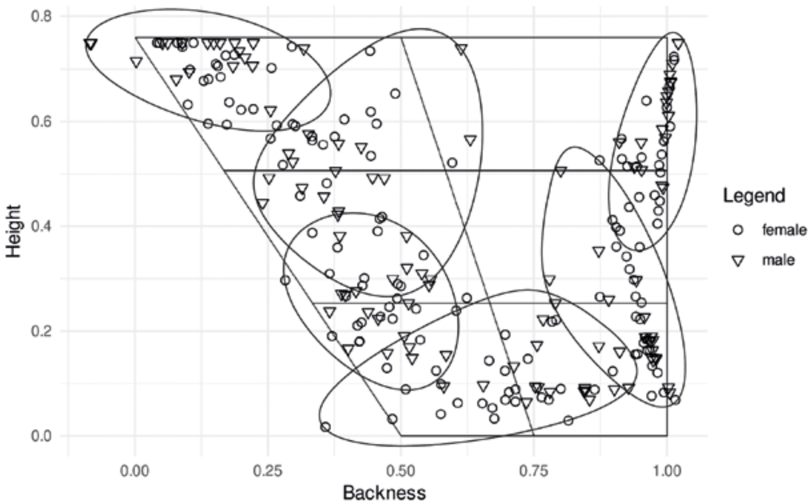

Fig. 4. Automatic placement of articulations by speaker gender. Vowel areas are marked with oval outlines

Source: Author's own research.

What is central to this study, however, are the positions of vowel centroids, or average vowel placements, in relation to the corresponding approximate locations suggested in the literature discussed in section "Polish phonemic vowels". In figure 5, the former are marked as unfilled shapes, and the latter are marked as dark shapes. The centroids are generally close to the assumed positions, indicating that the models used in this study produce results consistent with the intuitive judgements found in the literature on Polish phonetics. Nevertheless, it is important to note that the centroids tend to be located further from the edges of the IPA Vowel Diagram, suggesting less tense articulations than those often assumed for Polish vowels. These more centralised locations may in fact be more accurate for two reasons. First, the results are generated by models trained on actual Cardinal Vowel productions by several phoneticians, all mapped onto a coordinate system based on a consistent version of the IPA Vowel Diagram. This introduces a level of objectivity and consistency that is not necessarily found across the various publications cited in section "Polish phonemic vowels". Second, since the Polish vowel inventory is relatively simple and consists of only six phonemic segments, the principle of sufficient perceptual separation (Tatham, Morton, 2006) does not require tense articulations. There is enough articulatory space for more lax productions while still maintaining perceptual distinctiveness. Additionally, the principle of ease of articulation (Shariatmadari, 2006) also supports the idea that Polish vowels may be produced with less muscular tension than some of the Cardinal Primary Vowels. It is therefore reasonable to conclude that Polish vowels should not be placed on the edges of the IPA Vowel Quadrilateral. The centroid positions shown as unfilled shapes in figure 5 may be a more accurate representation of their articulation within the current version of the IPA Cardinal Vowel system.

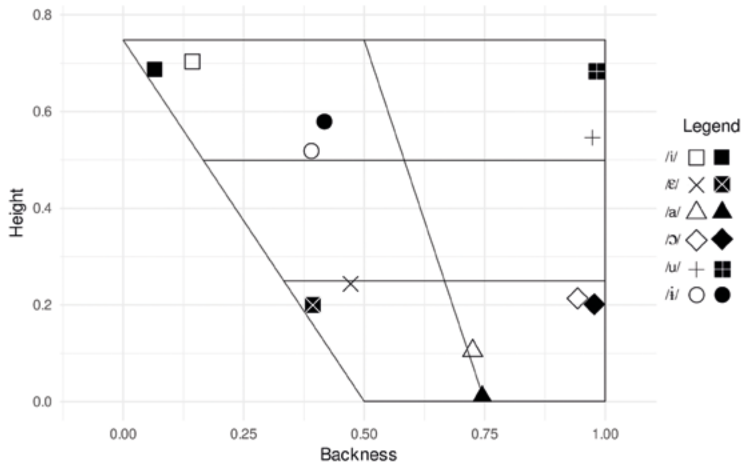

Fig. 5. The dark shapes are the approximate positions of Polish vowels assumed in the phonetic literature. The unfilled shapes are the corresponding average positions predicted by the neural network models (n=42)

Source: The approximate positions of Polish vowels are based on accounts found in Benni, 1959; Bartnicka--Dąbrowska, 1968; Jassem, 1974; 1975; 1981; Pilich, 1975; Rocławski, 1976; Biedrzycki, 1978; Dłuska, 1986; Jaworski, 1986; Strutyński, 1987; , Madelska, Witaszek-Samborska, 1988; Dukiewicz, 1995; Sawicka, 1995; Wiśniewski, 1997. The corresponding average positions predicted by the neural network models are based on the author's own research.

Conclusion

The results of the automatic placement of Polish vowel articulations in the IPA Vowel Diagram, as performed in this study, are similar to the approximate locations established based on the articulatory descriptions listed in section "Polish phonemic vowels". The centroids for each vowel category are situated near the theoretical approximate positions. Nevertheless, there is a consistent tendency for the centroids to be located slightly closer to the central region of the Diagram. Since these results are produced by neural network models trained on actual productions of Cardinal Vowels by a representative group of phoneticians, they may indicate more accurate positions of Polish phonemic vowels within the IPA Vowel Diagram than the rough approximations derived from phonetic literature. As discussed in "Results", these more central locations are also consistent with the overall characteristics of the Polish vowel system. Its relatively small inventory does not necessitate tense phonetic realisations.

In future studies, the neural network models made available through the web application at VovelMater (n.d.) could be employed to evaluate the positions of vowel categories in the IPA Vowel Diagram for languages other than Polish. This approach may contribute to greater objectivity and precision in the description of different vowel inventories.

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