Effect of Ageing on Acoustic Characteristics of Voice Pitch and Formants in Czech Vowels

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Summary: Background. The relevance of formant-based measures has been noted across a spectrum of medical, technical, and linguistic applications. Therefore, the primary aim of the study was to evaluate the effect of ageing on vowel articulation, as the previous research revealed contradictory findings. The secondary aim was to provide normative acoustic data for all Czech monophthongs.

Methods. The database consisted of 100 healthy speakers (50 men and 50 women) aged between 20 and 90. Acoustic characteristics, including vowel duration, vowel space area (VSA), fundamental frequency (f_o), and the first to fourth formant frequencies (F_1-F_4) of 10 Czech vowels were extracted from a reading passage. In addition, the articulation rate was calculated from the entire duration of the reading passage.

Results. Age-related changes in pitch were sex-dependent, while age-related alterations in F_2/a/, F_2/u/, VSA, and vowel duration seemed to be sex-independent. In particular, we observed a clear lowering of f_o with age for women, but no change for men. With regard to formants, we found lowering of F_2/a/ and F_2/u/ with increased age, but no statistically significant changes in F_1, F_3, or F_4 frequencies with advanced age. Although the alterations in F_1 and F_2 frequencies were rather small, they appeared to be in a direction against vowel centralization, resulting in a significantly greater VSA in the older population. The greater VSA was found to be related partly to longer vowel duration.

Conclusions. Alterations in vowel formant frequencies across several decades of adult life appear to be small or in a direction against vowel centralization, thus indicating the good preservation of articulatory precision in older speakers.

Key Words: Aging−Czech−Formant−Vowel−Acoustic analysis−Fundamental frequency.

INTRODUCTION

The quality and intelligibility of each vowel can be described mainly by its formant structure but also by the fundamental frequency (f_o) and vowel duration.[1] While the first (F_1) and second (F_2) formant frequencies are essential for phonemic recognition of various vowels,[2] the higher third (F_3) and fourth (F_4) formants contribute mainly to the expression of emotions.[1,3] From a physiological point of view, F_1 and F_2 frequencies reflect primarily tongue position and lips rounding[1] while F_3 and F_4 are thought to be related mainly to lip spreading or protrusion.[3,4] Since F_1 and F_2 frequencies have a well-defined acoustic-articulatory relationship, they were used for the definition of several derived metrics (see[2] for an overview). Among these, the most frequently reported acoustic measure was probably the vowel space area (VSA), typically calculated as the area of a triangular or quadrilateral polygon formed by the corner vowels in the two-dimensional formant plane ($F_1 \times F_2$), three-dimensional formant space ($F_1 \times F_2 \times F_3$), or potentially the four-dimensional formant hypercube ($F_1 \times F_2 \times F_3 \times F_4$), but the first of these is the most commonly used.[2] VSA is supposed to reflect the articulatory extrema of vowel production.[2] Therefore, vowel centralization, which is caused due to the limited articulatory range of motion (ie, formants with naturally higher frequencies tend toward lower frequencies, and formants with naturally lower frequencies tend toward higher frequencies), can be captured well by a reduced size of the VSA. From a clinical perspective, the evaluation of formant frequencies, VSA, or similar formant-based measures has proved its feasibility in many fields; specifically, they might be used to evaluate the effect of voice and speech therapy,[5−7] to serve as an early marker of Parkinson's disease[8] or other neurological conditions,[9] to ease the diagnosis of obstructive sleep apnoea,[10] and to monitor disease progression or the effect of drug introduction in neurodegenerative conditions.[11,12] Furthermore, the relevance of vowel formant measurements has also been noted across a spectrum of technical and linguistic applications, including automatic speech recognition,[13] age and sex identification,[14] forensic science,[15] dialect assessment,[16,17] and second-language studies.[18]

AGE-DEPENDENT ACOUSTIC CHARACTERISTICS

The elderly population is increasing dramatically across the world; as a result, the number of elderly subjects with speech

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and/or language disorders has also increased rapidly. Nevertheless, natural alterations in voice and speech also occur in healthy populations, and are attributed to anatomical and physiological changes in the larynx and other speech-related structures. For example, the speech performance of elderly people might be affected by worsening physiological conditions represented by factors such as longer processing times, reduced sensory feedback, general neuromuscular slowing, or peripheral degeneration of the speech mechanism.[19] In addition, sex-related differences might also occur between the sexes as a result of different laryngeal lowering and vocal tract lengthening, different rates of ageing, or the hormonal effects of menopause in women.[20,21]

Knowledge about the magnitude of physiological voice and speech alterations is essential for differentiating normal from pathological utterances. In fact, numerous studies have investigated the effect of ageing on speech production in order to identify specific speech alterations that commonly occur in healthy older adults.[2,19–32] It has been noted that, regardless of sex, people tend to have slower speaking and reading rates as they age,[19,26,29] and produce longer vowel segments.[22,25,26] Based on the results of both cross-sectional and longitudinal studies, the f_o in older women has been shown to decrease significantly.[21,24,27,31] However, the findings for the male population are somewhat inconsistent, as f_o is reported to decrease significantly,[23,27] remain unchanged[24] or even increase markedly[21,26,31] with advanced age. Considering age-related changes to F_1 and F_2 frequencies, the majority of the previous studies have observed vowel-specific alterations that are unique to male and female populations.[20,21,24,30] These changes in spectral patterns have been further hypothesized to be related to vowel centralization[22,30] that is present due to neuromuscular changes affecting the rate and precision of articulatory movements, or a general decrease in F_1 and F_2 frequencies that is mainly attributed to vocal tract lengthening.[28] However, more recent studies[24,25,31] do not appear to confirm these assumptions, as they have revealed no changes in F_1 and F_2 frequency for men or women over the age of 60,[25,31] nor of the trend towards VSA reduction.[24,25] In addition, the study published by Fletcher et al[25] revealed a significant relationship between speakers' average vowel durations and their VSA, indicating that speakers who had longer vowel durations produced vowels that were more spectrally distinct. Thus, some authors have suggested that a habitually slower speaking rate may be an effective compensatory mechanism that some speakers use to maintain acoustically distinct speech segments.[25] Finally, to the best of our knowledge, the age-related changes in F_3 and F_4 have not yet been investigated thoroughly, with only a very few studies generally reporting no age-related changes in higher formants.[20,24] Therefore, further research should be conducted in order to clarify these ambiguous findings.

CHARACTERISTICS OF CZECH VOWELS

Czech is a western Slavic language of the Indo-European family, and is spoken by nearly 10 million people in the Czech Republic and about two million people living abroad.[16] Compared to most other European countries, the Czech Republic does not exhibit large variations in local or social accents. Absence of such variations can be explained by the geographical compactness and relatively small size of the entire territory, combined with the traditionally unrestrained mobility of the population. Only the borders of the Czech territory, which are relatively sparsely populated, can claim to host true accents. The political development in recent decades and the influence of the media have also prevented the development of salient sociolects. However, remnants of local pronunciation features can still be traced in some regions such as southern Moravia or Silesia. Standard Czech pronunciation is based on the original accents of Central Bohemia—the region most densely populated and with the greatest political power.

The Czech vowel inventory contains 10 monophthongs and three diphthongs. The monophthongs consist of five different vowel qualities /a/, /ɛ/, /ɪ/, /o/ and /u/, occurring in two quantities as short and long. The long vowels are about 1.7 times longer than their short counterparts.[33] With the exception of /ɪ/ and /iː/, in which the short vowel is noticeably less close and more central than is the long one,[34] the pairs of short and long vowels are assumed to have similar spectral patterns.[16] However, only a few previous studies[35–37] have focused on the acoustic investigation of formant frequencies in Czech. These studies are further limited by the inclusion of a small number of nonrepresentative groups of subjects of a similar age and work status, such as university students[35,37] or professional actors.[36] Moreover, these studies have only analyzed F_1 and F_2 frequencies while neglecting higher formants,[35,37] have only considered short vowels,[35,36] and have only provided reference values for men.[37] Since there is tremendous phonetic diversity in the languages of the world and Czech belongs to underdocumented languages, there is a need for the definition of representative, normative acoustic data.

AIMS OF THE STUDY

The aim of the current study was to examine the acoustic characteristics of vowels in healthy Czech native speakers aged from 20 to 90 in order to evaluate the effect of ageing on vowel articulation. An additional aim was to provide normative data for Czech vowels. We decided to use a reading passage to create a more natural condition of connected speech while simultaneously maintaining a standardized speaking task. The set of acoustic characteristics chosen included f_o, F_1, F_2, F_3, F_4, VSA, vowel duration, and articulation rate. Since most of the previous studies,[21,22,24–27,32] with the exception of the study published by Sebastian et al[31] who focused only on participants aged from 60 to 80, have reported that the f_o in women and the vowel duration in both sexes were age-dependent, we expected the same trend in our data. With regard to formant frequencies, some of the previous studies indicated vowel-specific alterations in F_1 and F_2 frequencies as a function of age in at least 50%

of the formants investigated,[20,21,30] while more recent studies[24,25] do not appear to confirm these findings. Since these studies[24,25] investigated a larger cohort of participants, thus allowing for a more appropriate statistical design, we hypothesized that F_1 and F_2 frequencies would be age-independent for most of the vowels.

METHODS

Participants

A total of 100 Czech native speakers (50 men and 50 women) were recruited for the study. All the participants provided written, informed consent for the recording procedure, and the study was approved by the Ethics Committee of the Faculty of Biomedical Engineering at the Czech Technical University in Prague, Czech Republic. The age distribution in both sexes was balanced, with the males' ages ranging from 20 to 87 (mean 52.7 ± SD 20.1) years, and the females' ages ranging from 20 to 89 (53.2 ± 19.8) years. In addition, the age of each speaker in the male and/or female groups was different in order to provide a greater diversity of ages. The separate age distributions for the sexes are presented in Figure 1. The frequency of man and woman was similar in each age group. In particular, the percentage of men was 53% in 20−29 age group, 50% in 30−39 age group, 46% in 40−49 age group, 53% in 50−59 age group, 44% in 60−69 age group, and 52% in 70−89 age group. All the participants had completed 8 years of elementary education as a minimum, but most of the participants had higher educational levels (there were sociodemographic development disadvantages for the older generations—higher education was generally unavailable to them due to the political situation). All the participants were from the middle or upper-middle socioeconomic class, and had been living permanently or studying in Prague or in the Central Bohemian region for a minimum of 4 years at the time of recording. None of the participants was employed in professions that required the professional use of the voice such as acting, singing, or speech-language pathology. None of the participants suffered from depression or cognitive deficits that could have interfered with the recording procedure. To ensure a relatively homogenous database, all the participants were subject to a short interview and a careful, auditory-based dialect assessment was performed by a Czech phonetic specialist (JV) based on the reading text and on a monologue. Speakers who displayed clear traces of regional pronunciation were excluded from the analyses. All the participants spoke the standard language. The exclusion criteria for the participants were:

- a strong regional dialect;
- a history of developmental stuttering or other speech and/or language disorders;
- the use of hearing aids or medically diagnosed hearing loss;
- a history of neurological disorders;
- the current use of antidepressants or antipsychotics; and
- a history of excessive smoking (defined as more than 20 cigarettes per day for at least 3 years).[38]

Recording procedure

The audio data were recorded in a quiet room with a low level of ambient noise (< 40 dBA) using a head-mounted condenser microphone (Beyer dynamic Opus 55, Heilbronn, Germany) that was placed approximately 5 cm from the corner of the subject's mouth with 70° angle. The speech signals were sampled at 48 kHz with16-bit resolution. The recordings were collected during one session with a speech specialist (TT or DS) who explained the instructions to the subjects. Each participant was required to complete a series of speaking tasks including the standardized reading of a text as part of a longer protocol lasting about 25 minutes. There were no time limits during the recordings. All participants were asked to repeat their performance at any time if they or the examiner were not fully satisfied with their initial attempt. To ensure good concentration of speakers and to minimize fatigue, the complete reading text was divided into two passages. The first passage, which consisted of 257 words (Appendix A), was presented at the beginning of the recording session, while the second, consisting of 313 words Appendix B), was presented approximately 10 minutes later. The chosen passages (see the Appendix B and the first paragraph in the Appendix A) were extracts taken from books written by the famous Czech writer Karel Čapek. To facilitate the reading, the final text that was used was changed slightly from the original in some places in order to provide familiar, up-to-date vocabulary and grammatical structures. Since the long vowel /o:/ occurs very rarely in

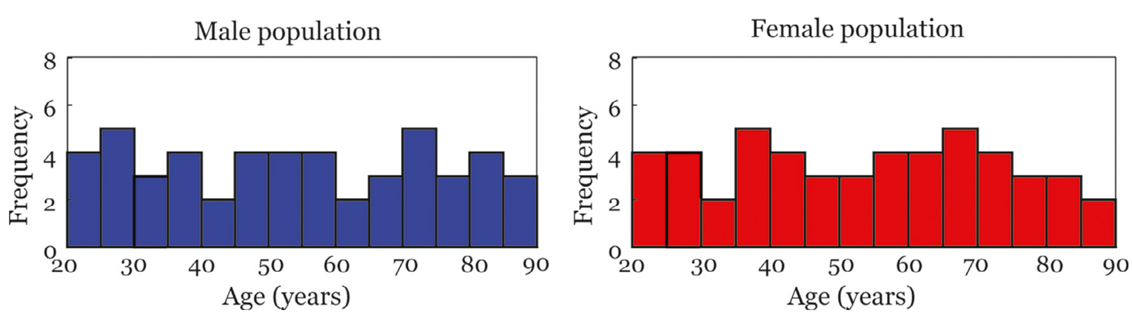

FIGURE 1. The age distribution of the participants.

Czech and almost exclusively in loanwords,[16] two additional, specially designed paragraphs were added in the middle of the reading text (see the second and third paragraphs in the Appendix A). During the recording session, each speaker was instructed to read the passages in a habitual manner with natural tempo and volume.

Selection of the target vowels

For the purposes of this study, 10 monophthongs, including five short vowels /a/, /ɛ/, /ɪ/, /o/, and /u/ and their long counterparts /aː/, /ɛː/, /iː/, /oː/ and /uː/, were of interest. Ten occurrences of each of these vowels were predefined within the reading passages (see the underlined vowels in Appendix A and Appendix B). To preserve the high diversity of the extracted vowels in order to represent the Czech language well while simultaneously maintaining good conditions for the evaluation of acoustic characteristics, the specific words and/or vowels were chosen according to the following criteria:

(1) The target words were selected from the entire duration of the passages at various positions within the sentences and intonation phrases to balance the influence of prosodic structure.
(2) Only one vowel in any given word was analyzed.
(3) The vowels were obtained equally from both stressed and unstressed syllables because Czech has a fixed stress on the first syllable of the word, but no direct reduction of vowel duration or vowel quality due to the occurrence in unstressed syllables.[39,40]
(4) To minimize the effect of coarticulation with surrounding phonemes, as well as the effect of the place of articulation, the vowels were chosen as much as possible
(5) to follow different voiceless plosives, fricatives, affricates, or no phoneme (only words at the beginning of intonation phrases).

In order to summarize the characteristics of the vowels analyzed, Table 1 presents the manner of articulation of the preceding consonant, the place of articulation of the preceding consonant, the syllable stress, the position of the target syllable within the word, and the position of the target word within the intonation phrase for the 10 occurrences of each of the vowels investigated.

Acoustic analysis

Six acoustic parameters, including vowel duration, f_o, F_1, F_2, F_3, and F_4, were evaluated for each vowel by means of specialized, widely used speech software PRAAT version

TABLE 1.
The Characteristics of the Preceding Consonant, As Well As the Syllable and Word Positions Related to the 10 Occurrences of Each Monophthong Investigated

	a	ɛ	ɪ	o	u	aː	ɛː	iː	oː	uː
Manner										
Stop	7	5	2	7	5	4	8	5	7	3
Fricative	2	2	3	1	3	3	1	3	3	3
Affricative	-	3	3	1	1	2	-	2	-	2
Liquid	-	-	-	-	-	1	1	-	-	-
No consonant	1	-	2	1	1	-	-	-	-	2
Place of articulation										
Bilabial	3	2	1	2	1	-	1	2	2	2
Alveolar	4	5	4	4	4	8	5	2	5	4
Postalveolar	-	2	2	-	-	1	-	3	-	-
Palatal	-	-	1	-	-	-	-	3	-	-
Velar	2	1	-	3	4	1	3	-	2	2
Glottal	-	-	-	-	-	-	1	-	1	-
No consonant	1	-	2	1	1	-	-	-	-	2
Syllable stress										
Stressed	5	5	5	5	4	3	4	5	5	4
Unstressed	5	5	5	5	6	7	6	5	5	6
Position of the Syllable										
Beginning	5	5	5	5	5	4	4	6	5	4
Middle	2	2	2	3	-	4	2	-	5	1
End	3	3	3	2	5	2	4	4	-	5
Position of the word										
Beginning	3	2	3	2	2	3	3	1	4	-
Middle	6	4	6	7	5	4	3	4	3	4
End	1	4	1	1	3	3	4	5	3	6

5.4.04.[41] The duration of a vowel was measured as the difference between the onset and offset of a vowel according to the criteria summarized in.[42] Specifically, the vowel onset was defined as the point of the abrupt onset of a periodic signal where the onset of f_o, F_1, and F_2 frequencies was evident, while the offset of a vowel was defined as the point of the abrupt offset of the periodic signal where the F_2 offset was mainly considered to be the indicator.[42] The f_o in Hz was calculated as a mean value from the entire vowel duration following the manual adjustment of the f_o range for each speaker. F_1, F_2, F_3, and F_4 frequencies in Hz were determined from 30-ms segment close to the middle section of a vowel where F_1 and F_2 formant patterns were visible and stable. In rare cases, when the steady-state segment of a vowel was not present but F_1 and F_2 formants were clearly visible and continuous, the 30-ms segment around the midpoint of the vowel duration was used. All the formant frequencies were extracted manually using a wide-band spectrogram with the formant contours depicted and the power spectral density displayed on the screen. The formant contours were analyzed using PRAAT default settings including the Burg method, 0.025 second duration of window length, and a maximum formant of 5000 Hz for men or 5500 Hz for women and five depicted formants. All the values obtained were checked with regard to phonetic knowledge in order to search for errors in the formant analysis, such as the merged or missing formants that commonly occur[2,43] due to reasons such as very strong first harmonic that hinders detection of a closely spaced F_1 or close proximity of formants (eg, F_2 and F_3 formants in vowel /iː/).[2] If the examiner concluded that there was a probable formant merge, no value was recorded for any of the higher formants frequencies (ie, the values for F_3 and F_4 were not considered in the event of an F_2−F_3 merger). A similar approach was applied for missing formants for example, the values of F_3 and F_4 were not considered in the event of a probable F_3 missing formant).

The VSA was calculated based on /a/, /ɪ/ and /u/ corner vowels using the following formula: VSA = ABS ((F_1/ɪ/ × (F_2/a/ − F_2/u/) + F_1/a/ × (F_2/u/ − F_2/ɪ/) + F_1/u/ × (F_2/ɪ/ − F_2/a/)/2).[2]

To determine the potential effect of speech tempo on vowel duration, the articulation rate was calculated from the entire reading passage as the number of words per second after removing periods of silence that exceeded 60 milliseconds.[44]

Nonmeasurable data

Some acoustic variables could not be obtained from the complete database that included 100 vowels for each subject due to various methodological constraints. Specifically, vowel duration was not assessed for 1% of the target vowels due to misreadings. The f_o, F_1, and F_2 frequencies were not found in 3%−4% of the data, mainly due to the short duration of a vowel (< 30ms), sudden pitch drops, or the overall weak energy of the signal. Finally, F_3 and F_4 formants were judged to be nonmeasurable in 15% and 23% of the data, respectively, mainly due to the presence of formants that were assumed to be merged or missing. As the unmeasurable data were distributed evenly across the reading passages, at least five occurrences of each monophthong were always available for further analysis.

Measurement reliability

Intrajudge reliability was assessed following a reanalysis of 10% of the recordings by the same investigator (TT) who performed the original set of measurements. A Pearson correlation analysis calculated across individual vowel qualities showed significant, positive correlations for f_o (r = 0.99, P < 0.001), F_1 (r = 0.97−0.98, P < 0.001), F_2 (r = 0.93−0.99, P < 0.001), F_3 (r = 0.95−0.98, P < 0.001), and F_4 (r = 0.93−0.99, P < 0.001), as well as for vowel duration (r = 0.97−0.99, P < 0.001). The mean intrajudge standard error of measurement calculated across individual vowel qualities was 5 ± 0 Hz for f_o, 8 ± 1 Hz for F_1, 21 ± 5 Hz for F_2, 33 ± 14 Hz for F_3, 65 ± 23 Hz for F_4, and 2 ± 1 milliseconds for vowel duration.

Interjudge reliability was evaluated based on reanalysis of 10% of the recordings by the second investigator (DS), who was well trained in analyzing procedure. A Pearson correlation analysis calculated across individual vowel qualities indicated significant, positive correlations for f_o (r = 0.99, P < 0.001), F_1 (r = 0.86−0.97, P < 0.001), F_2 (r = 0.77−0.98, P < 0.001), F_3 (r = 0.75−0.99, P < 0.001), and F_4 (r = 0.93−0.98, P < 0.001), as well as for vowel duration (r = 0.95−0.98, P < 0.001). The mean interjudge standard error of measurement calculated across individual vowel qualities was 5 ± 0 Hz for f_o, 13 ± 2 Hz for F_1, 35 ± 15 Hz for F_2, 57 ± 38 Hz for F_3, 68 ± 19 Hz for F_4, and 3 ± 1 ms for vowel duration.

Statistical analysis

For the subsequent investigation, the final data from all the available occurrences were averaged separately for each speaker, acoustic variable, and monophthong. The averaging of vowel formants was applied because

(a) it reduces the variability that is typical of formant frequencies and controls for lexical factors of phonological neighbourhood density, thus ensuring that all the available occurrences within the utterance have similar importance;
(b) it is a standard procedure that is commonly used in many applications[5,8,9,12,45−48]; and
(c) it allows for a comparison with the majority of the previous research in the area of vowel articulation.[21,25,30]

All the relevant data used for the statistical analyses are available in supplementary material S1 Table. The Kolmogorov-Smirnov test for independent samples did not reject the null hypothesis of normal distribution. In order to determine the age-dependent acoustic characteristics of vowels, we applied a 6 × 2 × 2 repeated measure analysis of variance (RM-ANOVA) with AGE (20−29, 30−39, 40−49, 50−59, 60−69, 70−89) and SEX (men, women) being treated as between-group factors and VOWEL (short, long) being treated as a within-group factor. *Post hoc* significance was assessed by the Fisher least-squares difference for the effect of AGE. The Bonferroni correction for multiple comparisons was applied for six tests that were conducted for each vowel quality individually, with a corrected P threshold equal to $P < 0.0083$ for $P < 0.05$. With regard to the articulation rate and VSA, the 6 × 2 ANOVA involving the factors of AGE (20−29, 30−39, 40−49, 50−59, 60−69, 70−89) and SEX (men, women) was applied. *Post hoc* significance was assessed by the Fisher least-squares difference for the effect of AGE. The nominal alpha level was set at 0.05. Statistical analyses were performed using Matlab (Mathworks, Massachusetts). The Pearson coefficient was calculated to determine correlations among the average vowel duration calculated across all monophthongs, the articulation rate, and VSA.

RESULTS

Age-dependent acoustic characteristics

The results of the acoustic analysis of the corner vowels /a/, /i/, and /u/ for the male and female populations are presented in Figures 2−4. The comparison of speech measurements for the vowels /ε/ and /o/ are included in supplementary S3 File.

For the vowel /a/, the RM-ANOVA showed a significant effect for AGE in F_2 [$F(5,88) = 5.1$, $P = 0.002$, $\eta2 = 0.23$] and in vowel duration [$F(5,88) = 9.7$, $P < 0.001$, $\eta2 = 0.36$]. *Post hoc* comparisons revealed significantly higher F_2 in 20−29 age group compared to 40−49 ($P = 0.03$), 50−59 ($P < 0.001$), 60−69 ($P = 0.004$) and 70−89 ($P < 0.001$) age groups as well as significantly increased vowel duration in 70−89 age group compared to 20−29 ($P < 0.001$), 30−39 ($P < 0.001$), 40−49 ($P < 0.001$), 50−59 ($P = 0.007$), and 60−69 ($P < 0.001$) age groups. The significant main effect for SEX was detected in f_o, F_1, F_2, F_3, and F_4 [$F(1,88) = 90−397$, $p < 0.001$, $\eta2 = 0.51−0.82$], as well as for VOWEL in f_o, F_1, F_2, F_3, and for vowel duration [$F(1,88) = 38−2396$, $P < 0.001$, $\eta2 = 0.31−0.97$]. Importantly, significant interaction was

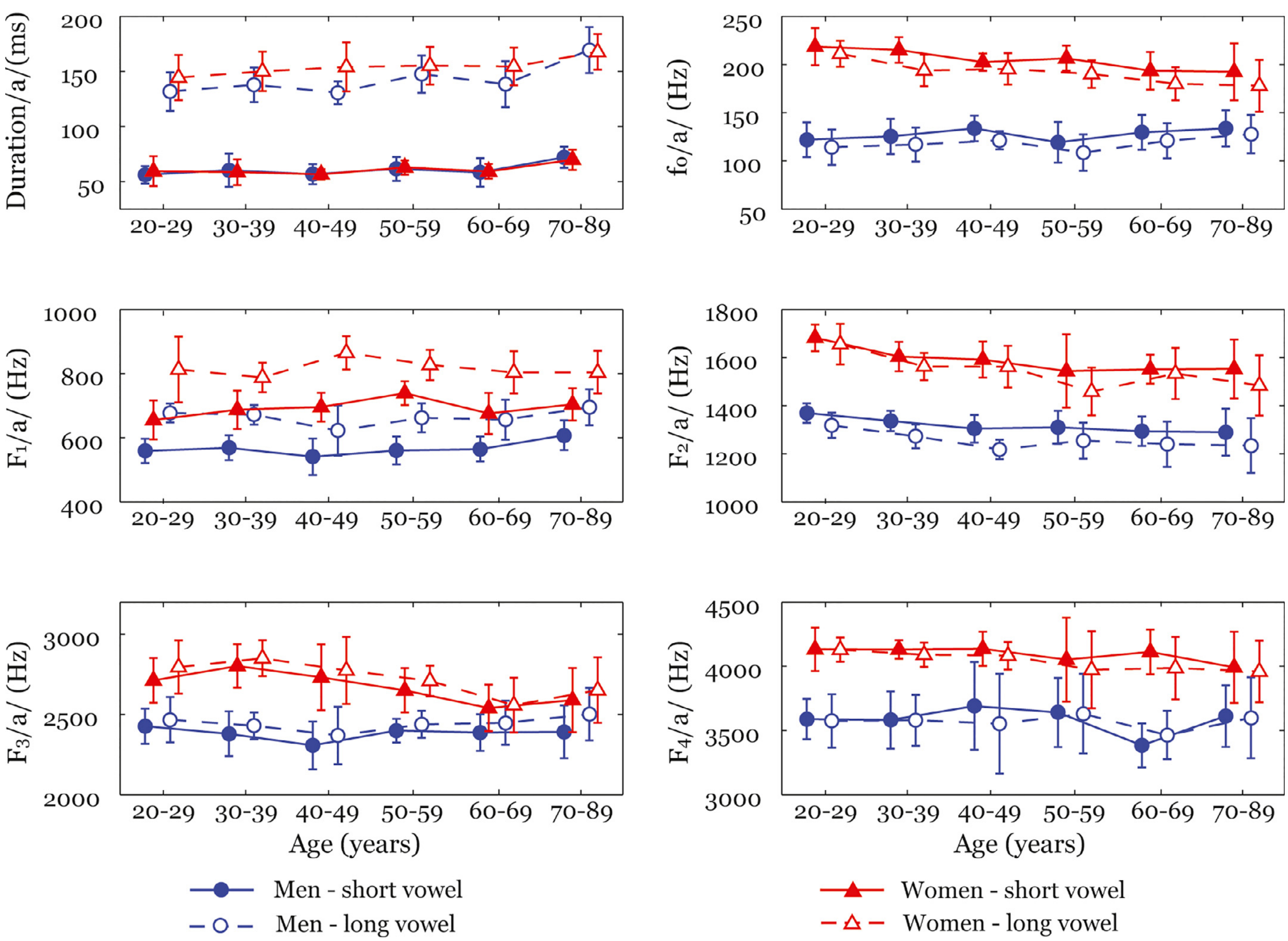

FIGURE 2. The comparison of speech measurements of the vowel /a/. Mean values and standard deviations (error bars) are depicted for both sexes (men, women), and vowel quantities (short, long), presented as a function of age.

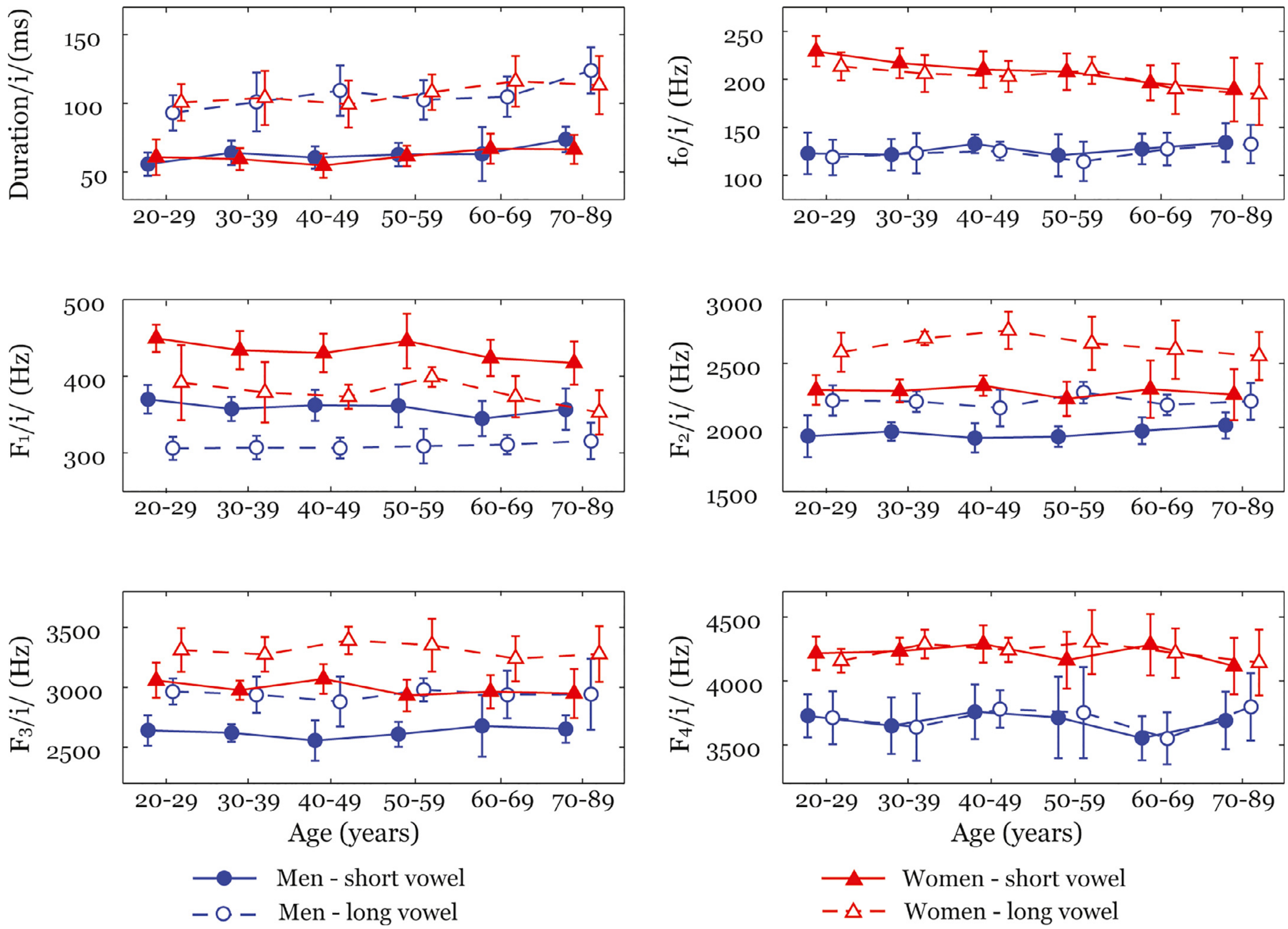

FIGURE 3. The comparison of speech measurements of the vowel /i/. Mean values and standard deviations (error bars) are depicted for both sexes (men, women), and vowel quantities (short, long), presented as a function of age.

revealed for AGE × SEX in f_o [F(5,88) = 3.5, P = 0.04, $\eta 2$ = 0.17]. In addition, we observed a significant interaction for VOWEL × SEX in F_1 [F(1,88) = 8.3, P = 0.03, $\eta 2$ = 0.09] and for vowel duration [F(1,88) = 10.3, P = 0.01, $\eta 2$ = 0.11].

For the vowel /i/, a significant effect for AGE was found in the vowel duration [F(5,88) = 5.0, P = 0.003, $\eta 2$ = 0.22]. *Post hoc* comparisons revealed significantly increased vowel duration in 70−89 age group compared to 20−29 (P < 0.001), 30−39 (P = 0.02), 40−49 (P = 0.009), and 50−59 (P = 0.05) age groups. In addition, a significant main effect was revealed for SEX in f_o, F_1, F_2, F_3 and F_4 [F(1,88) = 141−365, P < 0.001, $\eta 2$ = 0.62−0.81], as well as for VOWEL in f_o, F_1, F_2, F_3, and vowel duration [F(1,88) = 27−829, P < 0.001, $\eta 2$ = 0.23−0.90]. Importantly, we observed a significant interaction of AGE × SEX in f_o [F(5,88) = 3.6, P = 0.03, $\eta 2$ = 0.17]. We also found a significant interaction of AGE × VOWEL in F_2 [F(5,88) = 4.6, P = 0.006, $\eta 2$ = 0.21] associated with increase of F_2 in long vowels in 50−59 male age group and of VOWEL × SEX in F_2 [F(1,88) = 30, P < 0.001, $\eta 2$ = 0.26].

For the vowel /u/, the RM-ANOVA showed a significant effect for AGE in F_2 [F(5,88) = 4.3, P = 0.009, $\eta 2$ = 0.20] and for vowel duration [F(5,88) = 5.1, P = 0.002, $\eta 2$ = 0.23]. *Post hoc* comparisons revealed significantly higher F_2 in 20−29 age group compared to 50−59 (P = 0.05), 60−69 (P = 0.006), and 70−89 (P < 0.001) age groups as well as significantly increased vowel duration in 70−89 age group compared to 20−29 (P < 0.001), 30−39 (P = 0.01), 40−49 (P < 0.001), and 50−59 (P = 0.02) age groups. A significant main effect was revealed for SEX in f_o, F_1, F_3, F_4 [F(1,88) = 106−348, P < 0.001, $\eta 2$ = 0.55−0.80] and F_2 [F(1,88) = 15.1, P = 0.001, $\eta 2$ = 0.15], as well as for VOWEL in F_1, F_2, and for vowel duration [F(1,88) = 34−489, P < 0.001, $\eta 2$ = 0.28−0.85]. Interestingly, a significant interaction was observed for AGE × SEX in f_o [F(5,88) = 4.2, P = 0.01, $\eta 2$ = 0.19]. Finally, we also found a significant interaction of VOWEL × SEX in F_2 [F(1,88) = 8.5, P = 0.03, $\eta 2$ = 0.09] and in vowel duration [F(1,88) = 7.8, P = 0.04, $\eta 2$ = 0.08].

The results of the statistical analysis for the articulation rate and VSA are presented in Figure 5. For the articulation

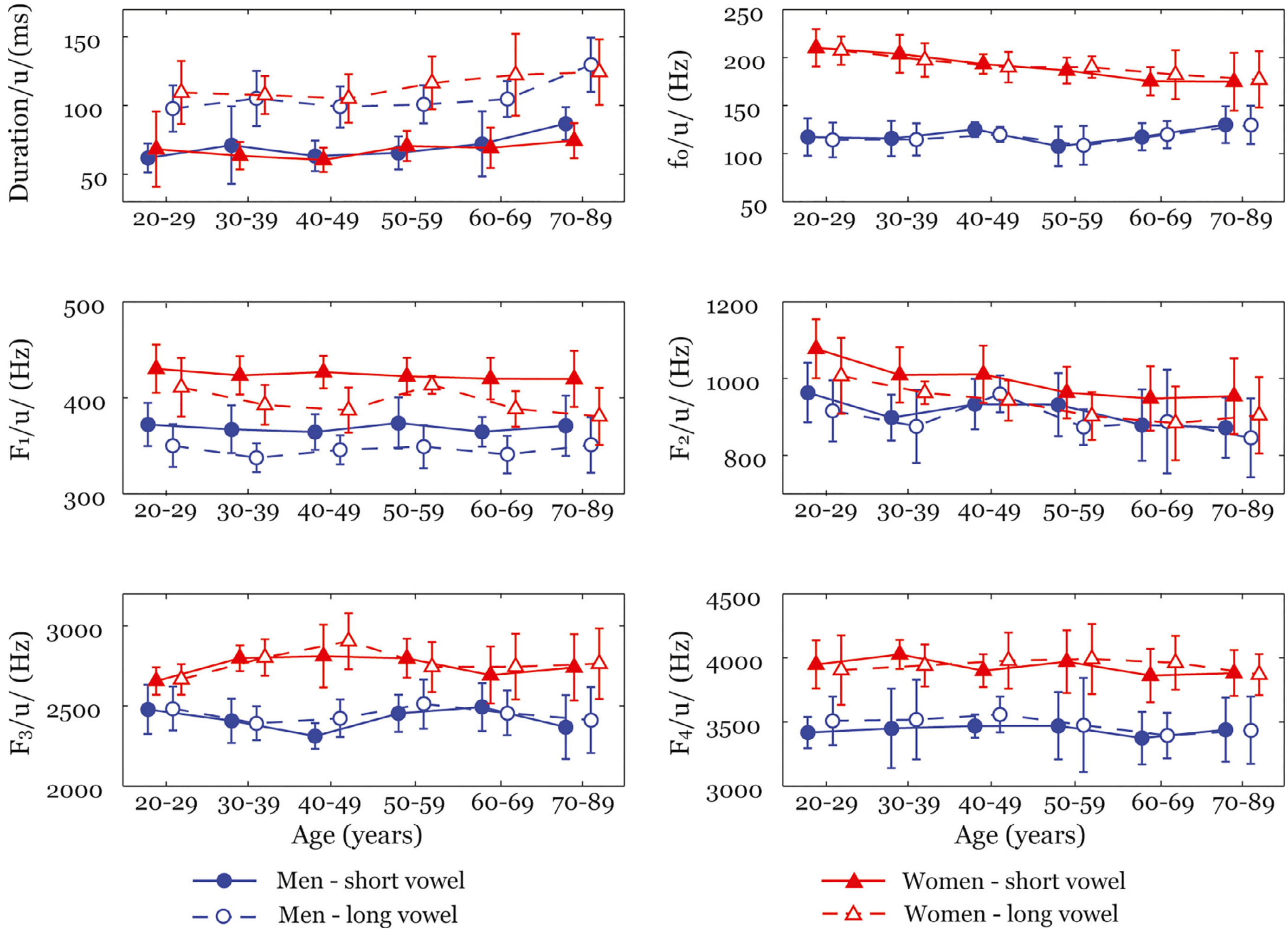

FIGURE 4. The comparison of speech measurements of the vowel /u/. Mean values and standard deviations (error bars) are depicted for both sexes (men, women), and vowel quantities (short, long), presented as a function of age.

rate, the ANOVA showed a significant effect of AGE [$F(5,88) = 7.5$, $P < 0.001$]. *Post hoc* comparisons revealed significantly slower articulation rate in 70−89 age group compared to 20−29 ($P < 0.001$), 30−39 ($P < 0.001$), 40−49 ($P < 0.001$), 50−59 ($P < 0.001$), and 60−69 ($P = 0.004$). With regard to the VSA, there was a significant effect of AGE [$F(5,88) = 2.8$, $P = 0.02$] and SEX [$F(1,88) = 53$, $P < 0.001$]. *Post hoc* comparisons revealed significantly greater VSA in 70−89 age group compared to 20−29 ($P < 0.001$) and 40−49 ($P = 0.04$) age groups. In addition, we found statistically significant correlations between the articulation rate and the average vowel duration ($r = -0.83$, $P < 0.001$) calculated across all monophthongs, as well as between the VSA and the average vowel duration ($r = 0.40$, $P < 0.001$).

There were no other statistically significant findings.

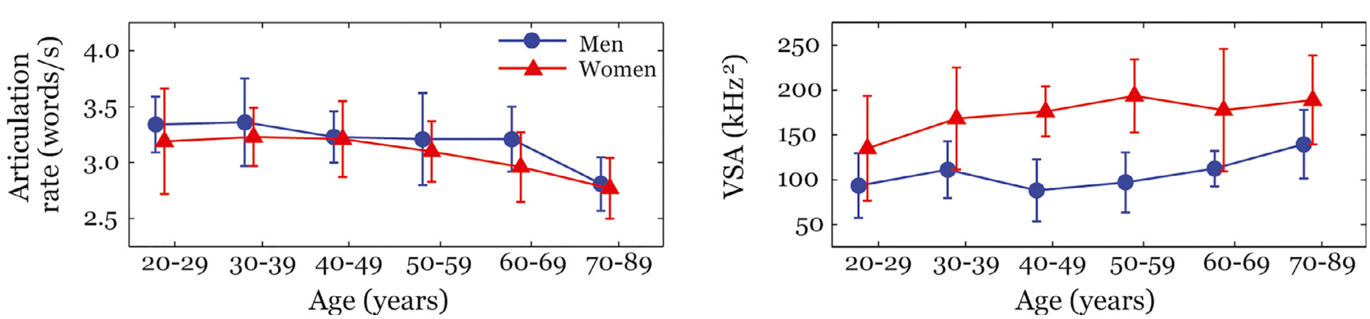

FIGURE 5. The results of the articulation rate and VSA. Mean values and standard deviations (error bars) are shown for both sexes (men, women), presented as a function of age.

TABLE 2.
The Acoustic Characteristics of Czech Vowels for the Adult Male Population

	Duration (ms) Mean/SD (range)	f_o (Hz) Mean/SD (range)	F_1 (Hz) Mean/SD (range)	F_2 (Hz) Mean/SD (range)	F_3 (Hz) Mean/SD (range)	F_4 (Hz) Mean/SD (range)
Short						
/a/	62/12 (39–84)	128/18 (89–173)	572/47 (458–674)	1316/72 (1139–1425)	2387/129 (2101–2700)	3586/241 (3116–4191)
/ɛ/	63/12 (42–97)	123/19 (81–169)	469/32 (371–538)	1658/74 (1514–1842)	2469/123 (2254–2835)	3609/218 (3211–4351)
/ɪ/	64/12 (40–106)	127/19 (88–173)	359/23 (304–410)	1962/112 (1659–2191)	2632/143 (2383–3207)	3685/223 (3268–4348)
/o/	63/12 (35–93)	126/20 (85–174)	460/32 (389–556)	1052/80 (894–1263)	2391/162 (2009–2735)	3424/217 (3079–4247)
/u/	72/19 (38–124)	120/19 (78–164)	369/24 (329–452)	910/81 (755–1085)	2418/158 (2128–2779)	3437/215 (2876–4088)
Long						
/aː/	146/23 (96–208)	119/18 (82–158)	669/54 (524–768)	1257/84 (1086–1442)	2452/138 (2146–2769)	3573/269 (3112–4235)
/ɛː/	127/18 (80–165)	122/18 (85–158)	525/42 (402–610)	1659/77 (1531–1835)	2495/117 (2306–2949)	3648/246 (3185–4327)
/iː/	107/19 (66–155)	124/19 (83–165)	310/18 (278–366)	2206/115 (1871–2402)	2945/193 (2526–3562)	3717/255 (3316–4532)
/oː/	133/23 (94–194)	121/20 (77–172)	465/35 (353–585)	930/78 (787–1177)	2432/164 (2062–2793)	3369/231 (3020–4314)
/uː/	109/21 (65–173)	119/18 (79–161)	347/22 (320–422)	887/94 (667–1096)	2446/154 (2144–2858)	3476/250 (2870–4259)

Characteristics of Czech monophthongs

The acoustic characteristics, including the vowel duration and f_o, F_1, F_2, F_3, and F_4 frequencies across 10 Czech monophthongs, are listed separately for the adult male and female populations in Tables 2 and 3. There were no statistically significant differences in vowel duration between the sexes (two sample *t* test: $P = 0.52$). The long vowels were 2.0 ± 0.3 (range 1.5–2.5) times longer than were their short counterparts. The average values of the F_1 and F_2 frequencies across 10 Czech vowels with ellipses fit to the data are presented in Figure 6. The marked difference in the spectral patterns of long compared to short vowel counterpart was only found for F_1/aː/, F_1/ɛː/ F_1/iː/, F_2/iː/, F_2/oː/ and F_3/iː/ formants (supplementary material S2 Table).

DISCUSSION

This study examined the age-related acoustic characteristics of vowels derived from a reading passage across a group of 100 healthy Czech speakers aged between 20 and 90. The primary aim of the study was to evaluate the effect of ageing on vowel articulation, as the previous literature provided

TABLE 3.
The Acoustic Characteristics of Czech Vowels for the Adult Female Population

	Duration (ms) Mean/SD (range)	f_o (Hz) Mean/SD (range)	F_1 (Hz) Mean/SD (range)	F_2 (Hz) Mean/SD (range)	F_3 (Hz) Mean/SD (range)	F_4 (Hz) Mean/SD (range)
Short						
/a/	62/10 (43–86)	203/22 (127–246)	692/57 (543–780)	1584/104 (1336–1841)	2659/181 (2218–2985)	4084/213 (3476–4671)
/ɛ/	66/10 (48–100)	196/25 (121–247)	551/39 (464–625)	1935/105 (1626–2137)	2787/149 (2375–3057)	4103/186 (3656–4440)
/ɪ/	62/11 (45–87)	206/25 (122–256)	432/28 (384–485)	2279/155 (1885–2648)	2988/152 (2554–3287)	4209/193 (3770–4632)
/o/	66/12 (40–98)	202/25 (119–254)	526/36 (447–621)	1206/91 (1022–1429)	2701/185 (2179–3037)	3890/183 (3534–4435)
/u/	68/15 (47–129)	189/24 (110–238)	423/22 (374–476)	990/90 (814–1189)	2745/163 (2344–3074)	3925/183 (3492–4342)
Long						
/aː/	155/19 (110–203)	190/21 (117–233)	815/68 (631–925)	1539/114 (1308–1805)	2711/189 (2264–3092)	4029/205 (3404–4369)
/ɛː/	137/17 (106–179)	194/24 (116–250)	651/57 (531–772)	1952/113 (1727–2210)	2820/147 (2437–3113)	4171/179 (3719–4532)
/iː/	108/18 (61–151)	199/24 (116–243)	376/34 (306–457)	2633/180 (2186–2991)	3302/187 (2902–3713)	4216/191 (3715–4607)
/oː/	145/21 (106–191)	194/22 (115–240)	537/33 (457–608)	1073/92 (914–1295)	2738/204 (2193–3070)	3833/209 (3334–4427)
/uː/	115/23 (79–169)	189/23 (117–240)	394/26 (311–476)	930/89 (758–1163)	2767/179 (2370–3172)	3935/210 (3496–4338)

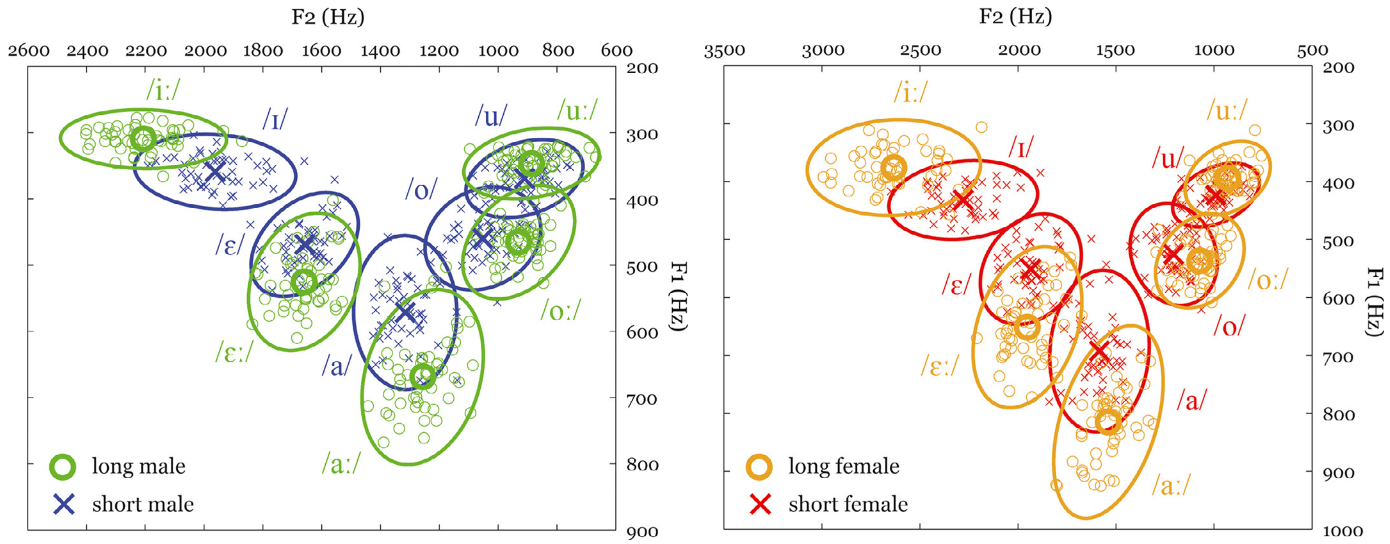

FIGURE 6. Average values of F_1 and F_2 across 10 Czech vowels with ellipses fit to the data presented separately for the male and female populations. Ellipses represent 95% confidence intervals

somewhat inconclusive findings.[2] In fact, knowledge about the typical changes in voice and speech parameters is not only essential for understanding the process of ageing, but may also help to differentiate normal from pathological speech. Since Czech belongs to underdocumented languages, the secondary aim was to provide normative data for the f_o, F_1, F_2, F_3, and F_4 frequencies of all Czech monophthongs.

The findings of this study indicate that age-related changes in pitch are sex-dependent, while age-related alterations in F_2/a/, F_2/u/, VSA, and vowel duration seem to be more consistent in both sexes. Specifically, we observed a clear lowering of f_o with age for women, but no change for men. With regard to formants, we found the lowering of F_2/a/ and F_2/u/ with increasing age, but no statistically significant changes in F_1, F_3, or F_4 frequencies with advanced age. Interestingly, although the alterations in F_1 and F_2 frequencies were rather small, they appeared to be in a direction against vowel centralization, resulting in a significantly greater VSA in the older population. However, it seems that a greater VSA is related partly to longer vowel duration.

Age-dependent acoustic characteristics

In line with the previous literature,[21,24,27,31,32] we observed a significant age-related lowering of f_o in women. By contrast, no alteration of f_o was found in men; this finding is consistent with a study published by Eichhorn et al,[24] but is inconsistent with other studies that reported significant decreases or increases in the male pitch with age.[21,23,26,27,31] The f_o changes in women may be related to a number of age-related physiologic changes, including hormonal changes after menopause, decrease in size of the laryngeal muscles, hardening and possible ossification of the laryngeal cartilages, decreased glandular function, and thickening of the vocal folds.[24] Given that only women showed a significant effect of ageing in this study, we hypothesized that a decrease in f_o for the women may be a consequence of the increase in vocal fold mass due to hormonal changes that occur during menopause.[49]

Across the different corner vowels investigated in our study, a statistically significant increase in vowel duration was revealed with advanced age for both sexes, which is in accordance with earlier studies that reported a longer segmental vowel duration in older men[22,25,26,29] as well as in women.[22,25] The lengthening of vowel duration was most prominent in the oldest group (aged 70−89). A strong, negative correlation between the articulation rate and the average vowel duration was found, indicating that a longer vowel duration is associated with a slowing down of the overall speech tempo. Similar findings were reported by Harnsberger et al,[26] who observed the lengthening of sentence, word, and diphthong durations as a function of age. Nevertheless, the effect of other factors such as preservative coarticulation on the lengthening of vowels in older speakers cannot be excluded.

Most of the previous studies found statistically significant, age-related, and vowel-specific alterations of F_1 and F_2 frequencies that were unique to male and female populations in at least 50% of the formants investigated.[20,21,30] By contrast, our results indicated that F_1 frequency was an age- and sex-independent parameter across all the vowels investigated, while F_2/a/ and F_2/u/ decreased for both sexes and F_2/i/ remained unchanged. These findings are generally in accordance with recent research[24] that investigated native English speakers, in which a marked decline was only reported for F_1/u/ and F_1/æ/ in women and for F_2/u/ in both men and women. Although the observed alterations of F_1 and F_2 frequencies in our cohort were rather small, they appeared to be in the direction against vowel centralization, resulting in a significantly greater VSA in the older population. Nevertheless, as shown previously, the greater VSA is partially related to a longer vowel duration.[25,50] In fact, we also observed a positive correlation between the size of the VSA and the average vowel duration in our speakers, thus supporting this hypothesis. With regard to the higher formants, former studies investigating F_3 frequency[20,21,24] reported no change[21] or a decline in only a small number of the vowels elicited.[20,24] As no alterations in F_3 or F_4 frequencies were revealed in our study, we agree with previous studies[20,24] neglecting the hypothesis of age-related vocal tract lengthening, which should result in a decrease in all formant frequencies. Since higher formants such as F_3 are thought to be related mainly to the vocal expression of emotions,[3] we hypothesized that no age-related alteration of F_3 and F_4 might be related to the preserved ability of spontaneous use of emotion regulation tactics in older persons.[51]

VOWEL $\times$ SEX interactions for F_1/a/, F_2/i/, F_2/u/, vowel duration /a/, and vowel duration /u/ were revealed, indicating vowel specific physiologic differences in measurement ranges between male and female sexes. No consistent AGE $\times$ VOWEL interactions were observed to enable thorough discussion.

Characteristics of Czech vowels

The average mean duration across all the Czech vowel qualities was 65 $\pm$ 3 milliseconds for short vowels and 128 $\pm$ 18 milliseconds for long vowels, with no statistically significant differences between the sexes, resulting in a duration ratio of 1:2 for short and long monophthongs. The observed ratio is slightly higher than it was in the previous study,[33] in which the long vowels were documented as being about 1.7 times longer than their short counterparts. However, the study by Podlipsky, Skarnitzl and Volin[33] analyzed the speech of six professional newsreaders employed by a public broadcaster, while we examined 100 healthy speakers with different professions. Therefore, one might expect professional newsreaders to read more quickly than would normal speakers. With regard to the formant structure of Czech vowels, in accordance with previous literature reporting the short /ɪ/ to be noticeably less close and more central than the long /iː/,[34] we revealed a marked difference in the spectral pattern between /ɪ/ and /iː/ that was associated with changes in F_1, F_2, and F_3 formant frequencies. Although we observed some alterations in the formant structure of F_1/aː/, F_1/ɛː/, and F_2/oː/, our results tended to confirm the earlier perceptual findings that reported minor qualitative differences in the formant structure of the short and long counterparts of /a/, /ɛ/, /o/, and /u/ vowels.[16]

Limitations of the study

One potential limitation of this study is that the results were based solely on an analysis of a reading passage; thus, the current findings may differ from those obtained via different speaking tasks. We decided to use a reading passage because it represents a more natural task with regard to the influence of lexical and syntactic variables compared to sustained vowel phonation, reading a word list or reading meaningless words in a carrier sentence. Moreover, compared to more complex speaking tasks such as monologues, a reading passage maintains strongly standardized conditions and enables the inclusion of less frequently occurring monophthongs in the investigation. Admittedly, each of the speaking tasks has both advantages as well as disadvantages. For example, the analysis of sustained vowel phonation enables better interlingual comparison but does not reflect common connected speech well. Indeed, a previous study[8] showed two times greater VSA calculated from sustained phonation compared to sentence repetition or the reading passage. Nevertheless, while using the reading passage, we still cannot exclude the influence of prosodic structures and the coarticulatory context on the acoustic characteristics of vowels. Therefore, we decided to use diverse speech materials, including various places of articulation for the preceding consonant, and various positions of the syllables within the word or target words elicited from different positions within the sentence. Notably, we were also heavily limited by the natural structure of Czech; for example, the long vowels in Czech occur 3.5 times less frequently than do their short counterparts, and the vowel /oː/ occurs almost exclusively in loanwords.[16] Finally, the mixed group of healthy speakers aged between 20 and 90 may not have been the optimal age group for the definition of normative Czech formant data due to the possible effects of biological ageing or sociolinguistic differences between the age groups. The sociolinguistic development of Czech within the past 80 years has been traced in the lexical domain, but has not involved the sound patterns of the language. Both the postwar and the post-communist periods were more or less egalitarian rather than being divisive in terms of language use. Not a single account of any generational differences in the pronunciation of vowels or consonants exists. In addition, a comparison of the pronunciation norms across decades suggests an era of relative stability in the vocalic and consonantal systems of Czech.[52−55]

CONCLUSIONS

The acoustic properties of all 10 Czech monophthongs were defined, thus allowing for a comparison with the data reported by other investigators in relation to different languages. With regard to the effect of ageing, the alterations in the vowel formant frequencies across several decades of adult life appear to be small or in a direction against vowel centralization, either because physiological ageing has little effect on formant patterns or because individuals manage to develop a compensatory mechanism for age-related changes in their anatomy and physiology. Our results indicated that an extension of the vowel duration might be such a compensatory mechanism, which helps older subjects to maintain articulatory precision. Future longitudinal research is necessary in order to identify possible compensatory mechanisms for imprecise articulation. From a clinical point of view, as we did not observe any age-related trends towards the reduction or centralization of the VSA in older speakers, and as the decreased vowel area has been documented previously in the early stages of Parkinson disease[8] and in other neurological conditions,[9,56] the analysis of individual differences in vowel articulation and its variability may be suitable in future for the early detection of neurodegeneration.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at doi:10.1016/j.jvoice.2020.02.022.

APPENDIX A

The first reading passage with the labeled short and long vowels that were used in the acoustic analyses.

I na tom, že člověk si opatří psa, aby nebyl sám, je mnoho pravdy. Pes opravdu nechce být sám. Jen jednou jsem nechal Mindu o samotě v předsíni; na znamení protestu sežrala všechno, co našla, a bylo jí pak poněkud nedobře. Po druhé jsem ji zavřel do sklepa s tím výsledkem, že rozkousala dveře. Od té doby nezůstala sama ani po jedinou minutu.Když píši, chce, abych si s ní hrál. Když si lehnu, považuje to za znamení, že si mně smí lehnout na prsa a kousat mě do nosu. Přesně o půlnoci s ní musím provádět Velkou Hru,při níž se s velikým hlukem honíme, koušeme a kutálíme po zemi. Když se uřítí,jde si lehnout; pak si smím lehnout i já, ovšem s tou podmínkou, že nechám dveře do ložnice otevřené, aby se Mindě nestýskalo.

Laktóza je mléčný cukr skládající se z glukózy a galaktózy, který se vyskytuje v mateřském mléce všech savců včetně lidského. Laktóza v mateřském mléce slouží kojencům k tvorbě nervových buněk především pro rychle rostoucí mozek. Hlavním zdrojem laktózy jsou mléko, jogurt, tvaroh, smetana, pudink, sýr a máslo. Výrobky ze sóji a všechny další mléčné náhražky z ořechů či obilovin laktózu neobsahují.

Když jsem se blížil k náměstí, již z dálky jsem slyšel hudbu. Na pódiu umístěném ve středu náměstí tančilo a zpívalo několik dívek. Před pódiem postávaly hloučky lidí, další sledovali vystoupení z okolních balkónů. Od přihlížejících lidí jsem se dozvěděl, že zde probíhá celostátní soutěž v sólovém a chórovém zpěvu. Rozhodl jsem se chvíli zůstat a vychutnal atmosféru.

APPENDIX B

The second reading passage with the labeled short and long vowels that were used in the acoustic analyses.

Když člověk poprvé vsadí do země sazeničku, chodí se na ni dívat třikrát denně: tak co, povyrostla už nebo ne? I tají dech, naklání se nad ní, přitlačí trochu půdu u jejích kořínků, načechrává jí lístky a vůbec ji obtěžuje různým konáním, které považuje za užitečnou péči. A když se sazeničkapřesto ujme a roste jako z vody, tu člověk žasne nad tímto divem přírody, má pocit čehosi jako zázraku a považuje to za jeden ze svých největších osobních úspěchů.

Později je to už jiné; později člověk osadí svůj záhon s expertní nedbalostí, tak, a teď ukaž, co dovedeš. Když se některá sazenička nepovede, pokrčí nad ní rameny; je to její vina. A že ty druhé rostou, inu, to je samozřejmé; udělal jsem jim dobrou půdu, tak co; byl by jen holý nevděk, kdyby nerostly.

Když člověk jede poprvé v životě za hranice své vlasti, cítí především strach z toho neznáma, do kterého se vrhá, ale nedává to příliš najevo. Za druhé cítí ohromnou odvahu k dobrodružství, pýchu dobyvatele a statečnost objevitele; má v sobě malou dušičku, ale nesmírně jaksi načepýřenou a nadouvající se téměř bolestně. Abyste věděli, já jedu do širého a cizího světa; já nejsem jen tak někdo, nýbrž veliký dobrodruh.

A když člověk takto jede po desáté nebo po dvacáté, stáhne si cestovní čepici do očí, založí ruce a oddává se jakémusi sebelitování. Bože, jaká otrava, jaká obtíž! Zas abych se tloukl po všech čertech a ďáblech, měl nepříjemnosti s celníky, musel měnit peníze a hledal nocleh v hotelu, který neznám. Čert mi byl dlužen tuhle cestu.

A tak je to se vším, krom narození a smrti; to oboje má Člověk, bohudík, odbyto hned napoprvé. V tom pak je celá rovnováha a vyváženost života: že totéž, co jedna část lidí dělá po prvé, s objevitelským zápalem a úžasem, druhá část dělá po sté, zamlkle, nerada a s rutinou starého návyku.

REFERENCES

1. Kent RD, Weismer G, Kent JF, et al. Acoustic studies of dysarthric speech: methods, progress, and potential. *J Commun Disord*. 1999;32:141–186.
2. Kent RD, Vorperian HK. Static measurements of vowel formant frequencies and bandwidths: a review. *J Commun Disord*. 2018;74:74–97.
3. Waaramaa T, Alku P, Laukkanen AM. The role of F3 in the vocal expression of emotions. *Logoped Phoniatr Vocol*. 2006;31:153–156.
4. Titze IR. *Principles of Voice Production*. Iowa City, USA: National Center for Voice and Speech; 2000. Second printing.
5. Roy N, Nissen SL, Dromey C, et al. Articulatory changes in muscle tension dysphonia: evidence of vowel space expansion following manual circumlaryngeal therapy. *J Commun Disord*. 2009;42:124–135.
6. Sapir S, Spielman JL, Ramig LO, et al. Effects of intensive voice treatment (the Lee Silverman Voice Treatment [LSVT]) on vowel articulation in dysarthric individuals with idiopathic Parkinson disease: acoustic and perceptual findings. *J Speech Lang Hear R*. 2007;50:899–912.
7. Takatsu J, Hanai N, Suzuki H, et al. Phonologic and acoustic analysis of speech following glossectomy and the effect of rehabilitation on speech outcomes. *J Oral Maxil Surg*. 2017;75:1530–1541.
8. Rusz J, Cmejla R, Tykalova T, et al. Imprecise vowel articulation as a potential early marker of Parkinson's disease: effect of speaking task. *J Acoust Soc Am*. 2013;134:2171–2181.
9. Rusz J, Hlavnicka J, Tykalova T, et al. Quantitative assessment of motor speech abnormalities in idiopathic rapid eye movement sleep behaviour disorder. *Sleep Med*. 2016;19:141–147.
10. Ng AK, Koh TS, Baey E, et al. Could formant frequencies of snore signals be an alternative means for the diagnosis of obstructive sleep apnea? *Sleep Med*. 2008;9:894–898.
11. Rusz J, Cmejla R, Ruzickova H, et al. Evaluation of speech impairment in early stages of Parkinson's disease: a prospective study with the role of pharmacotherapy. *J Neural Transm*. 2013;120:319–329.
12. Skodda S, Gronheit W, Schlegel U. Impairment of vowel articulation as a possible marker of disease progression in Parkinson's disease. *Plos One*. 2012;7: e32132.
13. Plonkowski M. Using bands of frequencies for vowel recognition for Polish language. *Int J Speech Technol*. 2015;18:187–193.
14. Li M, Han KJ, Narayanan S. Automatic speaker age and gender recognition using acoustic and prosodic level information fusion. *Comput Speech Lang*. 2013;27:151–167.
15. Morrison GS. Likelihood-ratio forensic voice comparison using parametric representations of the formant trajectories of diphthongs. *J Acoust Soc Am*. 2009;125:2387–2397.

16. Simackova S, Podlipsky VJ, Chladkova K. Czech spoken in Bohemia and Moravia. *J Int Phon Assoc*. 2012;42:225–232.
17. Themistocleous C. Dialect classification using vowel acoustic parameters. *Speech Commun*. 2017;92:13–22.
18. McCarthy KM, Evans BG, Mahon M. Acquiring a second language in an immigrant community: the production of Sylheti and English stops and vowels by London-Bengali speakers. *J Phonetics*. 2013;41:344–358.
19. Ramig LA. Effects of physiological aging on speaking and reading rates. *J Commun Disord*. 1983;16:217–226.
20. Xue SA, Hao GJP. Changes in the human vocal tract due to aging and the acoustic correlates of speech production: a pilot study. *J Speech Lang Hear R*. 2003;46:689–701.
21. Torre P, Barlow JA. Age-related changes in acoustic characteristics of adult speech. *J Commun Disord*. 2009;42:324–333.
22. Albuquerque L, Oliveira C, Teixeira A, et al. Impact of age in the production of European Portuguese vowels. Presented at: *Interspeech 2014: 15th Annual Conference of the International Speech Communication Association*. 2014:940–944.
23. Cox VO, Selent M. Acoustic and respiratory measures as a function of age in the male voice. *J Phonet Audiol*. 2015;1:105.
24. Eichhorn JT, Kent RD, Austin D, et al. Effects of aging on vocal fundamental frequency and vowel formants in men and women. *J Voice*. 2018;32.
25. Fletcher AR, McAuliffe MJ, Lansford KL, et al. The relationship between speech segment duration and vowel centralization in a group of older speakers. *J Acoust Soc Am*. 2015;138:2132–2139.
26. Harnsberger JD, Shrivastav R, Brown WS, et al. Speaking rate and fundamental frequency as speech cues to perceived age. *J Voice*. 2008;22:58–69.
27. Harrington J, Palethorpe S, Watson CI. Age-related changes in fundamental frequency and formants: a longitudinal study of four speakers. Presented at: *Interspeech 2007: 8th Annual Conference of the International Speech Communication Association, Vols 1-4*. 20071081.
28. Linville SE, Fisher HB. Acoustic characteristics of womens voices with advancing age. *J Gerontol*. 1985;40:324–330.
29. Liss JM, Weismer G, Rosenbek JC. Selected acoustic characteristics of speech production in very old males. *J Gerontol*. 1990;45:P35–P45.
30. Rastatter MP, Jacques RD. Formant frequency structure of the aging male and female vocal-tract. *Folia Phoniatr*. 1990;42:312–319.
31. Sebastian S, Babu S, Oommen NE, et al. Acoustic measurements of geriatric voice. *J Laryngol Voice*. 2012;2:81–84.
32. S Schötz, Acoustic analysis of adult speaker age. In Müller C, ed. *Speaker Classification I. Fundamentals, Features, and Methods*. Berlin: Springer. 2007;88−107.
33. Podlipsky VJ, Skarnitzl R, Volin J. High front vowels in Czech: a contrast in quantity or quality? Presented at: *Interspeech 2009: 10th Annual Conference of the International Speech Communication Association, Vols 1-5*. 2009:144.
34. Dankovicova J. The domain of articulation rate variation in Czech. *J Phonetics*. 1997;25:287–312.
35. Grepl M, Furst T, Pesak J. The F1−F2 vowel Chart for Czech whispered vowels a, e, i, o, u. *Biomed Pap*. 2007;151:353–356. Available at: http://biomed.papers.upol.cz/magno/bio/2007/mn2.php. Accessed March 23, 2020.
36. Pribil J, Pribilova A, Matousek J. Comparison of formant features of male and female emotional speech in Czech and Slovak. *Elektron Elektrotech*. 2013;19:83–88.
37. Skarnitzl R, Volin J. *Referencni hodnoty vokalickych formantu pro mlade dospele mluvci standardni cestiny*. 2012. Akustické listy18:7-11. Available at: https://www.czakustika.cz/misc/aklisty/18-1.pdf. Accessed March 23, 2020.
38. Ayoub MR, Larrouy-Maestri P, Morsomme D. The effect of smoking on the fundamental frequency of the speaking voice. *J Voice*. 2019; 33:802.e11–802.e16.
39. Skarnitzl R, Eriksson A. The acoustics of word stress in Czech as a function of speaking style. Presented at: *Interspeech 2017: 18th Annual Conference of the International Speech Communication Association, Vols 1-4*. 2017:3221–3225.
40. Palkova Z, Volin J. The role of F0 contours in determining foot boundaries in Czech. Presented at: *ICPhS 2003: 15th International Congress of Phonetic Sciences*. 2003:1783–1786.
41. Boersma P. Praat, a system for doing phonetics by computer. *Glot Int*. 2002;5:341–345.
42. Novotny M, Rusz J, Cmejla R, et al. Automatic evaluation of articulatory disorders in Parkinson's disease. *Ieee-Acm T Audio Spe*. 2014;22: 1366–1378.
43. Hillenbrand J, Getty LA, Clark MJ, et al. Acoustic characteristics of American english vowels. *J Acoust Soc Am*. 1995;97:3099–3111.
44. Rusz J, Cmejla R, Ruzickova H, et al. Quantitative acoustic measurements for characterization of speech and voice disorders in early untreated Parkinson's disease. *J Acoust Soc Am*. 2011;129:35–67.
45. Lam J, Tjaden K, Wilding G. Acoustics of clear speech: effect of instruction. *J Speech Lang Hear Res*. 2012;55:1807–1821.
46. Liu HM, Kuhl PK, Tsao FM. An association between mothers' speech clarity and infants' speech discrimination skills. *Dev Sci*. 2003;6:F1–F10.
47. Liu H, Ng M. Formant characteristics of vowels produced by Mandarin Esophageal Speakers. *J Voice*. 2009;23:255–260.
48. Skodda S, Visser W, Schlegel U. Vowel articulation in Parkinson's disease. *J Voice*. 2011;25:467–472.
49. Abitbol J, Abitbol P, Abitbol B. Sex hormones and the female voice. *J Voice*. 1999;13:424–446.
50. Gendrot C, Adda-Decker M. Impact of duration on F1/F2 formant values of oral vowels: an automatic analysis of large broadcast news corpora in French and German. Presented at: *Interspeech 2005: 6th Annual Conference of the International Speech Communication Association, Vols 1-4*. 2005:2483−2456.
51. Livingstone KM, Isaacowitz DM. Age similarities and differences in spontaneous use of emotion regulation tactics across five laboratory tasks. *J Exp Psychol Gen*. 2019;148:1972–1992.
52. Hala B. *Vyslovnost Spisovne Cestiny I*. Praha: Academia; 1967.
53. Romportl M. *Vyslovnost Spisovne Cestiny II*. Praha: Academia; 1978.
54. Hurkova J. *Ceska Vyslovnostni Norma*. Praha: Scientia; 1995.
55. Stepanova V. *Vyvoj Kodifikace Ceske Vyslovnosti*. Praha: Academia; 2019.
56. Rusz J, Bonnet C, Klempir J, et al. Speech disorders reflect differing pathophysiology in Parkinson's disease, progressive supranuclear palsy and multiple system atrophy. *J Neurol*. 2015;262:992–1001.