

Vowel space in hypokinetic dysarthria

Preliminary investigations

Barbara Gili Fivela, Sonia I. d'Apolito, Francesco Sigona
University of Salento & CRIL-DReAM, Lecce - Italy

The paper discusses acoustic and articulatory data on the use of vowel space by speaker affected by Parkinson's Disease who developed hypokinetic dysarthria. Two experiments involving pathological subjects and matching controls are described, whose general aim is to better understand if the vowel space in Parkinson's Disease dysarthric subjects is always and homogeneously reduced. In the first investigation, acoustic and kinematic data are collected and analyzed to test if pathological speakers always use a reduced vowel space compared to control subjects, and if they adopt different articulatory strategies depending on the axis of the speech gesture (vertical vs horizontal). In the second investigation, various articulatory metrics are used to better investigate the dimension and position of the acoustic vowel space, and if they change in Parkinson's Disease subjects compared to controls. Results show that reduction takes place, but some subjects appear to compensate, widening their tongue gestures on the horizontal axis even though the lip gesture is not necessarily undershot. Nevertheless, metrics used in the second experiment do not allow to capture a reduction, even though, in line with results of the first experiment, they point to an asymmetry in the vowel space used depending on the axis considered.

Keywords: Parkinson's Disease, acoustic vowel space, speech gestures, Italian

1. Introduction

Dysarthria is “a collective name for a group of neurologic speech disorders resulting from abnormalities in the strength, speed, range, steadiness, tone, or accuracy of movements required for control of the respiratory, phonatory, resonatory, articulatory, and prosodic aspects of speech production” (Duffy 2005). It causes weakness, spasticity, incoordination, involuntary movements, excessive/reduced/variable muscle tone, and some specific characteristics that depend on the type of dysarthria. Six major types of dysarthria are reported in the litera-

ture (Darley et al. 1975), that are flaccid, spastic, ataxic, hypokinetic, hyperkinetic, and mixed.

The focus of the present paper is hypokinetic dysarthria, that is a crucial characteristic of Parkinson's Disease (Marsden 1989), being Parkinson's Disease, in turn, the major cause of hypokinetic dysarthria (Duffy 2005). Hypokinetic dysarthria is characterized by bradykinesia and hypokinesia, corresponding to a reduction in the speed and amplitude of movements (Darley et al. 1975; Ackermann & Ziegler 1991; Duffy 2005). Hypokinesia, in particular, is defined as involving a reduced range of simple limb movements with consequent target undershooting (Ackermann & Ziegler 1991).

In speech production, various studies, mainly on Germanic languages, reported a reduction of the vowel space (Darley et al. 1969; Turner et al. 1995; Kent & Kim 2003; Yunusova et al. 2008; Kim et al. 2009), together with a general reduction in the amplitude of speech gestures (e.g., Skodda et al. 2011, Skodda et al. 2012). Nevertheless, speakers generally preserve phonological contrasts (Duffy 2005), possibly by means of compensation strategies. For instance, Gili Fivela et al. (2014) and Iraci (2017) argue that the distinction between geminate and singleton consonants in Italian is preserved, though differences in duration between dysarthric (Parkinson's) and control subjects are observed.

As far as the vowel space is concerned, as already mentioned, a reduced space is expected due to articulatory undershoot. However, inconsistent results are reported in works based on acoustic measures (Fougeron & Audibert 2011, 2012; Weismer et al. 2012; Lansford & Liss 2014 a,b). For instance, Bang et al. (2013) report a vowel space reduction involving both F1 and F2 (though they focus more on voice quality), while more variability in F2 values is reported by Audibert and Fougeron (2012). Various measures regarding vowels are suggested to permit the identification of the type of dysarthria (Lansford & Liss 2014) or the description of the level of impairment in vowel articulation and its further decline. However, some authors argue that vowel space area account for only 6–8% of the variance in intelligibility ratings for females with Parkinson's Disease (Tjaden & Wilding 2004, 2011).

Metrics regard both acoustic and articulatory data. Concerning acoustics, various proposals are found in the literature, among which a quite traditional metric is the Vowel Space Area measure (VSA), composed by the first and second formant values (F1 and F2) of tense corner vowels (Lansford & Liss 2014; Skodda et al. 2011; Audibert & Fougeron 2012). For instance, the irregular polygon VSA formed by first and second formants of all (5) vowels is reported by Audibert and Fougeron (2012) to distinguish Parkinson's Disease subjects from

controls and other dysarthric speakers, with Parkinson's Disease subjects showing higher vocalic space and more closed vowels (lower F1). To overcome some faults in VSA, other metrics have been proposed, such as the Vowel Articulation Index (VAI), calculated as $(F2i + F1a) / (F1i + F1u + F2u + F2a)$ (Royet et al. 2009; Skodda et al. 2011). Skodda et al. (2011) for instance showed that VAI values were significantly reduced in male and female Parkinson's Disease subjects as compared with the matched control group. Articulatory measures are also available, based on Optical tracking, X-ray microbeam, Electromagnetic Articulography (EMA) data, that allow getting information on the position, duration and velocity of speech gestures. For instance, Yunusova et al. (2008) discuss measures concerning the position and velocity of flashpoint markers on X-ray microbeam, while Harrington et al. (2011) propose metrics to obtain a quadrilateral like vowel space on the bases of EMA data regarding the position and velocity of electrodes glued on the subject's tongue (tongue coils). Bunton and Leddy (2011) considered the sagittal-plane position for four tongue pellets at the temporal midpoint of each vowel, and defined the phonetic working space as the areas enclosed by tongue locations for the four vowels in each group of words. Specifically, the four points corresponding to the coils are connected to represent the area used to calculate the articulatory working space.

Research on Italian did not regard metrics for vowel space measurements, even though some works have described the characteristics of vowels produced by Italian subjects. Gili Fivela et al. (2020), for instance, showed that Parkinson's Disease speakers may produce wider tongue gestures in the front-back dimension probably because of compensation strategies (Gili Fivela et al. 2020).

In this paper, two experiments on the vowel space in dysarthric parkinsonian subjects and matching controls are described, with the general aim to better understand the use of vowel space in Parkinson's Disease subjects in comparison to that of matching controls.

2. Goals and hypotheses

Two investigations are reported in the present paper, both aiming at understanding if and how the Parkinson's Disease subjects vowel space is reduced in comparison to that of matching controls.

In the first investigation, acoustic and kinematic data are used to test if pathological speakers always use a reduced vowel space compared to control subjects and if they adopt different articulatory strategies depending on the axis of the movement (vertical vs. front-back). Our hypotheses, based on results de-

scribed in the literature (see §1) are that 1) a reduction of the vowel space may be observed, but it may concern only some axes or even some subjects; and 2) compensation strategies can be identified, whereby some articulatory gestures are not necessarily reduced.

In the second investigation, various articulatory metrics are used to better investigate the Parkinson's Disease vowel space dimension and if subjects always use a reduced vowel space compared to control subjects. The hypothesis is, again, that the reduction of the vowel space may concern only some axes or subjects.

The general method used in the two investigations is highly similar and, therefore, it is discussed before turning to each investigation specificity.

3. General method

Both experiments involved speakers who developed dysarthria together with Parkinson's Disease and reached a mild-to-severe severity level. These subjects, together with the control subjects, were born and lived in the area of Lecce, South Italy.

In the first experiment, 8 male subjects were involved (4 Parkinson's Disease subjects – PD - and 4 Controls - CTR), aged between 65 and 80, while 6 male subjects participated in the second experiment (3 Parkinson's Disease subjects and 3 Controls) aged between 65 and 74 (only male subjects were considered as they were most numerous in the data base available and in order to avoid variation related to the gender factor in the present investigation). In the experiments, speakers read aloud short sentences including disyllabic target (pseudo)words ('CVCV), where C could be /p/ or /b/ and vowels could be /a/, /i/ or /u/. More specifically, vowel cycles within a sentence could be /a/-/u/-/a/, /u/-/a/-/u/ in experiment I, and /a/-/i/-/a/, /a/-/u/-/a/, /i/-/a/-/i/ in experiment II. Examples of target sentences are *La pupa blu* 'the blue pupa' and *La pipa blu* 'the blue pipa'¹.

Recordings were performed by means of an EMA 3D-AG501 (Carstens Med., GmbH), that simultaneously records audio and kinematic data. The latter were recorded by two coil sensors placed on the tongue (tip and dorsum, aligned to the mid-sagittal plane) and two more sensors on the lips (upper and lower),

¹The use of pseudowords and specific vowel cycles, as well as the choice of a reading task, were due to the goal of the experiments (investigating vowel space, thus limiting the possible interference of consonantal gestures) and the experimental protocol including articulatory recordings, which require highly controlled speech materials.

while three more sensors, placed on the nose (between the eyebrows) and behind each ear, provided head-movement compensation data. Furthermore, at the beginning of each recording session the bite plane was also recorded, by means of a special plastic device equipped with three additional sensors. Together with the head-movement compensation data, this allows to roto-translate the frame of reference of the articulatory coordinates of the subject. Thus, in the new reference frame the horizontal plane (x, y) coincides with the bite plane, the vertical plane (x, z) coincides with the mid-sagittal plane, the x axis coincides with the front-back direction, and the z-axis coincides with the vertical direction.

Participants read aloud the corpus seven times minimum at regular speech rate. Segmentation and labelling were performed by means of PRAAT and MAYDAY (Boersma & Weenink 2021; Sigona et al. 2015; for segmentation criteria, Machač & Skarnitzl 2009).

Statistical analysis was realized by running mixed models in R (lme4 - R Core Team, 2021; Bates et al. 2015). The full model included Voicing (voiced vs. unvoiced plosives), Vowel cycle (Vowel cycle e.g., AU vs. UA for /a/-to-/u/ in /a/-/u/-/a/ vs. /u/-to-/a/ in /u/-/a/-/u/), Population (Parkinson's Disease subject vs. Control subject) and Repetition (7 levels) as fixed factors, with interaction, and intercept as well as random slope for Subject. Statistical significance ($p < 0.05$) was tested by a Likelihood Ratio Test (Winter 2013).

3. Experiment I

3.1 Method

For all stress vowels (V0), first and second formant values (average over the vowel duration) were extracted. As for kinematics, position values for all stress vowels were extracted on both front-back and vertical axes, when the tongue dorsum reached the 0 value on the velocity profile². We measured the vertical

²Normalization procedures are available for the acoustic F1xF2 vowel space, a.o., the Bark Difference Metric, the Lobanov's, the Nearey's, the Labov's and the Watt and Fabricius' method (respectively, Syrdal & Gopal 1986, Lobanov 1971, Nearey 1977, Labov et al. 2006 and Watt and Fabricius 2002). As for the articulatory space, normalization is far more problematic and results are not positive along all dimensions (Hashi et al. 1998, based on x-ray microbeam database corpora); not surprisingly, articulatory data have been rather used to normalize acoustic ones (Zhang et al. 2015, Wei et al. 2016). As it was not possible to refer to one and only normalization procedure for acoustic and articulatory data, no normalization was performed in order to avoid the introduction of a source of variation that depended on the

and horizontal, front-back, displacement of the tongue dorsum in the /a/-to-/u/ (AU) and in the /u/-to-/a/ (UA) gestures as well as the (lower) lip protrusion gesture, that is the amplitude of the lower lip front-back displacement in the gesture from the consonant in stress position to the poststress vowel.

3.2 Results

3.2.1 Acoustics

Statistical tests (on /a/-/u/-/a/ and /u/-/a/-/u/) show that F1 values for the stress vowel (V0) is affected by the Vowel cycle, the Voicing and the Population factor. Specifically, F1 for the /a/ vowel decreases by about $35.4\text{Hz} \pm 16.7$ (S.E.) in Parkinson's Disease subjects (in particular PD1) in comparison to Control subjects (/a/). On the other hand, F2 (V0) is affected by Vowel cycle and Voicing only, even though an interaction between Vowel cycle and Population is found. Specifically, F2 increases by about $300\text{ Hz} \pm 16$ (S.E.) in the UA vs. AU cycle, as expected, that is in /a/ vs. /u/ vowel, and, as the interaction shows, it is higher by about $174.37\text{ Hz} \pm 30.6$ (S.E.) in Parkinson's Disease subjects AU cycle (that is in /u/).

Vowel formant charts realization of stress /a/ and /u/ are plotted in Figure 1, on the left for Control subjects and on the right for Parkinson's Disease subjects (for data concerning /i/, see §3.3 and Gili Fivela et al., 2020).

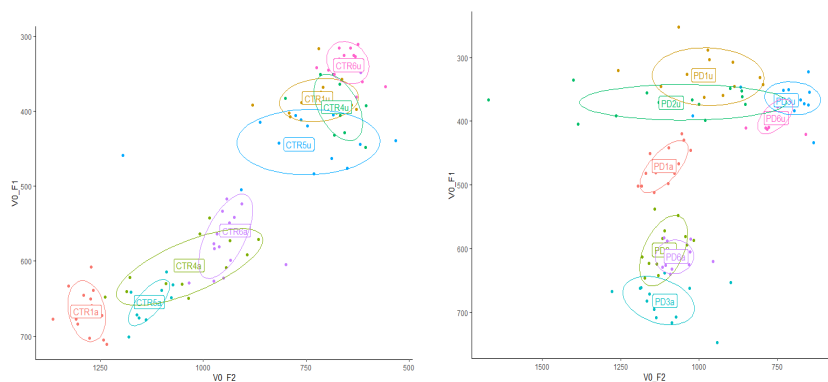


Figure 1. F1 x F2 formant plot (in Hz) for /a/ and /u/ in Controls (left) and Parkinson's Disease subjects (right).

normalization procedure itself (robustly performed on acoustic only, or differently performed on acoustic and articulatory data).

As the figure shows, in Parkinsonian subjects /a/ shows small variation in the front-back dimension, and it is particularly closed for PD1 (close to /u/). Further, /u/ is fronted for two Parkinson's Disease subjects (PD1, PD2). In Control subjects, /a/ is variable in the front-back direction and in height, but within speaker differences with /u/ are clear.

3.2.2 Kinematics

Kinematic data related to the tongue dorsum coil in /a/ and /u/ vowels show that, as expected, the tongue vertical displacement is affected by the Vowel cycle (/a/-/u/-/a/ and /u/-/a/-/u/), in both the gesture to and from the accented vowel. The tongue dorsum coil position is increased by about $14 \text{ mm} \pm 0.5 \text{ (S.E)}$ and $14.5 \text{ mm} \pm 0.53 \text{ (S.E.)}$ respectively in /a/ than in /u/. Further, the tongue position is slightly affected by voicing, which increases the value by about $1.28 \text{ mm} \pm 0.50 \text{ (S.E.)}$ and $1.30 \pm 0.50 \text{ (S.E.)}$ in the voiceless vs. voiced condition. Strong variation in the tongue position depends on the subject, but it does not appear to be related to the Population factor on the vertical axis.

On the other hand, the Population factor interacts with Vowel cycle as for data on the front-back dimension. Specifically, in the realization of the vowel cycle from /a/ to /u/ and from /u/ to /a/ (see Figure 2), the displacement along the front-back dimension is affected by the Voicing and the Vowel cycle factors, so that the produced /a/ stress vowel is more advanced by about $4.67 \text{ mm} \pm 0.44 \text{ (S.E.)}$ in comparison to the /u/ stress vowel. Further, the interaction between Vowel cycle and Population regards the wider gesture (by about 4.18 mm) in Parkinson's Disease subjects. As the plot in Figure 2 shows, the tongue seems to move more backward in Parkinson's Disease subjects than in Control subjects AU.

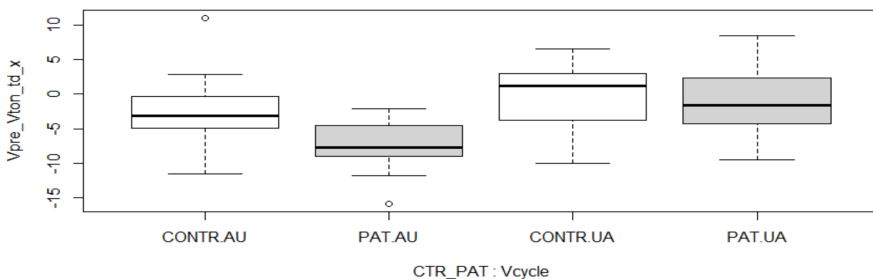


Figure 2. Amplitude (in millimeters) of the tongue front-back gesture in the /a/-to-/u/ (AU) and the /u/-to-/a/ (UA) gesture produced by Controls (white boxes) and Parkinson's Disease subject (grey).

Further, the lower lip shows a smaller protrusion movement, measured as the amplitude of the gesture from the prestress vowel to the stress consonant, in Parkinson's Disease subjects that in Controls – see Figure 3. The lip gesture is shorter by about $1.26 \text{ mm} \pm 0.44$ (S.E.) in Parkinson's Disease subjects than in Controls (for AU cycle and voiced consonant).

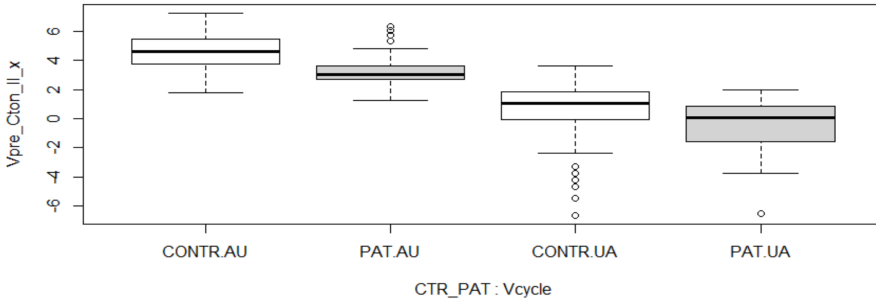


Figure 3. Amplitude (in millimeters) of the lip front-back gesture from the prestress vowel to the stress consonant in the /a/-to-/u/ (AU) and the /u/-to-/a/ (UA) gesture produced by Controls (white boxes) and Parkinson's Disease subject (grey) participants.

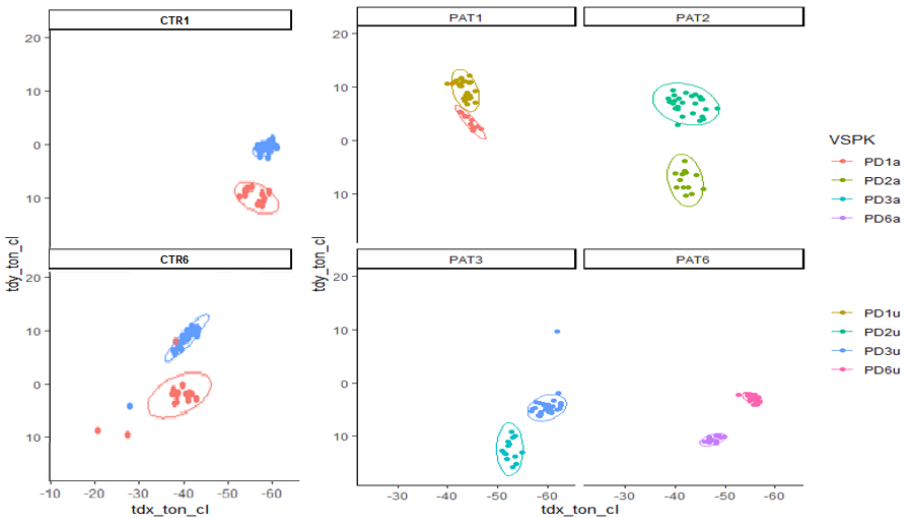


Figure 4. Position plot (in millimeters) for the /a/ and /u/ vowels produced by Control (left) and Parkinson's Disease subject (right) participants

However, plotting position data per single speaker (see Figure 4) shows that two Parkinson's Disease subjects in particular, that is PD3 and PD6, show a back-

ward position of the tongue in the realization of /u/ (even though the lack of F1xF2 normalization – see discussion in §3.1 – does not allow a robust comparison across speakers).

Interestingly, Parkinson's Disease subjects showing a more backward position of the tongue in /u/ also showed a wider lip protrusion, as a sort of hyper-articulation warranting the identity of the /u/ vowel (see Figure 5).

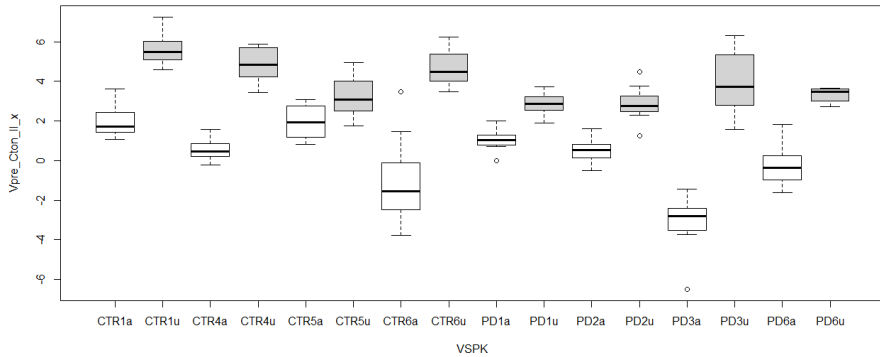


Figure 5. Amplitude (in mm) of the lip front-back gesture from the prestress vowel to the stress consonant in the /a/-to-/u/ (AU) and the /u/-to-/a/ (UA) gesture produced by Controls and Parkinson's Disease participants in /a/ (white boxes) and /u/ contexts (grey boxes).

3.3 Discussion on experiment I

As for acoustics, in Parkinson's Disease subjects /a/ shows small variation in the front-back dimension, and it is close for PD1 (close to /u/); /u/ is fronted for two Parkinson's Disease subjects (PD1, PD2). In Control subjects, variability is observed for /a/ in the front-back dimension and in height, but within-speakers differences in /u/ are also clear.

The overall picture on vowel space use is clearer when considering /i/ realizations too. As Gili Fivela et al. (2020) discussed, the analysis of the /i/-/u/-/i/ and /u/-/i/-/u/ shows that F2 values increase less in Parkinson's Disease subjects than in Control speakers and they are higher for /u/ and lower for /i/, thus showing a vowel space reduction in the anterior-posterior axis. Considering all the three vowels (Figure 6), plots show that there are clear differences in the formant values for /u/ and /i/ for each speaker, and the /u/ vowel is quite anterior in two out of four Parkinson's Disease subjects (PD1, PD2), who also show a slightly posterior /i/. Values for Control's /a/ are variable but, in Parkinson's Disease subjects, /a/ shows low variation in the front-back direction and greater

variation on the vertical axis, where it is higher in PD1 (who indeed shows values for /a/ that are close to those measured in /u/).

That is, phonemes realization are kept different, even though a strong interspeaker variation is found. As for dysarthric speakers, PD1 and PD2 show a reduced vowel space in the front-back dimension, and PD1 also shows reduction on the vertical axis.

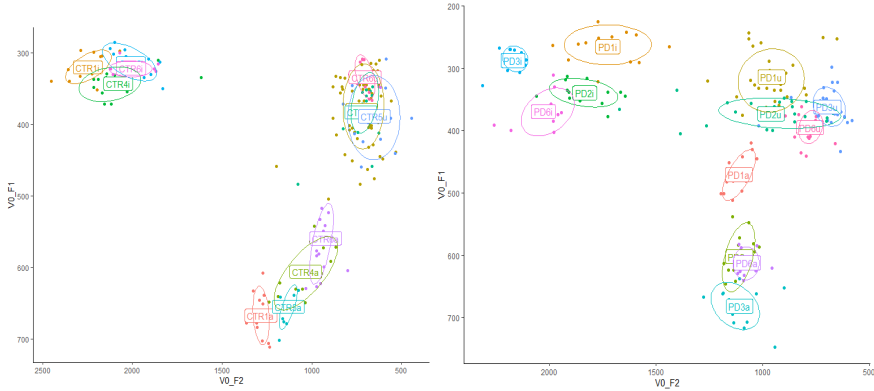


Figure 6. Formant plot (in Hz) for the /a/, /i/, /u/ vowels produced by Control (left) and Parkinson's Disease subject (right) participants.

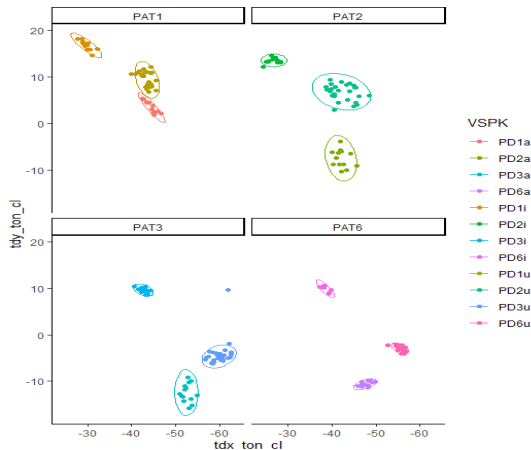


Figure 7. Position plot (in millimeters) for the /a/, /i/, /u/ vowels produced by Parkinson's Disease participants.

As for kinematics, two Parkinson's Disease subjects (PD3 and PD6) show a wider distance between tongue positions, and that their /u/ seems to be more backward. However, the overall view is again clearer when adding data for the /i/ vowel as well – see Figure 7. As Gili Fivela et al. (2020) discusses, besides the expected difference in the tongue vertical and front-back gesture, the tongue vertical and front-back movements are wider in Parkinson's Disease subjects than in Control subjects, both in the cycle to the accented V and in the tongue vertical gesture from it. However, there are mainly two Parkinson's Disease subjects, that is PD3 and PD6, that show a wider distance between tongue positions, with a more backward /u/. Interestingly, they are also the Parkinson's Disease subject speakers showing a wider lip protrusion.

Summing up results obtained here, acoustic data showed that phonemes realization are kept different, even though a strong inter-speaker variation is found.

Considering our first research question, regarding the systematic reduction in the vowel space used by dysarthric speakers, reduction is found on the front-back dimension for some subjects only, that is PD1 and PD2, and PD1 also shows reduction on the vertical axis. Kinematics shows that a wider gesture is found in Parkinson's Disease subjects, but a deeper by subject observation shows that two out of four Parkinson's Disease subjects realize wider gestures: PD3 and PD6 show a wider distance between tongue positions, realizing also a more backward /u/. Interestingly, they are also the Parkinson's Disease speakers showing a wider lip protrusion, as if they were hyper-articulating in order to make the vowel difference clear. Thus, reduction takes place, but apparently there are “compensating subjects” using wider front-back gestures. Importantly, this is found both when /u/ is produced in /a/ context and when it is produced in /i/ context, showing that the effort in differentiating vowels is always found and not only when /u/ needs to be differentiated by a closer vowel (e.g., /a/) than by a high, more distant vowel (/i/). Compensation strategies observed in the data bring into play the principles of motor equivalence, at least those related to the relevance of acoustic/auditory goals (see discussion in Perrier & Fuchs 2015). That is, some of our dysarthric speakers do not preserve articulatory goals, but rather try to keep acoustic/auditory ones.

Therefore, as for our second question, that is if articulatory data indicate the presence of compensation strategies, data point in the direction of a compensation on the front-back dimension, regarding both tongue and lips.

4. Experiment II

4.1 Method

Position values for all stress vowels were extracted on both front-back and vertical axes, in line with the procedure described in §3.1. However, besides extracting tongue dorsum position measures, various metrics were then considered, thanks to a Matlab script, after creating (1000) /i/-/a/-/u/ triplets of points via randomization (see Figure 8). In order to analyze the characteristics of the vowel space, different measures were considered, such as the area of the triangle connecting highest points in profile, the barycenter (or CoG) of the triangle with respect to z (Barycenter-z) and the barycenter (or CoG) of the triangle with respect to x (Barycenter-x).

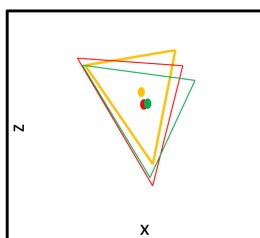


Figure 8. Graphical representation of the articulatory vowel space measure components

4.2 Results

The vowel space area is affected by the Voicing factor ($\chi^2(1)=4.192$, $p=0.040$) as the articulatory area is reduced in the context of unvoiced consonants in comparison to what found in the context of voiced consonants. However, no impact of Population, neither its interaction with Voicing is found.

The position of the vowel space measured by means of the Barycenter-x, in the front-back dimension, is also affected by Voicing ($\chi^2(1)=799.16$, $p<0.0001$) as areas are found to be slightly more anterior in the unvoiced context than in the voiced one. However, Population interacts with Voicing ($\chi^2(1)=123.73$, $p<0.0001$) as areas are found to be more anterior in unvoiced context for both groups, but the difference is particularly high for Parkinson's Disease subjects and for PD1 and PD2 in particular – see Figure 9.

The position of the vowel space on the vertical axis, measured by Barycenter-y, is also affected by Voicing ($\chi^2(1)=2180.7$, $p<0.0001$) as areas are found to be slightly higher in the unvoiced context than in the voiced one. However, Population interacts with Voicing ($\chi^2(1)=16.798$, $p<0.0001$), as areas are

higher in unvoiced context for both groups, but the difference is smaller for Parkinson's Disease subjects and for PD1 and PD5 in particular.

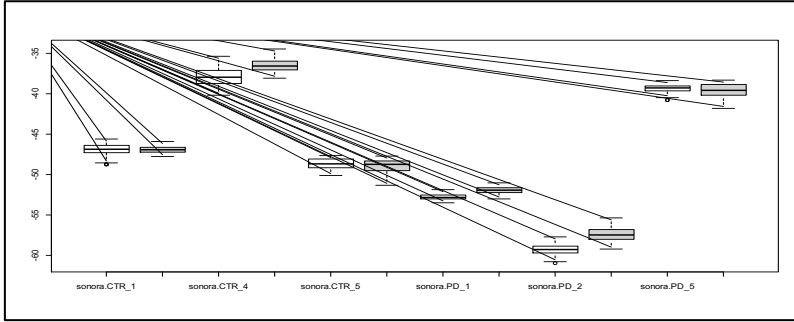


Figure 9. Barycenter-x (in millimeters) for Controls (left) and Parkinson's Disease subjects (right) in voiced (white boxes) and unvoiced (grey boxes) contexts.

4.3 Discussion on experiment II

Adopting metrics to measure articulatory vowel space in Parkinson's Disease subjects and Controls allows to gather information, though it does not seem to clearly differentiate the two populations.

In the present investigation, the working space is reduced, fronted and higher in unvoiced in comparison to voiced consonantal context for both groups, but Parkinson's Disease subjects (at least two out of three of them) in comparison to Controls show a greater difference in the voicing conditions in the front-back dimension and a smaller difference on the vertical axis.

The results obtained in the experiment described here are in line with what discussed in the scientific literature on the topic, that is measurements may be not conclusive in differentiating pathological and control subjects. Crucially, they do not capture any reduction in terms of the area of the vowel space and thus do not confirm our hypothesis on the possible reduction that could concern only some subjects. However, the hypothesis regarding the possible reduction on some axis only may be mirrored by the results obtained in relation with the Barycenter x and y measures. They showed that two out of three Parkinson's Disease subjects show a greater difference in the voicing conditions in the front-back direction, while they do not on the vertical one. This points to an asymmetry in the vowel space use depending on the axis considered.

5. Conclusion

Two experiments are described in the paper, both aiming at clarify whether Parkinson's Disease who developed hypokinetic dysarthria always reduce their acoustic and articulatory vowel space.

In the first investigation, acoustic and kinematic data are used to test if Parkinson's Disease speakers always use a reduced vowel space compared to Control subjects, and if they adopt different articulatory strategies depending on the direction of the movement (vertical vs front-back). Results show that reduction takes place, but some subjects appear to compensate, widening their tongue gestures on the front-back dimension even though the lip gesture is not necessarily undershot. Specifically, acoustic data show that a reduction is found in the front-back dimension for some subjects only, that is PD1 and PD2, and PD1 also shows reduction on the vertical axis. Kinematics, on the other hand, shows that a wider gesture is found in Parkinson's Disease subjects, even though a deeper observation of data on single subject behavior shows that only two out of four Parkinson's Disease speakers show wider gestures in the front-back dimension and a more backward /u/. Interestingly, these "compensating subjects" also show a wider lip protrusion, as if they were hyper-articulating in order to make the (/u/) vowel clear. This is in line with the principles of motor equivalence, at least those related to the relevance of acoustic/auditory goals, rather than articulatory ones (see discussion in Perrier & Fuchs 2015). In the case of dysarthric speech, phenomena driven by motor equivalence principles may indeed be crucial to approach the acoustic/auditory goal although it is reasonable that they may not be sufficient to reach the articulatory target.

In the second investigation, various articulatory metrics are used to better investigate the vowel space dimension and position, and if they change in Parkinson's Disease subjects compared to Controls. Results show that metrics used in the second experiment do not allow to capture any reduction and to clearly differentiate Parkinson's and Control subjects, as found in other work in the literature. However, in line with results of the first experiment, they point to an asymmetry in the vowel space use depending on the axis considered. More specifically, for both groups the working space appears to be reduced, fronted and higher in unvoiced in comparison to voiced consonantal context. However, Parkinson's Disease subjects (at least two out of three of them) in comparison to Controls show a greater difference in the voicing conditions in the front-back dimension, as shown here by the Barycenter-x measure; they also show a smaller difference on the vertical axis, corresponding to the Barycenter-y measure used in this work.

However, the investigations described here regard few subjects, due to the complexity and length of articulatory data collection and analysis. Thus, results can only suggest trends, and need to be confirmed by further investigations. Moreover, concerning the second experiment in particular, various metrics have been used in the literature and, therefore, our results may depend on the metrics we used, as adopting different ones could bring to different views on the matter. Further work will be devoted to larger populations and sets of data as well as to different metrics.

Acknowledgments

The work described in the paper was partially funded by the PRIN 2017 project 2017JNKCYZ. We thank M. Iraci and G. di Prizio for their help in the collection and segmentation of the corpora considered. We thank all the pathological and control subjects who participated in the experiments.

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