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Phonology Drives Compensation: bridging linguistic and clinical evaluation for a classification of speech impairment in dysarthria

Kinematic data collection is providing new possibilities to enhance (and objectivise) the evaluation of the impairment in Motor Speech Disorders. Focusing on Hypokinetic Dysarthria in Parkinson's Disease, recent studies reveal that pathological speakers, despite showing deficits in amplitude and coordination of speech gestures, are able to correctly realise kinematic and acoustic correlates of phonological contrast (such as in the alternation of singletons and geminates in Italian) through some compensatory strategies. Our hypothesis is that phonological constraints drive the compensation, but constraints due to the pathology act at the phonetic level, on contiguous gestures. This seems to be the case when analysing speech production. In order to check this hypothesis on listeners' perception of pathological productions, an auditory test aiming to collect both phonological and phonetic information was designed. Furthermore, the information collected were also used in order to more objectively classify pathological speakers' productions. Results seem to confirm our hypothesis and suggest that a phonologically-phonetically based evaluation of the level of Motor Speech Disorders's impairment may correspond to subjective clinical evaluation, and thus can be eligible for objectivising clinical assessment.

Key words: Parkinson's Disease, Dysarthria, Impairment evaluation, Articulatory Phonology, Compensation strategies.

Introduction

In the last decades, the research on Motor Speech Disorders (MSD) benefited of motion tracking instruments, such as Electromagnetic Articulography (EMA), in order to study this class of speech pathologies at the level of motion, i.e. measuring the production of speech sounds directly from the dynamics of articulators. Before researchers had the possibility to exploit motion tracking instruments for these purposes, the standard for the study of MSD was the perceptual evaluation – still in use in the clinical practise. Perceptual evaluation has been crucial for the classification of motor speech disorders as we know them, from the pioneering studies by Darley, Aronson and Brown (cfr. Darley, Aronson & Brown, 1969) to the most recent volume by Duffy (2005).

1. *Hypokinetic Dysarthria in Parkinson's Disease*

1.1 Amplitude and coordination of speech gestures

This study focuses on Hypokinetic Dysarthria (HD): HD is a motor speech disorder typically shown by people affected by Parkinson's Disease (PD) (Duffy, 2005). From the point of view of speech production, it entails disturbances to the execution and control of speech gestures' amplitude and coordination (as for the amplitude, Ackermann, Ziegler, 1991; Gili Fivela, Iraci, Sallustio, Grimaldi, Zmarich & Patrocinio, 2014; Iraci, Zmarich, Grimaldi & Gili Fivela, 2016; Skodda, Gronheit & Schlegel, 2012; Skodda, Visser & Schlegel, 2011; Wong, Murdoch & Whelan, 2010; 2011; as for coordination, Connor, Abbs, Cole & Gracco, 1989; Gili Fivela, Iraci, Grimaldi & Zmarich, 2015; Iraci, Grimaldi & Gili Fivela, in revisione; Tjaden, 2000; 2003; Tjaden, Wilding, 2005; Weismer, Yunusova & Westbury, 2003). Actually, the issue is quite controversial since, on the one hand, speech gestures' amplitude has been found to be both reduced (Skodda et al., 2011; 2012) or increased (Wong et al., 2010; 2011). Moreover, this happened simultaneously in native Italian dysarthric PD speakers, depending on the axis of movement (Gili Fivela et al., 2014; 2015; Iraci et al., 2017b): more in detail, given a mid-sagittal plane of observation, Italian pathological speakers, when compared to control speakers, can show increased tongue gestures' amplitude on the anterior-posterior dimension, while the opposite happens on the vertical dimension (reduced gestures' amplitude). On the other hand, studies on coordination still report uncertain results probably because of methodological differences. While Connor et al. (1989) find that the coordination between lips and jaw fails in the production of bilabial consonants, Tjaden, despite some slight coordination deficit, states that patterns of coordination are mostly preserved (Tjaden, 2000; 2003; Tjaden, Wilding, 2005). Finally, Weismer et al. (2003) report similar considerations, noticing only differences in the timing of lip protusion for the production of /u/. Concerning Italian, also Gili Fivela et al. (2015) can infer some slight differences between PD and control speakers in the coordination between tongue and lip, but the patterns of supposed incoordination remain unclear in their preliminary study.

1.2 Phonology and compensatory strategies

Despite the patterns of misarticulation and/or incoordination that the research on this topic individuates and describes, dysarthric PD speakers appear to be able to realise meaningful differences mainly based on articulatory gestures' amplitude and duration (such as singleton vs. geminate consonants in Italian; Gili Fivela et al., 2014; 2015; Iraci et al., in revisione; 2017b). This can be possible hypothesising that HD does not carry any direct effect at the phonological level, but only indirect effects due to extreme lack of accuracy. In other words, speech alterations (due to misarticulation and/or incoordination) affect the range of phonetic variation without threatening the phonological contrast. This is true at least when the level of impairment is not extremely severe (Iraci et al., in revisione). For instance, the difference in the acoustic duration, which is one of the main correlates of the singleton vs. geminate contrast, is maintained even though the average geminate duration in PDs' production is similar to the singleton duration in controls' production (Gili Fivela et al., 2015). In fact, dysarthric speakers seem to exploit some compensatory strategies (Schröter-Morasch, Ziegler, 2005; McCabe, 2010) that are not functional to the accuracy of speech but, as we hypothesize, are likely to maintain the phonological plan – or, in other words, they are driven by phonological constraints. For example, in a preliminary study, Iraci et al. (in revisione) individuated and described subject-specific articulatory strategies of dysarthric PD speakers relying on EMA data (AG 501, Carstens GmbH): subjects were all able to realise both acoustic and articulatory correlates of singleton vs. geminate contrast, showing some subjective alterations to contiguous (or co-produced secondary) gestures.

1.3 Bridging phonetic and clinical assessment: a summary of research questions

Our general hypothesis about the conservation of the phonological plan through compensatory strategies affecting the accuracy of speech has been tested in studies on speech production so far. As mentioned above, MSD's impairment evaluation has been based on auditory analysis and this method is the one the clinical practise is mostly relying on. Thus, in order to bridge production and auditory analysis, it seems crucial to test our hypothesis through perceptual data from experimental subjects listening to pathological voices. Especially, we wonder if listeners will recognise those consonants which in our previous studies are said to be consistently realised by pathological speakers as examples of the expected categories.

In addition to this, when consonants are correctly recognised by listeners, we wonder which will be their evaluation about the accuracy of the whole production. This kind of information is useful as to measure the extent to which the pathological realisation is well-suited or at the edges of the admitted range of phonetic variation.

However, the answers to these two questions will offer us an objective evaluation of both the phonological and the phonetic characteristics of the PD productions.

Furthermore, bridging perception and production might also mean bridging linguistic-phonetic and clinical evaluation. Researchers never know whether the clinically established level of impairment corresponds to the phonetically established one. Bridging phonetic (objective) and clinical (subjective) assessment is of crucial importance for the definition of common starting points and aims for both linguistic and medical sciences.

1.4 Bilabials, geminates, voicing and nasality

In order to test our hypothesis, the same items collected for the study of pathological speech production (Gili Fivela et al., 2014; 2015; Iraci et al., in revisione; 2017b) have been administered to non-pathological native Italian listeners coming from the same area of pathological speakers. Items were acoustic recordings of pseudo-words coupled in minimal pairs differing for the medial consonant. Such consonant could be a bilabial singleton or the corresponding geminate – whose correlates of contrast are also kinematically based (Gili Fivela, Zmarich, 2005; Gili Fivela, Zmarich, Perrier, Savariaux & Tisato, 2007; Zmarich, Gili Fivela, 2005; Zmarich, Gili Fivela, Perrier, Savariaux & Tisato, 2007; 2009; 2011) and have been demonstrated to be realised as such by pathological speakers from a kinematic and acoustic point of view (Gili Fivela et al., 2014; 2015; Iraci et al., in revisione; 2017b).

The contrast between Italian singletons and geminates has been selected as a factor of interest for two reasons. As already stated, it is also based on kinematic correlates such as amplitude and duration of gestures, whose implementation is problematic in HD (see §1.1 for references). Moreover, syllable structure is supposed to switch from CV.CV in the case of singleton, to CVC.CV in the case of geminate (Bertinetto, 1981; Loporcaro, 1996). So, this contrast allows to check whether a switch from a simple to a (more) complex syllable structure influences pathological speakers' performances.

Among potential items to administer, bilabials have been selected for continuity with our production studies. In fact, in Gili Fivela et al. (2014; 2015) and Iraci et al. (2017b), bilabials have been exploited as a baseline case to check for the phasing of gestures, specifically for the purpose of the singleton vs. geminate contrast which the phasing should be relevant for: this choice allowed to exclude cases of shared articulators between consonants and vowels' gestures and concentrate only on productions whose consonants were associated to a bilabial gesture, and vowels to a tongue dorsum gesture.

Moreover, voicing and nasality have been included in this experiment because PD speakers can show alterations to the management of vocal folds and/or the velopharyngeal sphincter. The first case is acknowledged in the classical literature reporting, for example, reduced vibratory intensity, incomplete vocal closure, increased phonation threshold pressure and glottal tremor (cfr. Duffy, 2005, but also Zhang, Jiang & Rahn, 2005). On the contrary, there is a limited amount of studies on the effects of the Velopharyngeal dysfunction (VPD) on speech (e.g. see Hammer, Barlow, Lyonsc & Pahwac, 2011 for the treatment of VPD in PD through Deep Brain Stimulation). VPD consists in inadequate velopharyngeal control, the latter crucial for the realisation of velum opening gestures for nasal consonants. Analysing voicing and nasality can provide new information about articulators which are hard to be instrumentally inspected.

It is worth reminding that voicing and nasality are to be considered not only as physical components which can clinically stress HD speakers. Following the theoretical framework of Articulatory Phonology (cfr. amongst others, Browman, Goldstein, 1989; 1990; cfr. for recent developments, Gafos, Goldstein, 2011), voicing and nasality should be considered as two gestures, the first realised by the vocal folds, the second by the velum[1]. They are produced in coordination with the other oral gestures. For these reasons, items containing voiced and nasal bilabials will be analysed as within an increasing scale of phonetic demand, in comparison with the baseline case (the simplest case) represented by unvoiced segments.

[1] Despite Articulatory Phonology considers voicing to be a default modality (hence, less marked than lack of voicing, i.e. glottal abduction), for the clinical reasons above exposed, this study will consider vocal folds vibration to be more problematic than glottal abduction for unvoiced consonants.

2. *Experiment*

2.1 Aims and hypotheses

Despite HD entails disturbances to the execution and control of speech gestures' amplitude and coordination, dysarthric PD speakers are able to realise meaningful differences mainly based on articulatory gestures' amplitude and duration. For this reason, our main hypothesis, driven by production results is that HD does not carry any direct effect at the phonological level (but only indirect effects): speech alterations are supposed to affect the phonetic characteristics of speech, while clear inconsistencies with the phonological form manifest when execution is too much disrupted. Given those premises, we intend to verify from the aural-perceptual point of view:

i. if minimal pairs realised by pathological speakers, and consistently differentiated on the kinematic and acoustic dimension, will correctly be categorised by non-pathological listeners,
ii. the phonetic accuracy in PD productions, as evaluated by listeners.

In line with our main hypothesis and with the observation of cases in which, given a significant difference between singleton and geminates by PD speakers, the average geminate duration in PDs' production is similar to the singleton duration in control speakers' realizations (see §1.2.), we expect results to correlate with the level of impairment.

Therefore, we would expect that:

1. the higher the impairment, the higher the number of minimal pairs not correctly categorised by listeners,
2. the higher the impairment, the lower the accuracy of pathological productions.

However, our corpus includes bilabial consonants, whose voiced segment, in the area where recordings took place (Lecce), shows *rafforzamento* in intervocalic medial position (Gaillard-Corvaglia, Kamiyama, 2008) and domain initial position (Gili Fivela, d'Apolito, Stella & Sigona, 2008; 2010). For this reason, it may be hard to distinguish between a singleton and the corresponding geminate, which, as will be discussed in the following sections, are our main term of comparison. Thus, for what concerns the voiced bilabial we expect:

1a anomalous results (i.e. not in line with expectations above exposed), in that the geminate should be hardly distinguished from the singleton showing *rafforzamento* (and vice-versa);

2a results in line with previous expectations as for accuracy, in that the phenomenon of *rafforzamento* has no effects on the phonetic accuracy of the consonant realisation.

Nevertheless, as mentioned in §1.2, we cannot take for granted that the clinically established level of impairment corresponds to the phonetically established one. Rather, we assume that measuring the amount of alterations of both the original phonological plan and the actual phonetic execution (of the expected phonological plan) might provide a phonetically and phonologically-based rating of the impairment, offering a satisfying description (and hopefully classification) of the speech impairment itself.

Interestingly, in the literature on second language acquisition, Guion, Flege, Akahane-Yamada & Pruitt (2000) proposed an index to measure the accurateness in L2 speech, in which no perfect match with the ideal L2 production is expected. In their study on Japanese learners of English, "English consonants with relatively high *fit indexes* would be readily accepted as instances of a Japanese consonant category, whereas those with relatively low fit indexes would be heard either as "foreign" or as distorted instances of a Japanese category" (Guion et al., 2000). In our opinion, a similar index may be useful to measure the accurateness also in pathological speech, since no perfect match with the ideal production is expected in this case as well[2]. Thus, a similar index – intended to correspond to a phonetically and phonologically-based rating of the impairment – is proposed in this paper, and the expectations in 1) and 2) are checked with reference to such index (see §2.4 for this index calculation).

Therefore, we even intend to verify:

iii. if, and to what extent, a phonetically and phonologically-based classification matches with the clinical assessment.

In this respect, as a working hypothesis, we assume that:

3. clinical evaluation resembles the phonologically-phonetically obtained index of classification.

2.2 Corpus and subjects

The corpus is composed of disyllabic pseudo-words inserted in a carrier phrase such as "La CVC(C)V blu" (transl. "The CVC(C)V blue"). Consonants are all bilabials and can be unvoiced, voiced and nasals; the medial consonant can be singleton and geminate; the vocalic context can be aCiCa o iCaCi (corpus: /'pa.pi/, /'pi.pa/, /'ba.bi/, /'bi.ba/, /'mi.ma/ and corresponding geminates in medial position). Speakers repeated the corpus 6/7 times; listeners heard all repetitions for every item/speaker.

Pathological speakers are 5, all affected by PD and having developed a HD. According to the clinical evaluation, their level of impairment can vary from mild-to-moderate to moderate-to-severe (see Tab. 1). All speakers come from Lecce's area and are aged 64 to 81; speakers declared to have not being diagnosed of any other neuro-cognitive impairment or other speech-language-hearing disease.

[2] For a comparable application of the fit index by Guion et al. (2000) to pathological speech, we refer to Iraci, Grimaldi & Gili Fivela (2017) where indexes attributed to pathological productions have been compared to indexes derived from typical speech. In this study, only the creation of a similar index for the purpose of pathological speech study will be illustrated and used for comparison with the clinical assessment.

Listeners are 11, all coming from Lecce's area, aged 22 to 36 and holding a degree (though from high school to university). They all declared to have never reported any neuro-cognitive impairment or speech-language-hearing disease.

All subjects (speakers and listeners) read the informative sheet and signed the consensus module.

Table 1 - *Summary of pathological speakers*

Speaker	*Age*	*Clinical evaluation*
PD-1	65	Moderate-to-severe
PD-2	81	
PD-4	74	
PD-3	75	Mild-to-moderate
PD-5	64	

2.3 Perceptual test

Target sentences produced by pathological speakers have been automatically segmented[3] and inserted in a data base (10 pseudo-word x 6/7 repetitions x 5 speakers = 335 items). The data base has been randomised and then presented to the listeners in the form of a perceptual test (realised on Praat, Boersma, Weenink, 2009) characterised by two tasks: an identification and a goodness rating task. In details, firstly listeners had to reply to a phonemic categorisation test aimed to the recognition of the word-internal target consonant's status (identification test with forced binary choice, singleton vs. geminate); secondly, an evaluation of the whole sentence's accuracy was required (goodness rating, on a 1-5 Likert scale).

The corpus was illustrated to the listeners in a short training phase in which the target consonant(s), target of the first task, was/were explicitly pointed out. During the same phase, listeners were informed that in second task they would have evaluated the entire production and that, the higher the rating, the most fluent, accurate and well-controlled the production. The test's average duration was about 40 minutes. Listeners used headphones at comfortable volume level and were allowed to take a break whenever they liked. None of them benefited from more than a 5 minutes break.

After starting the script on Praat, a list of instructions appeared on the screen: "Dopo aver ascoltato una parola, clicca sul numero 1 se hai sentito una sola consonante, altrimenti clicca sul numero 2 se hai sentito una consonante doppia. Poi valuta se il parlante ha prodotto la parola che hai ascoltato in maniera fluente, accurata e ben controllata in una scala da 1 a 5" (trans.: "after every sentence, click number 1 if you heard a singleton consonant, or click number 2 if the consonant was geminate. Then evaluate if the sentence you heard was accurate, fluent and well-controlled in a scale from 1 to 5"). Then, clicking on any point on the screen, the first audio stimulus was played and the listener could visual-

[3] For details on data collection and post-processing see Gili Fivela et al. (2014; 2015) and Iraci et al. (2017b).

ise a question: “Hai sentito una consonante scempia o una geminata” (trans. “Did you hear a singleton or a geminate consonant?”). Following the question, two buttons were displayed, one showing a number “1”, the other a number “2”, respectively corresponding to “singleton” and “geminate”. Once clicked on the selected button, another question was unlocked in the lower part of the screen: “La frase era accurata, fluente e ben controllata?” (trans. “To what extent was the sentence accurate, fluent and well-controlled?”). Following the question, five buttons reporting number from 1 to 5 were displayed: once listeners expressed their evaluation by clicking on the selected button, the next audio stimulus was automatically launched (unless the listener decided to take a break).

2.4 Measures

In order to verify our hypothesis we measured:

1. Percentages Of Categorization (POC): the number of times the listener choice concerning the medial consonant matched the expected consonantal status – the expected consonantal status corresponded to the form reported in the script the speakers read in the course of kinematic recordings. Such percentages have been calculated on the whole number of listeners’ responses as a function of
   a. consonant status: singleton vs. geminate. For example, in order to calculate the POC of all singletons, we used the following formula (1):

(1) $$POC_{singleton} = \frac{\text{number of all listeners' correct match}}{\text{sample of all speakers' singletons}} \times 100^{4};$$

   b. consonant distinctive features: unvoiced vs. voiced vs. nasal. For example, for unvoiced consonants POC, we used formula (2):

(2) $$POC_{unvoiced} = \frac{\text{number of all listeners' correct match}}{\text{sample of all speakers' unvoiced}} \times 100;$$

   c. the single pathological speaker:

(3) $$POC_{PD\text{-}1} = \frac{\text{number of all listeners' correct match}}{\text{sample of all PD1's realisations}} \times 100;$$

2. Goodness Rating’s Average (GRA): values contributed to averages only when the item was correctly categorised in the previous task[5]; averages are calculated

[4] In this paper, “correct match” corresponds to the cases in which the listener’s choice corresponds to the script the speaker read during the kinematic production recordings, e.g. when /b/ was identified as /b/. When /b/ was identified as /b:/ (or the opposite), “no match” can be used in the text.

[5] When an item was not identified in the first task, its goodness rating did not contribute to the GRA. This choice is due to the impossibility of accepting an evaluation of accuracy on a word that has not been understood. In other words, the phonological plan failed in being implemented (i.e. the produced consonant(s) in the minimal pair could not be successfully identified). Let’s hypothesise the extreme case in which only 1 item’s repetition out of 7 was identified (1 correct match, 6 no match) by a given listener, and that item was assigned a very high goodness value: GRA will however be equal to that single goodness value because we assume that speaker to show clear problems to the preservation

out of the number of repetitions of a given pseudo-word produced by a given speaker and evaluated by a single listener, i.e. we calculated one value per word/speaker/listener[6] in order to measure differences as a function of
a. consonant status: singleton vs. geminate
b. consonant distinctive features: unvoiced vs. voiced vs. nasal;
c. the single pathological speaker;

The effect of these three factors were calculated through a statistical test (see §2.5).

3. classification index (INDEX): obtained multiplying the index of categorization (the number of times the item was identified divided by the number of repetitions produced by the PD speaker for the given pseudo-word) by the GRA calculated by item/speaker/listener[7]. As already mentioned, this corresponds to the *fit index* proposed by Guion, Flege, Akahane-Yamada & Pruitt (2000) to investigate the relations between cross-language mapping and discrimination. Indeed, in our opinion the index is useful to measure the accurateness in both L2 or pathological speech as in both cases no perfect match with the ideal production is expected. Factors considered for the analysis of INDEXes are
   a. consonant status: singleton vs. geminate
   b. consonant distinctive features: unvoiced vs. voiced vs. nasal;
   c. the single pathological speaker.

To sum up, for the purpose of this study we will consider
- POC to represent the phonological information since it is generated by the amount of times the minimal pair was not correctly identified;
- GRA to represent the phonetic information since it is generated by the listener's perception of speech accuracy.

Thus, our INDEX is defined as phonologically-phonetically obtained since it is a function of
a. speaker's accuracy (when the phonological plan's execution is not altered)
b. the inferred number of times the phonological plan's execution is altered

(4) $$\text{INDEX}_{\text{word}} = \text{POC}_{\text{word}} \times \text{GRA}_{\text{word}}$$

of the phonological planning, but when the latter is preserved, the phonetic form may be not entailed. GRA measures only the phonetic form.

[6] E.g., listener F6's $\text{GRA}_{\text{mimma}}$ for PD-2 = 2.75. Listener F6 recognised item /'mim.ma/ produced by speaker PD-2 4 times out of 7. So, 3 values were excluded (the 3 previous task's no match); resting values are 3, 3, 2, 3; the formula is (3+3+2+3)/4 = 2.75.

[7] Given the example in footnote 4, the INDEX attributed to listener F6 for the item /'mim.ma/ produced by PD-2 is equal to 1.57. The listener recognised the item 4 times out of 7, so the formula is (4/7)*2.75= 1.57.

2.5 Statistical tests

Data obtained from the categorization test are calculated in percentage out of:
- all observations concerning singletons (1848 observations) and geminates (1837) produced by all pathological speakers (for the analysis of consonant status);
- all observations concerning unvoiced (1485), voiced (1432) and nasal (770) segments produced by all pathological speakers (for the analysis of distinctive features);
- all observations concerning a pseudo-word (from 77 to 154) for inter-speaker differences[8].

As for GRAs and INDEXes, they have been analysed through a linear mixed effects model (Bates, Maechler, Bolker & Walker, 2014), in the R environment (R Core Team, 2015). The model was aimed to evaluate the effect of the following fixed factors: "consonant status" (henceforth *status*: 2 levels, singleton vs. geminate) and "distinctive features" (henceforth *feature*: 3 levels, unvoiced vs. voiced vs. nasal). Moreover, in order to inform the model that items were produced by 5 speakers, and further analyse inter-speaker differences, a fixed effect called *speaker* was included[9]. Finally, the model was attributed two random effects: one to account for listeners', another for items' variability.

(5) *Dependent variable ~ status + features + speaker + (1|listeners) + (1|items)*

Post-hoc tests have been run with package *multcomp* (Hothorn, Bretz & Westfall, 2008); significance threshold was considered <0.05.

3. *Results*

3.1 Percentages of Categorisation

The categorisation test revealed that singleton consonants have been correctly identified 77,92% of times (1440/1848), while geminates 83,66% (1537/1837).

However, the following percentages reveal differences as a function of consonant's distinctive features: listeners recognised the consonant 94,94% of times (1410/1485) when it was an unvoiced obstruent (including both singletons and geminates), 59,77% (856/1432) when it was a voiced one, and 87,01% (670/770) when nasal.

[8] Observations are to be considered always out of the total of all listeners. E.g. 77 observations for PD-3's /'mi.ma/ means that speaker produced 7 repetitions of that pseudo-word but the sample is calculated out of 11 listeners.

[9] Of course, no factors have been included as to account for speech impairment level since we wanted this information to arise from our results.

Table 2 - *Speakers ranked by global POCs*

Speakers	*in %*
PD-5	89,58
PD-3	82,46
PD-4	79,41
PD-2	77,2
PD-1	75,89

Considering the observations per speaker, pathological subjects report POCs between 75% and 89%. In particular, PD-5's POC is 89,58% (611/682), PD-3's 82,46% (635/770), PD-4's 79,41% (594/748), PD-2's 77,2% (586/759), PD-1's 75,89% (551/726).

Concerning PD-1, $POC_{singleton}$ is 96,41% (350/363), $POC_{geminate}$ is 55,37% (201/363): in particular, $POC_{singleton}$ of only unvoiced segments is 99,35% (153/154), $POC_{singleton}$ of voiced segments 99,24% (131/132), $POC_{singleton}$ for nasals is 85,71% (66/77); $POC_{geminate}$ for unvoiced, voiced and nasals is respectively 70,12% (108/154), 27,27% (36/132) and 74,02% (57/77)[10].

PD-2's $POC_{singleton}$ is 71,42% (275/385), while $POC_{geminate}$ is 83,15% (311/374): as for singletons, unvoiced segments were identified 92,85% of times (143/154), voiced segments 38,31% of times (59/154), nasals 94,8% of times (73/77); as for geminates, unvoiced segments were identified 100% of times (154/154), voiced segments 76,22% of times (109/143), nasals 62,33% (48/77).

PD-3 reports $POC_{singleton}$ of 68,05% (262/385), and $POC_{geminate}$ of 96,88% (373/385): concerning singletons, respectively, unvoiced, voiced and nasal segments were identified 99,35% (153/154), 20,77% (32/154), and 100% of times (77/77); concerning geminates, unvoiced, voiced and nasal segments, were respectively identified 99,35% (153/154), 100% (154/154) and 85,71% of times (66/77).

As for PD-4, $POC_{singleton}$ is 70,58% (264/374), $POC_{geminate}$ is 88.23% (330/374): in particular, $POC_{singleton}$ of only unvoiced segments is 94,15% (145/154), $POC_{singleton}$ of voiced segments 31,46% (45/143), $POC_{singleton}$ for nasals is 96,1% (74/77); $POC_{geminate}$ of only unvoiced segments is 99,3% (142/143), $POC_{geminate}$ of voiced segments is 77,27% (119/154), $POC_{geminate}$ of nasals is, 89,61% (69/77).

Concerning PD-5, $POC_{singleton}$ is 84,75% (289/341), $POC_{geminate}$ is 94,42% (322/341): $POC_{singleton}$ for only unvoiced, voiced, and nasal segments respectively is 98,48% (130/132), 72,72% (96/132), and 81,81% (63/77); $POC_{geminate}$ for unvoiced, voiced and nasals is respectively 97,72% (129/132), 87,87% (116/132) and 100% (77/77).

[10] All speakers' results are grouped in Tab. 3 for better reading.

Table 3 - *Summary of by-speaker/by-word POCs*

In %	PD-1		PD-2		PD-3		PD-4		PD-5	
	sing	gem	sing	gem	sing	gem	sing	gem	sing	gem
Unvoic.	99,35	70,12	92,85	100	99,35	99,35	94,15	99,3	98,48	97,72
Voiced	99,24	27,27	38,31	76,22	20,77	100	31.46	77,27	72,72	87,87
Nasal	85,71	74,02	94,8	62,33	100	85,71	96,1	89,61	81,81	100

3.2 Goodness Rating Averages

GRA does not change as a function of *status* ($\chi 2(1)=3.02$, $p=0.08$) but significantly varies both as a function of *feature* ($\chi 2(2)=13.38$, $p=0.001$) and *speaker* ($\chi 2(4)=211.8$, $p<0.0001$), with an interaction between *status* e *feature* ($\chi 2(2)=18.86$, $p=0.0008$). GRA is lower when the target consonant is voiced, if compared to nasals and unvoiced respectively. Concerning the factor *speaker*, GRA differs by *speaker* as follows: PD-2 < PD-4, PD-1 < PD-5 < PD-3. The post-hoc on the interaction shows that GRA is definitely lower in case of voiced singleton; voiced and nasal geminates report intermediate values; finally, higher values are reported in case of unvoiced singletons and geminates (the nasal singleton let report intermediate, but not significantly different values between the last two groups).

3.3 Index of classification

INDEX does not change as a function of *status* ($\chi 2(1)=1.43$, $p=0.23$) but factors *feature* and *speaker* are both significant (respectively [$\chi 2(1)=15.5$, $p=0.0004$] and [$\chi 2(4)=151.51$, $p<0.0001$]), as well as the interaction between *status* and *feature* ($\chi 2(2)=18.93$, $p=0.0007$). INDEX is lower when *speaker*s are realising voiced consonants; higher values are reported respectively in case of nasals and unvoiced. According to the factor *speaker*, pathological speakers are exactly grouped following the clinically established level of impairment: PD-2, PD-4, PD-1 < PD-5, PD-1. The post-hoc reveals that INDEX values distribute as follows in ascending order: voiced singleton < voiced geminate < nasal geminate (nasal singleton) < unvoiced geminate, unvoiced singleton. Mean INDEXes grouped by pseudo-word and speaker are reported in the following table:

Table 4 - *Summary of by-speaker/by-word mean INDEXes*

	PD-1		PD-2		PD-3		PD-4		PD-5	
	sing	gem	sing	gem	sing	gem	sing	gem	sing	gem
[‘pa.pi]	3.99	3.65	2.42	3.58	4.8	4.72	3.19	3.63	4.20	4.07
[‘pi.pa]	4.11	2.20	2.94	3.54	4.67	4.47	3.52	3.25	4.02	4.31
[‘ba.bi]	3.18	0.55	0.44	2.37	0.82	4.63	0.87	2.12	2.98	2.86
[‘bi.ba]	3.59	1.10	1.04	2.36	0.33	4.73	0.59	2.77	1.99	3.81
[‘mi.ma]	2.72	2.36	2.87	1.51	4.84	4.04	3.18	2.73	2.90	3.75

4. *Discussion*

Overall results from the first test (identification test with forced binary choice, singleton vs. geminate) showed higher rates of correct match in the case of geminates, rather than singletons.

Despite so, analysing this outcome in terms of distinctive features can provide a different point of view. Looking at results for only unvoiced consonants (the least in a scale of phonetic demand), it is possible to notice that speakers' productions are recognised in a higher percentage of cases, with the only exception being PD-1's unvoiced geminates (<75%). In fact, PD-2 and PD-4 show lower percentages in case of unvoiced singletons if compared to other speakers, though these are greater than 90%. The productions by most impaired speakers (PD-1, PD-2 and PD-4) seem to be more easily identified if they were intended to correspond to singletons (PD-1) or geminates (PD-2 and PD-4). Since subjects are said to differently compensate, this result may be seen in terms of subjective "preferences" for two hypothesised distinct patterns of production. The first (related to PD1) maybe a preference for a CV.CV pattern, or a general tendency towards hypoarticulation with no explicit compensation leading to correctly articulating singletons, while showing reduction in case of switch to a different dynamical regime (e.g. in case of geminates, where syllable structure is supposed to change to a structure as CVC.CV). The second (PD-2 and PD-4) maybe a preference for a CVC.CV pattern, where compensation to hypoarticulation leads to lengthen the slots of time useful for articulating sounds (thus showing target reaching only in case of geminates).

When considering nasality, the productions by all speakers generally correspond to comparable or lower POCs if compared to results for unvoiced segments. Looking at plain data, when comparing nasal singletons to unvoiced singletons, no evident distinctions arise: PD-1 and PD-5 report lower proportions in the case of nasals; PD-2, PD-3 and PD-4 nasal singleton > unvoiced singleton but these differences seem to be negligible (respectively in percentage, PD-2, 94,8 vs. 92,85; PD-3, 100 vs. 99,35; PD-4 96,1 vs. 94,15). Turning the comparison to geminates, it is possible to notice that PD-2, PD-3 and PD-4 report lower POCs in the case of nasals, while PD-1 and PD-5 nasal geminate > unvoiced geminate, but proportions are comparable (respectively in percentage, PD-1 74,02 vs. 70,12; PD-5 100 vs. 97,72). This result suggest that nasality can slightly worsen the identification of minimal pairs. Nevertheless, major differences lay in the relationship between singletons and geminates belonging to the same group (i.e. nasal singletons and geminates): all speakers show lower POCs for geminates (with the only slight exception being PD-5) as if, increasing phonetic demand (that is, adding a nasal gesture), there is a general preference for CV.CV patterns, thus showing a general trend towards degemination. It is crucial to consider that in the case of nasal consonants not only a linguistic feature is added, but a specific clinical factor has to be considered as well: a great number of subjects affected by PD can show a VPD (see §1.4; cfr., for example, Hammer et al., 2011 for the treatment of VPD in PD through Deep Brain

Stimulation), consisting in inadequate velopharyngeal control, the latter crucial for the realisation of velum gestures for nasal consonants.

Results for voiced segments are to be considered apart from the rest of data because of the regional variety typical pronunciation of intervocalic voiced bilabial plosives as lengthened. Indeed, in production it is possible to notice extreme values, such as for PD-2, PD-3 and PD-4 that probably always produced lengthened consonants due to *rafforzamento*, and PD-1 that, instead, still confirms his preference for simple syllable structures maybe just due to greater difficulties in producing longer segments (which could be related to the slightly lower POCs obtained by his geminates). On the contrary, PD-5 report uncertain results, as no clear trend is detectable, probably because, in these cases, it was very hard to distinguish between a singleton showing *rafforzamento* and a geminate.

Finally, looking at POCs registered for every speaker out of the total of realisations, speakers seem to follow the clinical evaluation's tendency since most impaired speakers have been attributed to values under 80%, and less impaired ones to higher values: PD-1 (75,89), PD-2 (77,2), PD-4 (79,41), PD-3 (82,46), PD-5 (89,58). However, POCs seem to suggest a scalar difference in the productions of most PD speakers and a quite clear differentiation of PD-5's productions only. It may be the case, then, that POCs allow a more fine grained classification of speech by PD speakers which are borderline at a specific intermediate impairment level.

Results from the second task show that there are no consistent differences in terms of accuracy, depending on the alternation of singleton and geminate consonants. In particular, significant differences are found because of the alternation of distinctive features here considered, and by-word results are even helpful for inferring information on the relationship between singletons and geminates: lowest GRAs are attributed to the voiced singleton, followed by the respective geminate that, in turn, is accompanied by the nasal geminate; higher GRAs are attributed to unvoiced segments, while the nasal singleton lays somewhere in between the last two groups. Though differently arisen, the same picture depicted in discussing results from the first test seems to come out of this test as well. Possibly, there are fewer differences due to the alternation of singletons and geminates when segments are unvoiced (that is, for the lowest phonetic demand). But when segments are nasalised, geminates are regularly more inaccurate. On the contrary, voiced segments are definitely not accurate when they are singletons, probably because they can be hardly distinguishable from geminates, mainly because of *rafforzamento*; otherwise because, if not lengthened, they might even be approximated. By-speaker's result still look very close to both POCs and clinical evaluation's trend: PD-2 < PD-4, PD-1 < PD-5 < PD-3.

The INDEX produced after crossing the two information obtained "classifies" single words realisation very similarly to what seen in terms of GRAs, with the only difference being the nasal geminate, this time differing also from the voiced geminate. Again, it is interesting to notice that no statistical differences are found for the *status* factor, but the nasal singleton seem to be better perceived than the respective geminate. Looking at Tab. 3 – and bearing in mind Tab. 2 – it is possible to notice that those preferences exhibited in relation with productions by most impaired speakers (in terms of POCs) for singletons (PD-1) or geminates (PD-2 and PD-4), now are slightly more evident, though not completely for PD-4. Nasality still lowers INDEXes and the nasal singleton (rather than the geminate) is again confirmed as the best output, as shown by listeners, together with the only exception of PD-5. Voicing strongly lowers INDEXes for the reasons already exposed and tied to the regional variety. Finally, it is worth to notice that the clinical evaluation matches with the statistically-individuated inter-speaker differences (PD-2, PD-4, PD-1 < PD-5, PD-3).

5. *Summary and Conclusions*

PD speakers are able to realise meaningful differences mainly based on articulatory gestures' amplitude and duration despite Hypokinetic Dysarthria entails disturbances to the execution and control of speech gestures' amplitude and coordination. According to our previous works, in order to do so, PD speakers seem to exploit some compensatory strategies. These strategies are supposed to be aimed to the conservation of the phonological plan, though at the expenses of speech accuracy. Our hypothesis is that phonological constraints drive the compensation, but constraints due to the pathology act on contiguous gestures. Hence, Hypokinetic Dysarthria would not carry any direct effect (but only some indirect effects) at the phonological level. As a consequence, speech alterations would mainly remain within a range of phonetic variation that is consistent with the expected message interpretation, apart from the case of speech produced by high severity level patients. Thus we believe that measuring the amount of alterations at both the phonological and the phonetic level might provide a satisfying and objective description (and hopefully evaluation) of the speech impairment. In order to obtain a measure of this kind we set-up a perceptual experiment that allowed us to extract these two source of linguistic information, and further crossed the two information for the purpose of evaluation.

First, we wondered whether minimal pairs (differing for the medial consonant being singleton or geminates) realised by pathological speakers, and differentiated on the kinematic and acoustic dimension, were correctly categorised by non-pathological listeners. We hypothesised that the higher the speakers' impairment, the higher the number of minimal pairs not correctly categorised by listeners. We considered the impairment level expected on the basis of the clinical evaluation and that calculated on the basis of listeners' judgements and, further, we compared the two. Results have been analysed in order to even check for the influence of consonant status (singleton, geminate), distinctive features (voiced, unvoiced, nasal, plosive), and the single speaker. Less impaired speakers, eventually, showed no relevant alterations at the phonological level. On the contrary, according to the POCs registered as a function of the singleton vs. geminate relation, most impaired speakers showed some alterations differently distributed for the presence/absence of some specific distinctive features (nasality).

At the lowest level of phonetic demand (unvoiced bilabial plosive segments), most impaired speakers are hypothesised to follow two distinct patterns. When the lowest percentages of match have been found in case of geminates (e.g. PD-1), a preference for a CV.CV pattern was hypothesised. This should be due to a general tendency towards hypoarticulation with no explicit compensation, leading to correctly articulating singletons, but showing reduction in case of switch to a different dynamical regime (e.g. in case of geminates where syllable structure is supposed to change to a structure as CVC.CV). The second hypothesised pattern may be a preference for a CVC.CV pattern (e.g. PD-2 and PD-4). In this case, compensation to hypoarticulation leads to target reaching only in case of geminates, that is when a lengthened slot of time is available for articulating sounds.

Out of these two supposed patterns, independently of the clinically-established level of impairment, only the first was found in case of nasals. This means that nasal geminates were identified less frequently than nasal singletons. We suppose this happened not only because of the increase of phonetic demand, but also because most people affected by PD can show an inadequate control of the velopharyngeal sphincter (VPD) that probably prevent pathological speakers from switching to a different dynamical regime. Indeed, the nasal geminate seem to be generally penalised if compared to the nasal singleton and the unvoiced segments. However, we need further check on nasal segments and on the switch to different dynamical regime in order to confirm what supposed.

Voiced segments represented a special case in that, in the area where recordings took place, the singleton shows *rafforzamento*. For this reason, it was expected to be hardly distinguished from the respective geminate. Anomalous results were expected and soon found: two speakers have been likely considered to always realise lengthened singletons, while two other speakers represented a matter of confusion for our listeners in both cases. One speaker (PD-1) is an exception again, as he mainly produced segments identifiable as singletons and showed clear difficulties with geminates.

Independently of the status of the consonant and/or distinctive features, speakers can be roughly grouped by POCs (i.e. the identification of phonological categories) into two different levels yet at this stage, resembling the clinical assessment, though not precisely.

Secondly, we wondered the extent to which listeners would have evaluated the phonetic accuracy. We hypothesised that the higher the impairment, the lower the accuracy of pathological productions. The status of the consonant seemed to play a clear role on the accuracy. The nasal geminate still have been penalised by listeners, probably because of the reasons exposed before. Surprisingly, even the voiced segments was attributed to low values. Concerning the latter, results in line with our main hypothesis were expected since the phenomenon of *rafforzamento* was hypothesised not to influence the phonetic accuracy of the consonant realisation.

Instead, the lowest GRAs have been reported exactly in case of voiced segments. Listeners referred that it was always very hard to distinguish between a bilabial singleton vs. geminate so, often, they assigned low goodness ratings to items that in the previous task were identified with difficulties (i.e. listeners were not self-confident with what they were evaluating). Moreover, it has to be considered that the singleton showing *rafforzamento* is not a geminate but a sort of halfway. This fact probably generates confusion because listeners are asked to choose between two categories that actually manifest themselves as three ones, and probably not always realised within the ranges of expected (non-pathological) phonetic variation. These three categories are not necessarily distinguishable from each other since, in this area, a trustful contrast between a real singleton vs. a real geminate in the case of voiced bilabial consonants can be found only in very highly-controlled realisations.

At this stage, speakers grouped by GRAs (i.e. the degree of appreciation of the actual phonetic implementation) reflected a trend similar to the clinically-established level of impairment, though slightly different from the trend obtained when speakers have been grouped by POCs (i.e. the phonological information). It is likely that compensatory strategies have an amount of "subjectivity" such as non-pathological speech with subjective idiosyncrasies. On the contrary, linguistic constraints seem to play a stronger role and the phonetic alteration seem to be directly proportional to the phonological one. This is the case of voiced segments that, since they were not easily recognised, they have been even evaluated as inaccurate. Or still, it is the case of the nasal geminate, that in the previous task resulted to be among the most penalised and, when identified, it even resulted to be quite inaccurately produced.

Finally, the phonetically and phonologically-based INDEX obtained showed to be sensitive to differences for the status of the consonant (despite this did not come from statistical tests) and to distinctive features differences already individuated across the two previously reported analysis. Again nasality played a crucial role lowering values, and nasal geminates were finally penalised. Concerning the influence of VPD in the realisation of geminates, it seems plausible that a mechanical/physical (pathological) constraint limit the phonological structure's expected execution. In gesture-based phonologies like Articulatory Phonology, linguistic constraints are supposed to interact with mechanical/physical constraints, finally producing the phonetic execution with its amount of variation. When pathological constraints intervene in this process, variation can go out of what listeners perceive as an admitted range in their mother-tongue. Without phonological constraints (whose absence would be attributed to lesions to speech production/comprehension's areas, rather than to MSD) speech probably would be totally disrupted. In our opinion, in HD related to PD, compensatory strategies are supposed to be driven by phonological constraints. This means that the articulators, hindered by pathological constraints, (i) may tend towards a new resting position, and/or (ii) may reach targets with evident limits in the phonetic parameters (amplitude, duration), but without limits in the phonological/dynamic parameters (target, stiffness, damping coefficients) of the gesture (cfr. Nam, Saltzman, 2003; Goldstein, Byrd & Saltzman, 2006). Nevertheless this is just a hypothesis that still has to be confirmed crossing this data with previously recorded kinematic data.

Thus, summing up, although with the abovementioned differences related to the variation in articulatory demand required for different distinctive features and despite the anomalous results related to bilabial voiced plosives, our findings confirm that

1. the higher the impairment, the higher the number of minimal pairs not correctly categorised by listeners;
2. the higher the impairment, the lower the accuracy of pathological productions;
3. the phonologically-phonetically obtained index of classification resembles clinical evaluation.

Thus it is supposed that basing the clinical evaluation on some objective indicators of the phonological level alterations and of the phonetic accuracy alterations as well, it is possible to offer an objective evaluation of the speech impairment at least in HD, hopefully to extend to MSDs in general.

6. *Future investigations*

Findings from this study suggest at least two directions for further researches. First, this classification method needs to be tested on a greater number of pathological speakers and possibly listeners as well; further, it needs to be tested on different types of MSDs. Second, we will cross perceptual data with acoustic and kinematic data in order to look at every realisation from all possible points of view: articulation, acoustic and perception. This will allow us to focus on the reciprocal interactions between the three phonetic dimensions.

Bibliography

Ackermann, H., Ziegler, W. (1991). Articulatory deficits in Parkinsonian dysarthria: an acoustic analysis. In *Journal of Neurology, Neurosurgery, and Psychiatry*, 54, 1093-8.

Bates, D., Maechler, M., Bolker, B. & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1-5. http://CRAN.R-project.org/package=lme4/Accessed 18.05.16.

Bertinetto, P.M. (1981). *Strutture prosodiche dell'Italiano*. Firenze: Accademia della Crusca.

Browman, C., Goldstein, L. (1989). Articulatory gestures as phonological units. In *Phonology*, 6, 201-51.

Browman, C., Goldstein, L. (1990). Tiers in articulatory phonology, with some implications for casual speech. In Kingston, J., Beckman, M. (Eds.), *Papers in Laboratory Phonology I: Between the Grammar and the Physics of Speech*. Cambridge: Cambridge University Press, 341-97.

Connor, N.P., Abbs, J.H., Cole, K.J. & Gracco, V.L. (1989). Parkinsonian deficits in serial multiarticulate movements for speech. In *Brain*, 112, 997-1009.

Darley, F.L., Aronson, A.E. & Brown, J.R. (1969). Differential Diagnostic Patterns of Dysarthria. In *Journal of Speech, Language, and Hearing Research*, June 1969, 12, 246-69.

Duffy, J.R. (2005). *Motor Speech Disorders: Substrates, Differential Diagnosis, and Management*. 2°ed. Elsevier Mosby.

Gafos, A., Goldstein, L. (2011). Articulatory representation and organization. In Cohn, A., Huffman, M. & Fougéron, C. (Eds.), *Handbook of Laboratory Phonology*. Oxford University Press.

Gaillard-Corvaglia, A., Kamiyama, T. (2008). La /b/ "forte" in salentino (Puglia): uno studio acustico, percettivo e fisiologico. In Pettorino, M. (Ed.), *La Comunicazione Parlata: atti del congresso internazionale*, Napoli, 23-25 febbraio 2006. Napoli: Liguori, 87-99.

Gili Fivela, B., d'Apolito, S., Stella, A. & Sigona, F. (2008). Domain Initial Strengthening in sentences and paragraphs: preliminary findings on the production of voiced bilabial plosives in two varieties of Italian. In Sock, R., Fuchs, S., Laprie, Y. (Eds.), *Proceedings of the International Seminar on Speech Production*, Strasbourg, France, 8-12 December, 205-208.

Gili Fivela, B., d'Apolito, S., Stella, A. & Sigona, F. (2010). Domain initial strengthening: dati acustici e articolatori relativi a due varietà di italiano. In Cutugno, F., Maturi, P., Savy, R., Abete, G. & Alfano, I. (Eds.), *Parlare con le persone, parlare alle macchine: la dimensione interazionale della comunicazione verbale, Atti del VI Convegno Nazionale AISV - Associazione Italiana di Scienze della Voce*, Università di Napoli, 3-5 febbraio 2010. Torriana (RN): EDK Editore, 173-195.

Gili Fivela, B., Iraci, M.M., Grimaldi, M. & Zmarich, C. (2015). Consonanti scempie e geminate nel Morbo di Parkinson: la produzione di bilabiali. In Vayra, M., Avesani, C. & Tamburini, F. (Eds.), *Il farsi e il disfarsi del linguaggio. Acquisizione, mutamento e destrutturazione della struttura sonora del linguaggio/Language acquisition and language loss. Acquisition, change and disorders of the language sound structure*. Milano: AISV, 247-273.

Gili Fivela, B., Iraci, M.M., Sallustio, V., Grimaldi, M., Zmarich, C. & Patrocinio, D. (2014). Italian Vowel and Consonant (co)articulation in Parkinson's Disease: extreme or reduced articulatory variability?. In *Proceedings of the 10th International Seminar on Speech Production (ISSP'14)*, Cologne, Germany, 5-8 May 2014, 146-9.

Gili Fivela, B., Zmarich, C. (2005). Italian Geminates under Speech Rate and Focalization Changes: Kinematic, Acoustic, and Perception Data. In *InterSpeech 2005*, Lisbon, Portugal, 2897-2900.

Gili Fivela, B., Zmarich, C., Perrier, P., Savariaux, C. & Tisato, G. (2007). Acoustic and kinematic correlates of phonological length contrast in Italian consonants. In *Proceedings of International Conference of Phonetic Sciences (ICPhS'07)*, Saarbrücken, Germany, 6-10 August 2007, 469-472.

Goldstein, L., Byrd, D. & Saltzman, E. (2006). The role of vocal tract gestural action units in understanding the evolution of phonology. In Arbib, M.A. (Ed.), *Action to Language via the Mirror Neuron System*. Cambridge: Cambridge University Press, 215-49.

Guion, S.G., Flege, J.E., Akahane-Yamada, R. & Pruitt, J.C. (2000). An investigation of current models of second language speech perception: The case of Japanese adults' perception of English consonants. In *Journal of the Acoustical Society of America*, 107(5), Pt. 1, May 2000, 2711-2724.

Hammer, M.J., Barlow, S.M., Lyonsc, K.E. & Pahwac, R. (2011). Subthalamic nucleus deep brain stimulation changes velopharyngeal control in Parkinson's disease. In *Journal of Communication Disorders*, 44(1), 37-48.

Hothorn, T., Bretz, F. & Westfall, P. (2008). Simultaneous Inference in General Parametric Models. In *Biometrical Journal*, 50(3), 346-363.

Iraci, M.M., Grimaldi, M. & Gili Fivela, B. (2017). Dalla L2 al parlato patologico: un indice di categorizzazione fonemica per la valutazione dell'intelligibilità del parlato disartrico. In *XVII Congresso Internazionale dell'Associazione Italiana di Linguistica Applicata (AItLA)*, Università degli Studi di Napoli "L'Orientale" - Università della Campania "Luigi Vanvitelli", S. Maria Capua Vetere, 23-25 febbraio.

Iraci, M.M., Grimaldi, M. & Gili Fivela, B. (in revisione). Il contributo della Fonologia alla riabilitazione logopedica personalizzata di soggetti parkinsoniani disartrici. In Dovetto, F. (Ed.), *Lingua e Patologia: le frontiere interdisciplinari del linguaggio, Linguistica delle differenze*, II incontro di studio tra Medici e Linguisti, Accademia Pontaniana e Societa Napoletana di Scienze, Lettere ed Arti, Napoli, 10-11 dicembre 2015.

Iraci, M.M., Zmarich, C., Grimaldi, M. & Gili Fivela, B. (2017b). Il parlato nel morbo di Parkinson: ampiezza dei gesti articolatori e distintività dei suoni linguistici. In Sorianello, P. (Ed.), *Il linguaggio disturbato. Modelli, strumenti, dati empirici*. Roma: Aracne Editrice.

Loporcaro, M. (1996). On the analysis of geminates in Standard Italian and Italian dialects. In Hurch, B., Rhodes, R. (Eds.), *Natural Phonology: The State of the Art. Papers from the Bern Workshop on Natural Phonology*, September 1989. Berlin-New York-Amsterdam: Mouton de Gruyter, 153-87.

McCabe, P. (2010). Advances in Motor Learning: Emerging evidence and new ideas. In *ACQuiring Knowledge in Speech, Language and Hearing*, 12(1), 3-1.

Nam, H., Saltzman, E. (2003). A competitive, coupled oscillator model of syllable structure. In *Proceedings of the 12th International Congress of Phonetic Sciences*, Barcelona, 2253-6.

R Core Team (2015). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/Accessed 18.05.16.

Schröter-Morasch, H., Ziegler, W. (2005). Rehabilitation of impaired speech function (dysarthria, dysglossia). In *GMS current topics in otorhinolaryngology, head and neck surgery*, 4, 1-13.

Skodda, S., Gronheit, W. & Schlegel, U. (2012). Impairment of Vowel Articulation as a Possible Marker of Disease Progression in Parkinson's Disease. In *PLoS ONE*, 7(2), 1-8.

Skodda, S., Visser, W. & Schlegel, U. (2011). Vowel Articulation in Parkinson's Disease. In *Journal of Voice*, 25, 4, 467-72.

Tjaden, K. (2000). An Acoustic Study of Coarticulation in Dysarthric Speakers with Parkinson's Disease. In *Journal of Speech, Language and Hearing Research*, December 2000, 43, 1466-1480.

Tjaden, K. (2003). Anticipatory Coarticulation in Multiple Sclerosis and Parkinson's Disease. In *Journal of Speech, Language and Hearing Research*, August 2003, 46, 990-1008.

Tjaden, K., Wilding, G.E. (2005). Effect of rate reduction and increased loudness on acoustic measures of anticipatory coarticulation in multiple sclerosis and Parkinson's disease. In *Journal of Speech, Language and Hearing Research*, April 2005, 48(2), 261-77.

Weismer, G., Yunusova, Y. & Westbury, J.R. (2003). Interarticulator Coordination in Dysarthria: An X-ray Microbeam Study. In *Journal of Speech, Language and Hearing Research*, 46, October 2003, 1247-1261.

Wong, M.N., Murdoch, B.E. & Whelan, B.M. (2010). Kinematic analysis of lingual function in dysarthric speakers with Parkinson's disease: An electromagnetic articulograph study. In *International Journal of Speech-Language Pathology*, 12, 414-25.

Wong, M.N., Murdoch, B.E. & Whelan, B.M. (2011). Lingual Kinematics in Dysarthric and Nondysarthric Speakers with Parkinson's Disease. In *Parkinson's Disease*, 1-8.

Zhang, Y., Jiang, J. & Rahn, D.A. (2005). Studying vocal fold vibrations in Parkinson's Disease with a nonlinear model. In *Chaos*, 15, 033903, 1-10.

Zmarich, C., Gili Fivela, B. (2005). Consonanti scempie e geminate in italiano: studio cinematico e percettivo dell'articolazione bilabiale e labiodentale. In *Atti del Convegno Nazionale AISV (Associazione Italiana di Scienze della Voce) "Misura dei parametri"*, Padova, 2-4 dicembre 2004. ISBN 88-88974-69-5. Torriana (RN): EDK, 429-448.

Zmarich, C., Gili Fivela, B., Perrier, P., Savariaux, C. & Tisato, G. (2007). Consonanti scempie e geminate in italiano: studio acustico e cinematico dell'articolazione linguale e bilabiale. In *Atti del Convegno Nazionale AISV (Associazione Italiana di Scienze della Voce) "Scienze vocali e del linguaggio. Metodologie di valutazione e risorse linguistiche"*, Povo di Trento, 29-30 November-1 December 2006. Torriana (RN): EDK, 151-163.

Zmarich, C., Gili Fivela, B., Perrier, P., Savariaux, C. & Tisato, G. (2009). L'organizzazione temporale dei gesti vocalici e consonantici nelle consonanti scempie e geminate dell'Italiano. In Romito, L., Galatà, V. (Eds.), *Atti del IV Convegno Nazionale AISV (Associazione Italiana di Scienze della Voce) "La Fonetica Sperimentale: Metodo e Applicazioni"*. Torriana (RN): EDK, 89-104.

Zmarich, C., Gili Fivela, B., Perrier, P., Savariaux, C. & Tisato, G. (2011). Speech timing organization for the phonological length contrast in Italian consonants. In Cosi, P., De Mori, R., Di Fabbrizio, G. & Pieraccini, R. (Eds.), *Proceedings of InterSpeech 2011*, Florence, 28-31 August 2011, 401-4.