INTRINSIC FUNDAMENTAL FREQUENCY RELATED TO LEXICAL STRESS IN THE SPEECH OF PEOPLE WITH PARKINSON'S DISEASE

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DOI: http://doi.org/10.35520/diadorim.2015.v17n2a4073

ABSTRACT

Intrinsic fundamental frequency (IF0) refers to a systematic difference in f0 between vowels of different heights in a similar phonetic context: high vowels tend to have higher f0 than lower vowels. Various hypotheses as to the cause of IF0 have been raised, differing mainly on the nature they attribute to the phenomenon: whether it is passive (automatic), resulting from articulatory movements that reach these segments without intending IF0 specifically; or active (controlled), deliberately generated due to reasons of perception or compensatory processes. In this article, we hope to contribute to the debate with f0 data obtained from patients suffering from Parkinson's disease (PD). 631 / a, i / vowels were analysed from recordings of an extract of text read aloud. As a result, IF0 was observed not only in participants from the control group, but also from the PD group, and the trends for participants with dysarthria were no different from those in the control group in the stressed syllable. The fact that we did not observe significant differences between the groups favours the hypothesis that IF0 is automatic. As dysarthric subjects have impaired motor control, the fact that they display IF0 with no difference from the individuals in the control group suggests that the mechanism involved in the phenomenon is similar for both. Our data does not permit us to indicate clearly which biomechanical mechanism would be the best causal explanation for these differences between high and low vowels, but they appear to be consistent with the hypotheses that emphasize the importance of tongue height.

KEYWORDS: Fundamental frequency, Parkinson's disease, dysarthria, speech production, experimental phonetics.

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RESUMO

Frequência fundamental intrínseca (f0i) refere-se a uma diferença sistemática de f0 entre vogais de altura diferente em um contexto fonético semelhante: vogais altas tendem a ter uma f0 mais elevada do que vogais baixas. Várias hipóteses sobre a causa da f0i foram levantadas e diferem principalmente sobre a natureza que atribuem ao fenômeno: se é passivo (automático), resultantes de movimentos articulatórios destinados a atingir esses segmentos sem visar f0i propriamente; ou se é ativo (controlado), se deliberadamente gerada por razões de percepção ou processos compensatórios. Neste artigo, pretendemos contribuir para este debate com os dados de f0 obtidos de pessoas afetadas pela doença de Parkinson (DP). Foram analisados 631 vogais / a, i / a partir de gravações de um trecho de texto lido. f0i verificou-se não somente nos participantes do grupo controle, mas também no grupo DP, e os padrões dos participantes com disartria não foram diferentes daqueles do grupo controle na sílaba tônica. O fato de que não encontramos diferenças significativas entre os grupos favorece a automaticidade de f0i. Uma vez que sujeitos disártricos têm prejudicado o controle motor, o fato de que eles apresentam f0i sem distinção com os indivíduos do grupo controle, nos diz que o mecanismo envolvido no fenômeno é semelhante para ambos. Nossos dados não nos permitem indicar claramente qual mecanismo seria a melhor explicação biomecânica causal para estas diferenças entre vogais altas e baixas, porém eles parecem concordar com aqueles que supõem ser importante a altura da língua.

PALAVRAS-CHAVE: Frequência fundamental, doença de Parkinson, disartria, produção da fala, fonética experimental.

INTRODUCTION

The term "intrinsic fundamental frequency" (IF0) refers to a systematic difference between f0 in vowels of different heights in a similar phonetic context: high vowels tend to have greater f0 than low vowels (OHALA, 1977; LADD & SILVERMAN, 1984; SAPIR, 1989; STEELE, 1986; FISCHER-JØRGENSEN, 1990; WHALEN & LEVITT, 1995; KINGSTON, 2007). The term thus refers to a phenomenon, rather than to a specific value, as suggested by Van Hoof & Verhoeven (2011). Various hypotheses as to the cause of IF0 have been raised. They diverge principally regarding the nature of the phenomenon: whether it is passive (automatic), resulting from articulatory processes aimed at segment production, without being intended itself; or whether it is active (controlled), deliberately generated due to perceptive reasons or compensatory functions. In this article, we hope to contribute to the debate, with f0 data obtained from the project "Análise acústica da prosódia na fala de sujeitos disártricos: uma comparação entre três populações neurológicas" ("Acoustic analysis of prosody in the speech of dysarthric subjects: a comparison between three neurological populations") (MACHADO, 2011). Changes to the neuronal circuits involving the basal nuclei (a subcortical structure of the central nervous system) imply impairment to the control of voluntary body movements. As such, illnesses which alter its functioning, such as Parkinson's disease, may generate abnormal hypo- or hyperkinetic movements, which interfere with the motor control of speech as a result, and these symptoms may supply us with the means of investigating the control and automaticity of IF0, as will be demonstrated.

The Intrinsic f0 Phenomenon (IF0)

This phenomenon has been observed in various languages of different families and typologies. This fact suggests its universality, a theory supported by the presence of IF0 in the babbling of babies recorded from six to twelve months of age (WHALEN & LEVITT, 1995). However, the Mambila language constitutes one example that contradicts the universality hypothesis (CONNELL, 2002). Escudero et al. (2009) have obtained results confirming the existence of IF0 in both Brazilian and European Portuguese.

However, Umeda (1981) argues that IF0 disappears in fluent reading, and suggests therefore that it is an artificial effect of experiments conducted using carrier sentences. Other authors, such as Ladd & Silverman (1984) and Steele (1986), disagree. In particular, they highlight the lack of control of both the position of the vowels in a sentence and the prosodic and segmental context. Ladd & Silverman (1984) tested Umeda's (1981) hypothesis in a controlled environment, concluding that although the magnitude of IF0 was significantly higher in carrier phrases, the phenomenon does not disappear in connected speech.

One property of IF0 that has been demonstrated is the reduction, or even the elimination, of f0 difference in low-pitch environments (WHALEN & LEVITT, 1995; LADD & SILVERMAN, 1984; BERRY & MOYLE, 2011). Whalen & Levitt (1995), in their critical revision of the subject, point out that in tonal languages, such as Yoruba, low tone tends not to display IF0. They also point out, using the data of Shi & Zhang (1987), that in Tone 4 (*high-low*) of Mandarin, IF0 was found in the high onset, but not in the low offset of the vowel. This supports the hypothesis that "low pitch, rather than low-stress or phrase-final position per se, is the relevant factor" (LADD & SILVERMAN, 1984, p. 36). In addition, Berry & Moyle (2011) have analysed two reading conditions: habitual f0 and increased f0. Their results indicate larger IF0 size in the latter condition, corroborating the hypothesis of IF0 reduction in a low pitch context.

Another interesting factor is the effect of gender on IF0 size (WHALEN & LEVITT, 1995; TURNER & VERHOEVEN, 2011). It was found that females displayed significantly larger IF0 than males on a Hertz scale, though this was inverted upon converting to semitones. However, these results were not corroborated by Van Hoof & Verhoeven (2011), who found no significant difference in IF0 according to gender and suggest that high individual variation may have concealed the effect.

As has already been mentioned, the nature of IF0 remains unclear and has been a cause of debate for some time.[3] The main discussion concerns the attribution of an active role to the speaker in the occurrence of IF0. The aforementioned **passivity or automaticity hypotheses** defend the idea that IF0 is a by-product of acoustic and/or biomechanical couplings; in short, an effect which is not controlled by the speaker. Other hypotheses attribute the speaker an active role in the phenomenon, suggesting that they produce f0 differences in vowels to enhance category distinctions or create compensatory effects. These hypotheses may be called the **enhancement hypotheses**. Finally, some researchers believe that the two types of hypotheses are in fact complementary, rather than being mutually exclusive. They believe that IF0 is indeed a phenomenon

3 There have been three significant reviews of the subject: Fischer-Jørgensen (1990); Sapir (1989) and Whalen & Levitt (1995).

of physiological nature, but which may nonetheless be enhanced or even supplemented by muscular actions controlled by the speaker, in order to ensure improved linguistic distinctions. We call these hypotheses the **mixed hypotheses.**

Acoustic, Biomechanical and Neural Coupling Hypotheses

Due to the universal character of the phenomenon, it is natural to assume that it is the result of certain configurations of the vocal tract, since the laryngeal and supralaryngeal structures are similar in all humans, excluding pathological cases. IF0 is thus considered as a by-product of articulations rather than as a phenomenon intended by the speaker. This passivity is characteristic of the coupling hypotheses, of which, in particular, the acoustic, biomechanical and neural coupling hypotheses require discussion. Here, we will follow Sapir's revision (1989).

An acoustic coupling hypothesis was put forward by Lieberman (1970), who suggests that the supralaryngeal configurations of the vocal tract may affect the sensitivity of the larynx to changes in subglottic and transglottic pressure. The greatest effects of this change in pressure are found in segments in which the first formant is lower, generating an increase in f0 as a consequence, due to their proximity (acoustic coupling). Sapir (1989), however, obtained results which contradict this hypothesis. For example, lateral and nasal segments, the F1 of which is low, do not display IF0 as would be expected. In addition, even in speech in which F1 has been increased by helium gas, IF0 continues to exist. As a result, the acoustic coupling hypothesis has fallen out of fashion, with recent studies preferring biomechanical coupling hypotheses.

Different mechanisms have been suggested in biomechanical hypotheses. Ladefoged (1964) and Ohala & Eukel's (1978) are known as *tongue-pull hypotheses*. The mechanism suggested by Ladefoged (1964) is a biomechanical coupling, through which, due to the elevation of the tongue for the execution of a high vowel, there is an advance and elevation of the hyoid bone, which in turn moves the thyroid cartilage forwards. The action is similar to that of the cricothyroid muscle; it increases the stiffness of the vocal folds, generating an increase of f0. However, physiological findings do not support this hypothesis. The vowel [u] has a lower laryngeal position, despite being a high vowel with greater f0 in relation to the low vowels. As such, Ohala & Eukel (*apud* SAPIR, 1989), have reformulated the hypothesis. Ohala (1977) argues that the position of the larynx is not the only important factor, but that the condition of the soft tissues within it is also relevant. He bases his argument on previous studies indicating a greater correlation between the size of the ventricle and vowel f0 (as generally they are presented in relation to IF0), than between vowel f0 and the height of the larynx. This would be the foundation used by later researchers:

> They suggested that the tissues connecting the tongue dorsum with ary-epiglottic folds could exert an indirect pull on the ventricular and true vocal folds and thus induce or increase vertical tension in the folds. In addition, the superior tongue pull may enlarge the laryngeal ventricles and pull the false vocal folds away from the true folds; the latter would result in reducing the damping effect of the false vocal folds on the true folds. Thus, an increase in vertical vocal fold tension, a reduction in vocal fold damping, and enlargement of laryngeal and pharyngeal ventricles, all due to tongue pull, should increase f0 during the production of high vowels (SAPIR, 1989, p.45).

The proposal of Ewan (1979) changed the focus of the analysis of the phenomenon: while the higher pull of the tongue may participate in the differences found, another physiological mechanism, for the production of lower vowels, could also be responsible for the phenomenon. Sapir (1989) calls this the *tongue-compression hypothesis*. Ewan (1979) argues that there is a compression of the aryepiglottic folds on the vocal folds, associated with the pressure of the tongue backwards and below, along with the narrowing of the pharynx. This generates an increase in the thickness of the vocal folds, along with a reduction of their stiffness, resulting in lower f0. According to this point of view, tongue pull, through its elevation, would contribute to increased f0 in the high vowels, while tongue compression, through its lowering and posteriorization, would contribute to lowering of f0 in low vowels, thus generating IF0.

In contrast, Sapir's (1989) *hypothesis of horizontal and vertical pull* attributes the speaker an active role. He argues that the movements of the larynx and hyoid bone during vowel production could be the result of a voluntary activation of some of the extrinsic muscles (SAPIR, 1989). He suggests that the contraction of the suprahyoid muscles – in particular, the geniohyoid muscle – act on the advance of the hyoid bone, generating an increase of the laryngeal and pharyngeal ventricles, contributing to lower F1. It also generates an increase in the vertical and horizontal tension of the vocal folds through the stretching of the aryepiglottic folds and the thyroid cartilage tilting in an anterior and frontal direction, respectively. In addition, Sapir suggests that the tilting of the thyroid cartilage may generate all these effects, as well as lower F2 in the back vowels, independently of the advance of the hyoid bone. Broadly speaking, Sapir argues that the configuration of the vocal tract and the action of the extrinsic muscles that enable the production of different vocalic qualities contain IF0 as their by-product. Therefore, IF0 is not intended (as such, this is a passivity hypothesis), but a consequence of an optimum articulation for the realization of different vocalic qualities. Sapir bases this argument in the results of physiological analysis of muscular action in the elevation and/or lowering of f0. Nonetheless, it is worth pointing out that his own experiment, which he uses as supporting evidence, had as its participant a trained singer, who may have implemented or exaggerated certain muscular actions for vowel realization.

Finally, Sapir (1989) suggests one other coupling possibility: neural or sensory-motor. The main idea is that the specific articulations for vowel production may generate reflexes in the muscular activity of the larynx, thus altering it. However, Sapir concedes that the sensory-motor mechanisms and their level of interference with f0 are unclear.

Enhancement Hypotheses

Enhancement hypotheses, in most cases, are not concerned with the physiological mechanisms involved in IF0. As they are based on the notion that differences between vowels are generated deliberately, the generating mechanism is not the central question – any mechanism to raise or lower f0 could achieve it. Rather, these hypotheses are concerned with the objective of the speaker in establishing this contrast. The increase in distinction between vowels and compensatory effects of duration and intensity are those aims of IF0 reported here.

Resonance frequencies, present at the centre of each formant of a given vowel, are not the most relevant factor when analysing absolute values in the differentiation of vocalic quality. Rather, it is the distance between each amplitude peak, the space between each formant, which is the most important data in terms of distinguishing vocalic qualities.[4] Considering that high vowels have lower F1, the hypothesis is that when f0 is increased, the distance between it and F1 will reduce, and therefore, the difference between high and low vowels will become clearer. In her review of the subject, Fischer-Jørgensen (1990) cites various studies supporting this hypothesis. One possible – indeed, almost inevitable – consequence of this position is that languages with a more distinctive vowel inventory have greater IF0 range, as they need to ensure distinction between a greater number of candidates.

Whalen & Levitt (1995), having analysed a number of studies, arrived at the conclusion that there are no significant differences between languages of different size inventories. In addition, they argue that the movement of F1 in relation to f0 is below a perceptual threshold, and it is not plausible that extra effort be made to produce such a small – perhaps even imperceptible – result. This could even hinder comprehension in tonal languages, in which f0 is essential for lexical distinctions. However, Van Hoof & Verhoeven (2011), in their analysis of IF0 in Arabic (three distinct vowels) and Dutch (twelve distinct vowels), found greater differences between the vowels in Dutch than in Arabic. In addition, they obtained a result showing the F1 movement slightly above the perceptual threshold, thus arguing that the differences of 2.28 semitones between high and low vowels are sufficient to generate clear perception.

An approach at odds with these hypotheses of phonetic enhancement is that of Kingston (2007), which is based instead upon a functional vision based on information. He argues that the speaker can control many or all of the phonetic differences, and, according to context, may select properties which mutually enhance each other within that particular environment, in order to better convey information. In this sense, no property alone is essential and sufficient. According to this view, IF0 would be one of these properties applied in contexts of greater information.

Kingston (2007) bases his view of the phenomenon as having a volitional cause on the work of Fischer-Jørgensen (1990), who found greater f0 in high lax vowels [ɪ, ʊ], despite the fact that tongue height in these vowels was less than that of close-mid vowels [e, o], thus contradicting the tongue-pull hypothesis. He also cites Ladd & Silverman (1984) and Steele (1986), who showed that IF0 disappears or diminishes when syllables are not intentionally accentuated (pitch accent), as well as findings indicating greater activity of the cricothyroid muscle in high vowels (HONDA & FUJIMURA, 1991). Another factor that lends support to this enhancement hypothesis is the presence of IF0 in so-called "esophageal speech": that of individuals whose larynxes have been removed (precluding interpretation by coupling), who deliberately create differences between high and low vowels. Whalen & Levitt (1995) suggest however that the production of IF0 by these individuals could be merely a reproduction of that which occurs in natural speech automatically, in an attempt to replicate the speech of healthy individuals. Finally, Kingston (2007) also points out that the lack of consensus regarding the mechanisms involved in coupling hypotheses does not count in their favour.

Kingston's (2007) proposal is that speakers utilize IF0 in contexts of greater information in order to ensure that there is no doubt regarding the quality of the vowel. He separates languages into two groups: the first (TYPE I), languages in which tone (pitch accent) and prominence always

4 There are various versions of this theory, which is known as formant-ratio theory. A good summary has been provided by Miller (1989).

go together, like English; the second (TYPE II), tonal languages in which tone and prominence are separate, as in Yoruba. According to Kingston, TYPE I languages increase the differences between vowels in environments of greater information, independently of tone being high or low, in order to avoid confusion between the intended vowel and others with similar characteristics. TYPE II languages, on the other hand, increase this difference in the high tone, but not in the low tone, since if the speaker were to lower their tone further, eventually they would reach a limit beyond which they could not pass (floor), while if they increased it, they could pass the boundary separating high from low tone. Nevertheless, it is important to emphasize that the high information in these two types of languages is found in different domains: in TYPE I, high information is associated with the level of the sentence, and could be a phrase or word, though the stress falls on a particular syllable. In TYPE II however, high information consists of a distinction between lexical items, which are distinguished above all by their tones.

Kingston's (2007) results did not confirm his hypothesis, instead lending support to the notion that the phenomenon is automatic. Although he found IF0 in both high and low pitch accent, unlike Ladd & Silverman (1984) and Steele (1986), IF0 was similar in stressed and non-stressed syllables (stressed syllables being understood as those upon which the pitch accent is placed).

Mixed Hypotheses

Mixed hypotheses are often proposed by researchers who feel it is not possible to discount biomechanical couplings, even though such couplings do not sufficiently explain their results. In general, these hypotheses are not very in-depth, and as such, we shall limit ourselves to a discussion of a more concrete hypothesis by Honda & Fujimura (1991), as well as a few other examples of studies and their respective arguments.

The theory put forward by Honda & Fujimura (1991) departs primarily from physiological findings found in previous studies. The coupling proposed is that in which, upon raising the tongue to produce high vowels, there is an advance of the hyoid bone due to the contraction of the posterior genioglossus muscle, generating a bascule movement of the thyroid cartilage through the cricothyroid joint. This thyroid tilting implies an increase in longitudinal tension of the vocal folds, increasing f0 – as in the case of the cricothyroid and geniohyoid muscles.[5] The control function of f0 through the hyoid bone is therefore identified as a supplementary tensor mechanism. The authors also show that the activity of the cricothyroid muscle – involved in the active control of vocal fold tension – varies according to vocalic category (being greater in the case of high vowels). As a result, they suggest that IF0 is an automatic effect of a natural coupling, which is nonetheless actively enhanced to improve the characteristics of vowels based on a previous phonologization of IF0. In their own words:

> Our interpretation is that while the biological circumstances create a phonetic tendency for high vowels, for example, to be associated with high f0, such a tendency has to go through a process of phonologization to create as language-specific rule, in order to account for all aspects of observed characteristics associating intrinsic f0 with vowels in different languages. (HONDA & FUJIMURA, 1991, p. 151).

5 The authors reiterate that the geniohyoid muscle is active during the phonation production of high f0, as it also causes an advance in the hyoid bone, and consequently, the anterior pull on thyroid cartilage.

Aside from the proposal of Honda and Fujimura (1991), Fischer-Jørgensen's (1990) results can be cited as a prime example of those producing mixed hypotheses. Upon analysing tense and lax vowels in German, she found that the hierarchy of f0 values in both types of vowels was consistent with that expected of IF0 when they were treated as separate groups. In other words, the lower F1 became, the greater f0 became, thus supporting the tongue-pull hypothesis. However, in dealing with tense and lax vowels together, the researcher encountered a problem: the lax vowel [ɪ] had greater FI than the tense vowel [e], suggesting that the position of the tongue was lower in the first instance than the second. According to the coupling hypothesis therefore, greater f0 should be found in [e] than in [ɪ]. The fact that the analysis shows that [ɪ] has higher f0 than [e] suggests that biomechanical coupling is not sufficient. In addition, it was shown that the tense vowels and their lax counterparts have similar f0, despite the tongue being in a lower position in the latter.

Fischer-Jørgensen uses previous studies to try to correlate f0 with the jaw opening, since this relation corresponds to IF0 hierarchy. She even suggests that a better relation might be tongue pull dependent on the jaw opening, in which the sternohyoid muscle is the most appropriate for the realization of IF0 contrasts, as it could lower both the jaw and f0. One of her participants, however, displayed independence between the jaw opening and fundamental frequency. As a result, she indicated possible explanations compatible with enhancement hypotheses, such as compensation for the short duration of lax vowels. In addition, she puts forward the hypothesis that stronger airflow (breathy phonation) in the production of this type of vowel could lead to an increase of f0.

What characterizes this hypothesis as mixed is the fact that it considers that some kind of coupling as the base of the IF0 phenomenon, although in the particular case of lax vowels, compensatory mechanisms could also be active. Kingston (2007) offers a phonological interpretation of this study, in which he suggests that f0 does not differ in vowels of the same phonological height, despite the differences in tongue height. For example, [ɪ], though the tongue is in a lower position than in [e], phonologically is [+high], and as such, possesses greater f0, being similar to its tense counterpart [i].

The work of Van Hoof & Verhoeven (2011) may also be considered an example of a mixed hypothesis. They found IF0 in Arabic and Dutch, though with a significant difference between them regarding the range of the difference between high and low vowels, with IF0 being greater in Dutch than in Arabic. Again, the coupling hypotheses cannot be discounted, due to the high correlation between F1 and the f0 changes. However, through the normalization of formants, possible differences in the distribution of F1 and F2 were shown to be inexistent, suggesting that there are no significant differences in the position of the tongue in the production of vowels in both languages. The reason for this difference in IF0 range would be due to a great difference in the vocalic inventory of the languages – Arabic having just three distinct vowels, while Dutch has twelve. The authors also suggest that as Arabic does not need to differentiate between as many vowels, IF0 in Arabic would be the closest to purely physiological causes. IF0 size in Arabic was 0.74 semitones, suggesting a small participation of biomechanical coupling in the constitution of IF0 results found in the studies of various languages.

In the same study, Van Hoof & Verhoeven also point out that high vowels, in both languages, behave in the same manner regarding f0, while in contrast, the low vowels display significant differences. As such, they conclude that the phenomenon occurs through the lowering of f0 in low vowels, rather than increased f0 in high vowels. They also revealed some interesting features of the phenomenon by studying native Arabic speakers who were Dutch learners. These individuals displayed equal IF0 range in Dutch and Arabic, which, according to the researchers, shows that vocalic quality and IF0 are realized separately, at least in part. This also suggests that IF0 is something learners have to acquire, a process which can produce other effects, since the Dutch learners displayed f0 in the low vowel [aː] the same as the native Dutch speakers, but they display lower f0 in the high vowels compared to what was expected for both languages. The researchers suggest therefore that once individuals have learnt that the low vowels in Dutch are lower in f0 than in Arabic, they tend to believe that Dutch in general has a lower average f0 than in Arabic, meaning they lower it for the high vowels as well.

A final example of the mixed hypothesis is that of Berry & Moyle (2011). They seek covariance between IF0, VOT and VID (Voiceless Interval Duration), on the assumption that these three measures undergo parallel alterations because they share a common biomechanical mechanism. In this manner, the researchers aimed to validate hypotheses of biomechanical couplings, based on the action of the genioglossus on the hyoid bone, and of the latter on the rotation of the thyroid cartilage. The expected covariance was observed in men, lending support to the automaticity hypotheses; however, it was not observed in women. They suggest that female speakers tended to speak more clearly in the process of data acquisition; in other words, with greater care, despite this not being requested. In addition, they displayed a tendency to reduce vowel duration when required to read something with greater f0. Berry & Moyle conclude that although IF0 is a passive phenomenon resulting from biomechanical coupling, the speaker, by opting to speak more clearly – as the female participants did in this study – may actively improve the acoustic cues through their laryngeal behaviour (BERRY & MOYLE, 2011, p. 369).

Dysarthria in Parkinson's Disease[6]

Idiopathic Parkinson's disease (PD) is a neuroprogressive degenerative disease resulting from the selective loss of dopaminergic neurons in the substantia nigra. The body's ability to produce dopamine is compromised, which ends up affecting the execution of voluntary movements. As such, dysarthria is an important characteristic of the disease.

The term "dysarthria" refers to a set of motor dysfunctions in the production of speech, of a necessarily neurological origin. This can affect the activity of supralaryngeal articulators as well as phonatory activity (dysphony). It is important to emphasize, like Pinto & Ghio (2008), that this term cannot be used exclusively to apply to neurogenic damage in articulation, as if it were the opposite of the term "dysphony", which relates to laryngeal dysfunction. It should also not be used to refer to articulatory dysfunction of non-neurological origin.

Types of dysarthria may vary according to the assessment criteria, whether location of the injury, age of manifestation or neurological diagnosis. The most widely accepted, perceptually-based scheme of dysarthria classification is that of Darley, Aronson & Brown (1975), according to which Parkinson's disease falls in the category of hypokinetic dysarthria.

6 The description to follow, except when specified, is based on Murdoch (2004; 2005), Viallet & Teston (2007), Pinto & Ghio (2008) and Pinto et al. (2010).

This type of dysarthria consists of a set of motor dysfunctions generated by damage to the basal nuclei, which form loops with the thalamus and cerebral cortex, permitting regulation of movement. Hypokinetic dysarthria is associated with an increase of outputs from the basal nuclei to the supplementary motor area, working as inhibitors of voluntary movement. The main characteristics of this type of dysarthria are the following: muscular rigidity, difficulty and slowness in initiating movement (akinesia); slowness during the execution of movement (bradykinesia); tremors (mainly when at rest) and reduction in movement amplitude and loss of automatic aspects of movement.

In terms of perception, dysphony is the characteristic most present in hypokinetic dysarthria from the pre-symptomatic stages. The voice is breathy and/or harsh, with few variations of fundamental frequency (monotone). Studies indicate that the presence of dysphony is most intense at the beginning of the disease, being reduced as it progresses, probably by compensatory mechanisms. Though some of the results are controversial, the fundamental frequency in tonic vowels tends to be higher than that produced by healthy individuals in the same context. At the prosodic level, there is difficulty in producing emphasis, not to mention pauses in inappropriate places and a general reduction of contrast and acoustic detail.

Viallet & Teston (2007) and Pinto et al. (2010) discuss the results of Logeman et al. (1978), interpreting them as indicative of a caudal-rostral direction of motor dysfunction, beginning with the larynx (dysphony), then affecting tongue-palate constriction, and finally affecting the most front articulators (lastly, bilabial sounds). At this point, speech is almost entirely unintelligible, due to the lack of precision in the articulation of vowels and consonants. There is also a tendency to reduce the area of the vocalic trapezoid. In addition, the lengthening of voiced sound has been observed, along with short plosive consonants with part of their constriction missing. These articulation problems seem to reduce in the stressed syllable and increase in the post-stressed segments. In the case of orofacial tremors, the individual seems not to be able to execute muscular contraction outside of the oscillatory cycle of the tremor. In summary, there is a reduction of acoustic contrasts in the speech of Parkinson's disease sufferers.

Physiologically, these damages in phonation and articulation come along with a respiratory dysfunction that is generated primarily by poor coordination of the muscles responsible for the expansion of the thoracic wall, and, as a consequence, the lungs. With reduced lung volume, vital capacity is also reduced, producing a reduction in general intensity, which is intrinsically related to subglottic pressure. The presence of irregular and inflexible respiratory patterns, alongside the lack of synchronicity between speech and respiration, produce frequent periods of highly accelerated speech, as well as long pauses in inappropriate places, such as in the middle of words or phrases. In the same way, phonation time is reduced due to the reduced volume of air. There is also a tendency to take longer to open the vocal folds, and not close them completely, as well as a difficulty in initiating phonation and coordinating phonation and gesture articulation. As a result, a frequently observed characteristic in the speech of Parkinson's sufferers is continuous voicing and reduction of voice onset time (VOT), which is interpreted as damage either to the central impulse of the posterior cricothyroid muscle or to neuromuscular control, though it may also be a compensatory strategy. In other words, as both beginning and end of phonation are difficult to execute – even more so given the alterations in articulators – maintaining phonation would be easier.

The effects of motor damage of hypokinetic dysarthria may be reduced by providing patients with sensory-perceptual information. This is because the basal nuclei do not have to regulate self-initiated activity, with an internal model (articulatory gestures), but can be supported by a given external model, such as a written text. As such, motor dysfunction is more obvious and intense during spontaneous speech than when reading aloud.

Objectives

This study aims to analyse IF0 by comparing the phenomenon in the speech of individuals from a control group with its possible occurrence in the speech of dysarthric subjects suffering from idiopathic Parkinson's disease. It will also assess possible distinctions in the range of differences between high and low vowels due to stress. Considering that tone is as important for lexical distinction in tonal languages as lexical stress in Brazilian Portuguese, following Kingston's (2007) reasoning, we may say that the differences in IF0 range between stressed and pre-stressed syllables indicate that IF0 is a controlled phenomenon, as long as the change in stress does not also imply a significant change in F1. Finally, a centralization of the f0 values of the pre-stressed syllable in relation to the stressed syllable, if accompanied by the same pattern in F1, would indicate a centralization of the articulation in a less marked position, and with it, a relationship between vowel height and f0. Broadly speaking, this is the reasoning applied by Van Hoof & Verhoeven (2011) in their comparison of Arabic and Dutch, two languages of different inventories: what is important is not the values, but the direction of difference.

Departing from the descriptions present in the research discussing impairment to the motor control of dysarthric patients, the following hypotheses were established:

1. If IF0 is a phenomenon of controlled nature, it is unlikely to appear in dysarthric speech, since this is characterized by difficulties in motor control.
2. If IF0 is an automatic phenomenon, it should appear in both the dysarthric individuals and those from the control group.
3. If there are differences in IF0 range between stressed and pre-stressed syllables, IF0 will be interpreted as a controlled phenomenon, as long as the change in stress does not also imply significant F1 change.

Methods

All the material analysed was obtained during the project "Análise acústica da prosódia na fala de sujeitos disártricos: uma comparação entre três populações neurológicas" ("Acoustic analysis of prosody in the speech of dysarthric subjects: a comparison between three neurological populations"), approved by COEP/UFMG on 16/07/2008. Following the description present in Machado (2011, p. 73), who was responsible for the registering process, the audio files were obtained in a silent environment at the Ambulatório Bias Fortes, Hospital das Clínicas – UFMG (noise level between 56 to 64 dB (FAST) and at the researcher's office (noise level between 53 to 66dB (SLOW). The noise level was measured using the digital decibel meter Icel DL-4020 during three periods of ten minutes each. The text recorded was the first three paragraphs of *O Sitio do Picapau Amarelo* by José Bento Renato Monteiro Lobato, which was first given to participants for silent reading. A Shure® head microphone was positioned 5cm from the mouth of the speaker, with a Marantz PMD 660® digital recorder used to record and digitalize the data.

Of the recorded audio, the tracks selected were those of the requisite acoustic quality, based on the accurate calculability of f0 and low external interference. For the same reason, participants whose clarity of articulation was extremely compromised, to the point of not permitting secure segmentation, were excluded from the group of Parkinson's sufferers. In the end, the PD group had six participants (four male, two female, off medication), while the control group had eight participants (five male, three female).

The participants in the control group were selected randomly, while the participants from the PD group were selected at the Ambulatório de Distúrbios de Movimento at the UFMG Hospital das Clínicas.[7]

The text was segmented into its stressed and pre-stressed vowels through different textgrids of the Praat software (BOERSMA & WEENINK, 2011). The parameter for segmentation was the stability of the second formant (F2) (PETERSON & LEHISTE, 1960). Nasal vowels were not included in the analysis, though those which were in part nasalized by a process of regressive assimilation were, except for the vowel /a/, which, when nasalized, is accompanied by the elevation of the tongue in Portuguese (MARCHAL & REIS, 2012), which would compromise the analysis. Diphthongs were also not considered in our analysis, though hiatuses were. In this case, the boundaries between vowels were established by analysing where abrupt formant transitions were.

When a word in the text was read incorrectly, if the word pronounced existed in Brazilian Portuguese, it was included in the database. The word "retrós" elicited a wide variety of pronunciations, probably because it was not well known by the participants. As such, we elected to discount it. In the case of reading errors or interruptions in which the participant repeated the same sentence or word, the best-preserved reading was segmented. When both were appropriate, they were both segmented.

The values were extracted using Katherine Crosswhite's Praat script, adapted for pitch range alterations and smoothing application of 10Hz bandwidth, and interpolation.[8] The script extracts values for f0, F1, F2, F3 (Hz) and segment duration (ms). Through previous analysis of each separate audio track, the values of 75Hz and 120Hz were adopted for pitch floor and 250Hz and 400Hz for pitch ceiling, for men and women, respectively.

For normalization of f0 and F1, we decided to express them in a standardized score (z-score) according to Lobanov's (1971) method – a vowel-extrinsic, subject-intrinsic and formant- or f0-intrinsic method (ADANK et al., 2004). For this conversion, the following formula was applied, via Praat script:

$$score\ z_{F_{nj}} = \frac{x_{F_{nj}} - \mu_{F_{nk}}}{\sigma_{F_{nk}}}$$

7 The details of the assessment criteria for the participants in the clinical groups, the demographic data of participants excluded from our sample and the description of the sampling process may be consulted in Machado (2011, pp. 69-74).

8 In this respect, we received the valuable assistance of Prof. Plinio Barbosa, whom we would like to thank.

$x_{F_{nj}} x_{F_{nj}}$ is the value of f0 or F1 in Hertz (indexed by '*n*') of a given occurrence ('*j*') of a given segment, and '*μ*' is the mean of f0 in all vocalic realizations of participant 'k' during the reading, with 'σ' its respective standard deviation. Then, for each vocalic realization, the standard deviation unit was how much the value of f0 or F1 deviated from the mean for each participant.

Finally, for the statistical analysis, we used only the values of /i, a/, as these were the extremes. The chosen method of statistical analysis was the mixed linear model with crossed random effects (BAAYEN, 2008), which allows for the estimation of variable dependent values, considering the effects of fixed (controlled) and random (uncontrolled) factors. For application of the model, the software R (R CORE TEAM, 2013) was used, in which we used the packages *languageR* (BAAYEN, 2013), *lme4* (BATES et al., 2014) *lmerTest* (KUZNETSOVA et al., 2015) and *ggplot2* (WICKHAM, 2009).

Results

Table 1 shows the descriptive statistics from the data obtained for this study, according to the following categories:

a. **Group (G)**: Parkinson's disease without medication (PD off) or Control (CNT)
b. **Sex (S)**: Male (M) or Female (F)
c. **Vowel (V)**: /a/ or /i/
d. **Stress (St)**: Stressed position (AC) or pre-stressed position (PRE)

G	S	St.	V	n	Mean (Hz)	Sd (Hz)	Median (Hz)	Min (Hz)	Max (Hz)	Se (Hz)	F0Lob
CNT	F	AC	a	60	192.47	39.23	180	122	323	5.06	-0.198
			i	59	209.69	33.74	206	137	308	4.39	0.352
		PRE	a	63	196.56	39.75	189	122	313	5.01	-0.100
			i	48	215.92	44.49	208	132	327	6.42	0.457
	M	AC	a	38	120.05	20.68	117.5	78	173	3.36	-0.082
			i	33	125.15	15.87	126	85	160	2.76	0.294
		PRE	a	38	119.92	16.69	117.5	96	163	2.71	-0.068
			i	27	119.22	17.65	116	97	166	3.4	-0.097
PD	F	AC	a	24	188.04	16.88	188.5	163	221	3.44	-0.173
			i	25	196.92	20.21	189	170	241	4.04	0.239
		PRE	a	24	182.17	14.32	179.5	159	210	2.92	-0.497
			i	16	194.25	18.01	191	172	241	4.5	0.143
	M	AC	a	50	148.54	25.97	153.5	77	194	3.67	-0.008
			i	50	155.7	23.36	161	77	187	3.3	0.410
		PRE	a	47	138.83	23.43	147	96	178	3.42	-0.579
			i	29	142.97	25.05	147	81	192	4.65	-0.378

Table 1 – Descriptive statistics of f0 values (Hz)[9]

The f0 data (Hz) showed results compatible with those in existing research: the f0 (Hz) observed was higher in women than in men in both groups. In the PD group, the men displayed higher f0

9 Key: n = number of observations by condition included in the sample; Sd = standard deviation; Se = standard error of the mean; F0Lob = Lobanov's transformation for z-score.

than those in CNT, while the women in contrast displayed lower values. With regard to IF0, the difference between f0 values for /i/ and /a/ amongst women were greater (17.22Hz in AC and 19.36Hz in PRE) than amongst men (5.01Hz in AC and 0.7Hz in PRE). In PD, IF0 was comparatively greater than in CNT amongst men (7.16Hz in AC and 4.14Hz in PRE) and lower amongst women (8.8Hz in AC and 12.08 in PRE).

The main concern of this study is whether f0 difference in vowels of different heights (IF0) is connected to tongue height. In acoustic terms, this would translate into a relationship between f0 and FI, the primary region of more intense frequencies in the vowel spectrum, which is traditionally associated with tongue height (the higher the tongue, the lower F1). In this study, however, the relationship was not particularly clear. The relationship between two variables can be measured by correlation statistics (R^2), which in this case, indicated the absence of a relationship both with raw f0 values ($R^2 = 0.017$) and with these values converted into z-score ($R^2 = 0.013$). Or, in more simple terms, around just 1.5% of the variation of f0 values (1.7% for f0 and 1.3% for F0Lob) can be explained by variation in F1 values. In Fig. 1 it is easy to see why this occurs. Though the points of the vowel /a/ clearly occupy the right side of the graph and those of /i/ the left, corresponding to the higher and lower regions of F1 respectively, the dispersion of points does not show any pattern on the F0Lob axis – except, perhaps, for the fact that the lower values were provided by PD and the higher values by CNT.

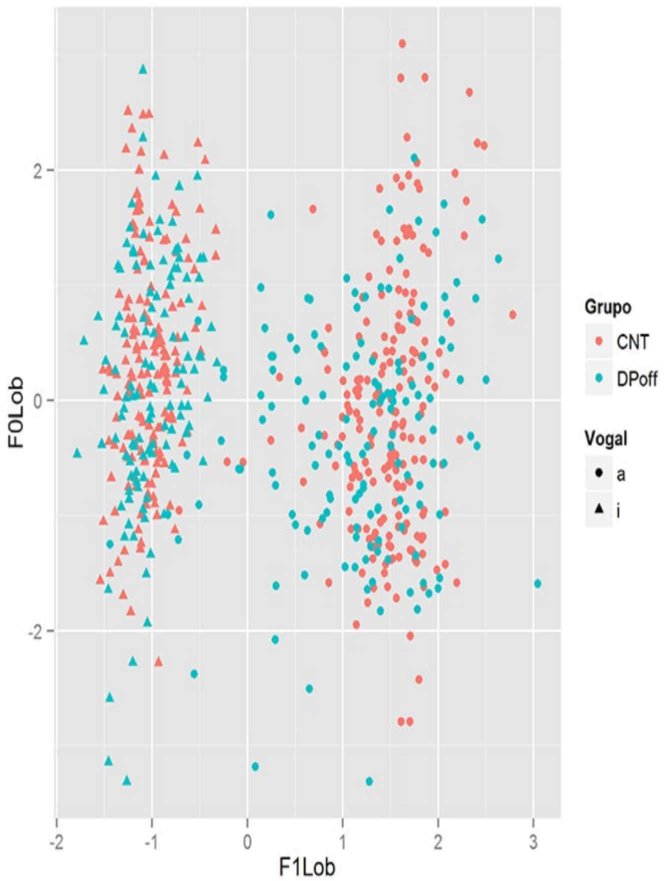

Figure 1 – Scatter graph of F0Lob values according to F1Lob values

On the other hand, in considering the distribution of f0 values according to group, vowel and stress (Fig. 2), it is possible to observe a pattern, in that f0 was higher in the vowel /i/ than in

/a/ for both groups in the two conditions in relation to lexical stress. There is also a notable pattern in the control group, in which f0 of /a/ increased while f0 of /i/ decreased in the pre-stressed syllable compared to the stressed syllable, which is consistent with the notion that f0 is related to tongue height and that the articulation of vowels tends to centralize outside of the stressed syllable. The same pattern was not observed in the PD group, in which the f0 values for /a, i/ were lower in the pre-stressed than the stressed syllable. In the absence of studies that investigate prosodic differences at the lexical level in PD individuals, we can only speculate that this is due to a marking of stress by intensity rather than duration, as seems to be the case in Portuguese (MORAES, 1987; SANTOS & LEAL, 2010). Finally, it is known that PD participants had difficulty controlling voice intensity and voice frequency independently from one another (MURDOCH, 2004).

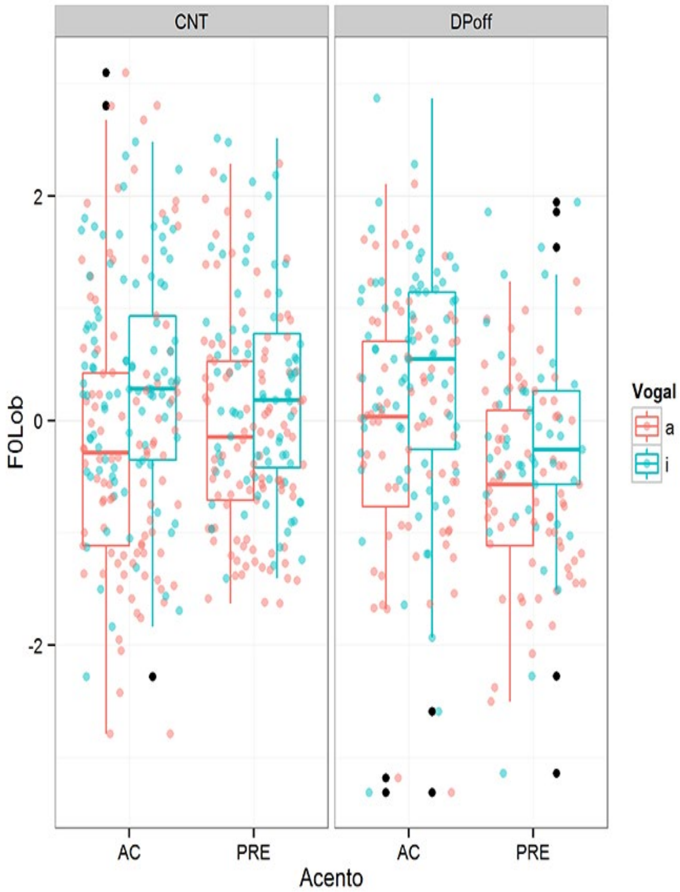

Figure 2 – Box plot and scatter diagram (F0Lob) by group, vowel and stress

For this reason, our analysis aimed to estimate the F0Lob difference between /a, i/ by stress and group. In order to do this, we used a mixed linear model with F0Lob as the dependent variable, and, primarily, sex, group, vowel and stress as the predictor variables (Table 2).[10] The first line of results (*Intercept*) assesses whether the estimated value is different to zero after the random effects of the participant for the term of comparison have been extracted; in this case, the term of comparison is the value of /a/ in the stressed syllable of the control group. It was not expected

10 Linear mixed model adjusted by Restricted Maximum Likelihood (REML). Control: lmerControl (optimizer = "optimx", optCtrl = list(method = "nlminb")), cf. Nash (2014); t-tests use Satterthwaite approximations to degrees of freedom (Kuznetsova; Brockhoff; Christensen, 2015).

to be different – as occurred in the assessment of the model – since we are using values converted into z-score. The second line tests whether the difference estimated between the values obtained from CNT and those from PD is significant; the answer is no. In spite of the results published regarding the differences in f0 (Hz) due to Parkinson's disease, it is important to keep in mind that the results obtained here may be due to the fact that we have just six participants in this group – a higher number of participants might provide an estimable significance. Another possible reason is that the Lobanov transformation also annulled the difference between the PD group and the control group, though it was not possible to find reports confirming this.[11] With so many examples of vowels for each participant, however, the actual number of participants did not impair our study. Finally, it was possible to confirm that the effect of gender is indeed eliminated with Lobanov's transformation.

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	-0.01368	0.09338	535.4	-0.146	0.88362
PDGroup	-0.15466	0.10030	10.4	-1.542	0.15293
SexM	-0.06421	0.09308	47.9	-0.690	0.49367
StressPRE	-0.16676	0.11104	621	-1.502	0.13365
StressAC:Vowel[i]	0.45754	0.11186	620.3	4.090	4.87e-05 ***
StressPRE:Vowel[i]	0.35836	0.1225	620.9	2.925	0.00357 **

Table 2 – Fixed effects of initial model estimated with all factors

According to the practice established, separate models were computed for each group, considering men and women without distinction. The ANOVA fixed effects (Table 3) show the influence of the remaining factors (stress and vowel) on F0Lob, the vowel being nested in stress in order for it to be possible to assess the difference between /i, a/ in pre-stressed and stressed syllables, respectively. For CNT, stress was not an important factor, although it should be emphasized that difference between the vowels /i, a/ is not the same according to stress, as is seen by the computation of estimates from the model considering all effects: in AC, IF0 = 0.484 and in PRE, IF0 = 0.345 (Fig. 3).

CNT (n=366, 8 participants)	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	-0.153	0.1062	362	-1.441	0.15053
StressPRE	0.0649	0.1491	362	0.435	0.66351
StressAC:Vowel[i]	0.4841	0.1526	362	3.172	0.00164 **
StressPRE:Vowel[i]	0.3455	0.1602	362	2.156	0.03171 *
PD (n=265, 6 participants)					
Intercept)	-0.06012	0.12262	32.4	-0.49	0.6272
StressPRE	-0.48424	0.16359	256.67	-2.96	0.00336 **
StressAC:Vowel[i]	0.41618	0.16129	255.89	2.58	0.01043 *
StressPRE:Vowel[i]	0.35415	0.18763	256.55	1.887	0.06022

Table 3 – Fixed effects of the models estimated by group

Although the effect of the difference between the groups was not assessed as significant, it is clear in Fig. 3 that in the stressed syllable, the magnitude and dispersion (represented here by the standard error) of F0Lob of the control group compared to the PD group are increased. These

11 This does not occur, for example, with transformation in semitones, covered in the literature (RUSZ et al., 2011).

results are therefore compatible with those previously discussed, but they are restricted to the stressed syllable. With the pre-stressed syllable, the difference between the groups is something else. CNT displays more centralized values, which makes sense if (a) the articulation of vowels in the pre-stressed syllable is more centralized; and (b) IF0 is related to tongue height. For this group, IF0 = 0.484 in AC, but IF0 = 0.345 in PRE. In contrast, for the PD group, the effect of stress was to increase f0 value significantly. In addition, IF0 in the stressed syllable was significant (0.416), but not in the pre-stressed syllable (0.35), which corresponds to lower f0. These f0 differences between vowels are less than those estimated by the model for the control group.

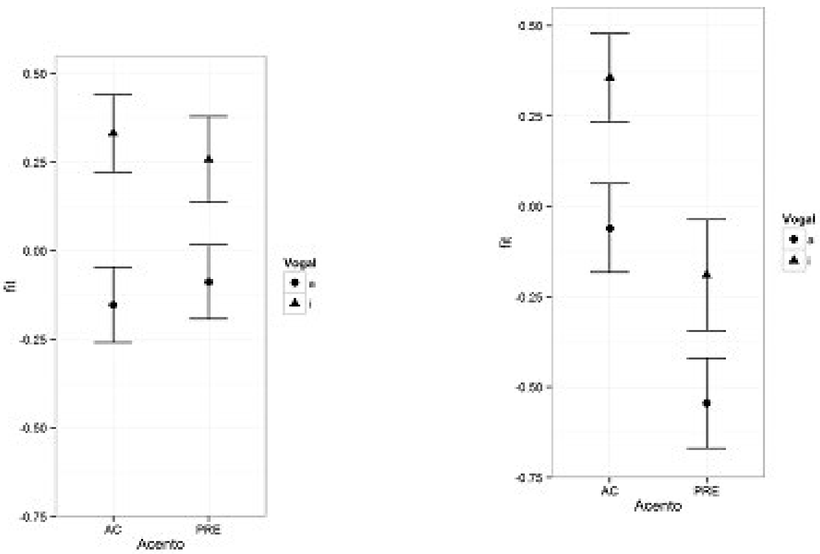

Figure 3 – Estimates of principal effects for CNT (left) and PD (right).

At this point, we may return to the initial hypothesis of mechanical coupling. According to this hypothesis, the f0 difference between vowels of different heights (IF0) must be related to a structural connection resulting in vocal folds traction due to tongue height. One of the alternative hypotheses, the control for contrast hypothesis, does not appear to satisfactorily explain the facts here discussed: the IF0 observed in a group of people with phonation control difficulties was not significantly different from that observed in a group without such difficulties. It was also greater in the stressed syllable than in the pre-stressed syllable. If IF0 were due to an attempt to increase contrast, it would follow that phonation control difficulties hindered or restricted IF0 in the PD group independently of whether the vowels occurred in the stressed or pre-stressed syllable. In this group, if there is f0 increase in the stressed syllable, it may be attributed to the need to distinguish this position using intensity (which is not always controlled independently of f0 in this group) and not to an exaggerated distinction between the vowels /i, a/, which ultimately was less than that observed in the control group.

However, the mechanical coupling hypothesis seems compromised by the absence of relationship that has been identified between f0 and F1. The F1 values are distributed – also converted into z-score – according to the same factors: group, vowel and stress (Fig. 4). In the case of the participants from the control group, the F1 values seem to correspond with the values estimated by the model for f0: /a/ is lower and /i/ is higher in the pre-stressed syllable than their equivalents in the stressed syllable (the scale is inverted on axis y, and in such a way that /i/ appears higher in the graph, just as occurs with tongue height). For the PD group, however, the distribution of

F1 values is only similar to the estimates of the f0 model for the vowel /a/ in the stressed syllable, which appears at more or less the same height as the pre-stressed /a/ in the control group. On the other hand, the pre-stressed /a/ behaves as expected for the control group: compatible with a more centralized articulation.

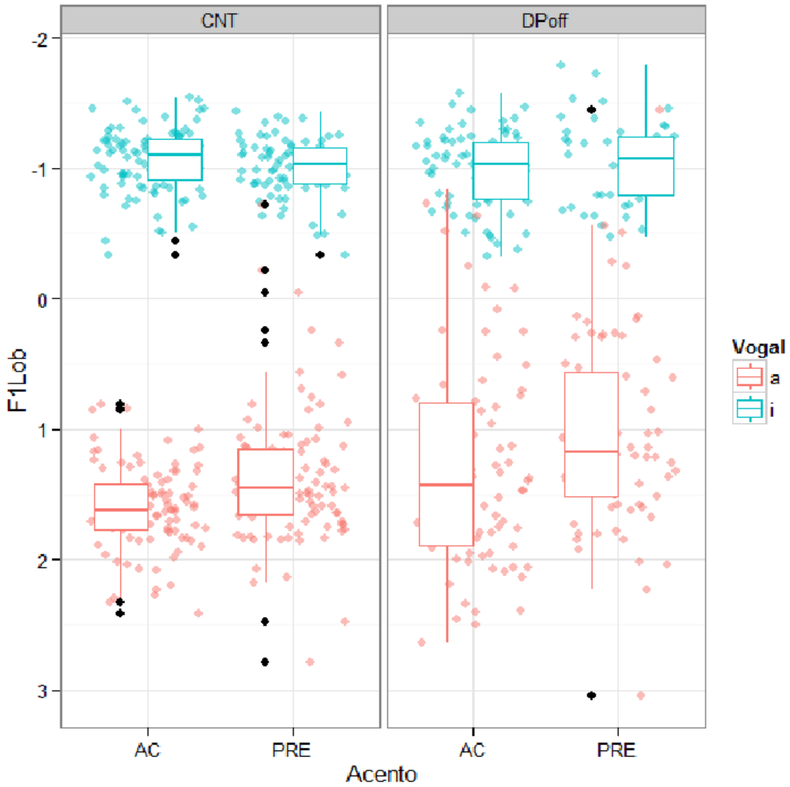

Figure 4 – Box plot and scatter graph (F1Lob) by group, vowel and accent

Looking at the distribution of f0 (Fig. 2), F1 (Fig. 4) and the estimates of the model for the control group (Fig. 3) together, it becomes clear that f0 and F1 go in the same direction, even though they are not related from a statistical point of view. For the vowel /a/, F1 values are higher, with the f0 values being lower than for the vowel /i/ in any stress condition. The difference between the vowels decreases in both sets of values in the pre-stressed condition compared to the stressed one. Finally, the difference between stressed and pre-stressed conditions – tested in the f0 model and here merely intuited for F1 values – is not significant, though the difference between the vowels always is. This leads to a question: why the similar behaviour, if different values are not associated by a common cause, for example, tongue height? If PD did not display the same association so clearly, it seems that the mechanical explanation does not sufficiently explain the change between the pre-stressed and stressed syllables for this group. Perhaps greater vocal folds tension is more important, as we know that the stressed syllable is the place in which intonational phenomena are marked. There are therefore reasons to believe that dysfunctional control of the vocal folds ends up exaggerating the effects of f0 in the stressed syllable, to the detriment of the pre-stressed. At the same time, and in both conditions, the phenomenon of IF0 is preserved.

Conclusions

This study aimed to investigate the existence of the IF0 phenomenon in the speech of dysarthric individuals suffering from idiopathic Parkinson's disease and compare the phenomenon in the speech of these individuals with participants from a control group. It also aimed to identify possible differences due to distinct stress conditions of syllables.

The first result to highlight is the presence of IF0 in Brazilian Portuguese, as already identified by Escudero et al. (2009). This difference was found although the prosodic/segmental environment was not controlled – a criticism levelled at Umeda (1981). The absence of IF0 in her work may be due to the fact that the research involved 20 minutes of reading recorded by just two participants, whose use of f0, according to Umeda herself, is clearly distinct (UMEDA, 1981, p. 350).

Secondly, IF0 was found not only in participants from the control group, but also in the speech of the PD group. The fact that we did not identify any significant difference between the groups supports the hypotheses that posit the automaticity of IF0. As the dysarthric participants have impaired motor control, the fact that they displayed IF0 without distinction from the participants from the control group suggests that the mechanism involved with the phenomenon is similar for both. It is worth recalling that dysarthria is a term applied to articulatory dysfunction due to neurological damage and not due to damage in the structure of articulators or vocal folds. In any case, we worked according to the premise that the PD participants display difficulties with fine motor control. It was still not possible to take into account possible compensatory mechanisms that could have led them to display speech similar to individuals in the control group.

Thirdly, no significant differences between pre-stressed and stressed syllables were found in the group with full motor control. This suggests that if Kingston's (2007) reasoning can be extended to the lexical stress of Brazilian Portuguese, our data does not corroborate the hypothesis that greater importance of information affects IF0. Once again, the hypotheses which best correspond to our data are those that suggest IF0 is a passive phenomenon.

Finally, gender differences were not significant in F0Lob. This may indicate that this factor does not affect IF0, or it may be attributed to the transformation itself. In Hertz, the descriptive statistics showed a trend for IF0 to be less in male speech than in female speech in both groups. Here, we broaden the discussion in the research about the reduction of IF0 in low pitch environments, arguing that a range of lower frequencies (in the case of the male tessitura) may lead to a lower IF0 in Hertz.

In conclusion, this study obtained results which support the view of IF0 as a passive phenomenon; in other words, as a by-product of articulations intended to achieve a certain vocalic quality, without IF0 itself being intended. Nonetheless, our data does not permit us to clearly identify which biomechanical mechanism would be the best causal explanation for the differences between high and low vowels, though it suggests that tongue height is relevant.

Artigo recebido: 13/10/2015

Artigo aceito: 19/10/2015

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