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How language flows when movements don't: An automated analysis of spontaneous discourse in Parkinson's disease

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ABSTRACT

To assess the impact of Parkinson's disease (PD) on spontaneous discourse, we conducted computerized analyses of brief monologues produced by 51 patients and 50 controls. We explored differences in semantic fields (via latent semantic analysis), grammatical choices (using part-of-speech tagging), and word-level repetitions (with graph embedding tools). Although overall output was quantitatively similar between groups, patients relied less heavily on action-related concepts and used more subordinate structures. Also, a classification tool operating on grammatical patterns identified monologues as pertaining to patients or controls with 75% accuracy. Finally, while the incidence of dysfluent word repetitions was similar between groups, it allowed inferring the patients' level of motor impairment with 77% accuracy. Our results highlight the relevance of studying naturalistic discourse features to tap the integrity of neural (and, particularly, motor) networks, beyond the possibilities of standard token-level instruments.

1. Introduction

Affecting more than 1% of individuals above age 60, Parkinson's disease (PD) is the second most prevalent neurodegenerative disease worldwide (de Rijk et al., 2000; Samii, Nutt, & Ransom, 2004). It is characterized by progressive basal ganglia degeneration and dopamine depletion, which disrupts corticostriatal circuits involved in motor function and multiple high-level cognitive domains (Fearnley & Lees, 1991; Mattay et al., 2002; McKinlay, Grace, Dalrymple-Alford, & Roger, 2010; Muslimovic, Post, Speelman, & Schmand, 2005; Rodriguez-Oroz et al., 2009). Thus, the impact of PD goes well beyond the presence of movement disorders (Mattay et al., 2002; Svenningsson, Westman, Ballard, & Aarsland, 2012).

This is particularly evident in linguistic performance. Indeed, articulatory disorders in PD (Goberman & Blomgren, 2003; Goberman, Blomgren, & Metzger, 2010) are often accompanied by impairments in grammar (Bocanegra et al., 2015; Hochstadt, Nakano, Lieberman, & Friedman, 2006; Lieberman et al., 1992), pragmatics (Holtgraves & McNamara, 2010; Monetta & Pell,

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2007), verbal fluency (Raskin, Sliwinski, & Borod, 1992), and action-verb semantics (García & Ibáñez, 2014a; Bak, 2013; Bocanegra et al., 2015; Cardona et al., 2013). While these findings are quite revealing about the physiopathology of PD, it is hard to assess their impact in real life, since they stem from highly artificial tasks in which disconnected stimuli are processed in random or arbitrary succession. Also, the active demands of such often exhausting tasks render them limited as tools for prospective diagnosis criteria.

Our aim was to address both issues using automated tools. Specifically, we examined whether PD patients exhibit distinguishing discourse-level features as they produce naturally unfolding texts. This process, termed logogenesis, is based on the accumulation of interrelated lexico-grammatical selections which create distributed patterns above the word and sentence levels (Halliday & Matthiessen, 2004). Insights into this dynamic process could afford a more ecological understanding of how this disease impacts verbal communication.

2. Background and hypotheses

Discourse production involves construing supra-sentential textual relations and deploying diverse communicative strategies (Halliday & Matthiessen, 2004). Emergent distributed patterns can be detected by considering semantic fields, lexicogrammatical choices, and relations between adjacent or neighboring words (Bedi et al., 2014, 2015; Mota, Furtado, Maia, Copelli, & Ribeiro, 2014; Mota et al., 2012). Analyses of these and other text-level variables have revealed population-specific patterns in various neurological disorders, such as frontotemporal dementia (Ash et al., 2006) and aphasia (Fergadiotis & Wright, 2011). However, evidence on altered discourse-level patterns in PD has been produced sparsely.

Relative to controls, PD patients produce similar amounts of verbal output during spontaneous speech (Illes, 1989; Illes, Metter, Hanson, & Iritani, 1988; Murray, 2000; Murray & Lenz, 2001; Vanhoutte, De Letter, Corthals, Van Borsel, & Santens, 2012). Yet, they exhibit more digressive grammatical choices (e.g., open phrases around the main clause) (Illes, 1989; Illes et al., 1988) and construe less informative (Murray, 2000) and concise (McNamara & Durso, 2003) texts. Finally, they find it difficult to self-monitor and correct output errors (McNamara, Obler, Au, Durso, & Albert, 1992). Indeed, iteration of syllables and words in PD proves more common in advanced disease stages, irrespective of medication (Benke, Hohenstein, Poewe, & Butterworth, 2000).

Though highly valuable, this evidence is scant, based on rather small samples, and rooted in subjective impressions of a few examiners. These limitations can be partly circumvented by conducting *automated* analyses of spontaneous texts produced by large groups. In previous works, computerized analysis of free speech robustly discriminated methamphetamine users from ecstasy users and controls by detecting differential conceptual fields (Bedi et al., 2014). Those same methods, complemented with grammatical analyses, predicted future psychosis in young individuals (Bedi et al., 2015). Also, speech-graph measures captured distinctive discourse patterns (e.g., logorrhea, divergent and recurring thought patterns) in varied populations. For example, they sorted schizophrenics from maniacs (Mota et al., 2012) and bipolar subjects from schizophrenics and controls (Mota et al., 2014).

Here we examined the extent to which PD patients and controls can be discriminated and classified via the abovementioned tools. To create stringent assessment conditions, we considered only brief monologues (around one minute per participant). We specifically tested hypotheses regarding the emergence of semantic fields, the incidence of distinctive grammatical features, and word-repetition patterns. First, motor diseases involve distinctive deficits in processing action language, that is, verbal stimuli denoting motor actions, including idioms (e.g., *cut a rug*) and action verbs (e.g., *clap*), with relative preservation of words which do not necessarily involve physical movements, such as cognitive or affective verbs (e.g., *see*, *feel*) or nouns (e.g., *chair*) –for a review, see García and Ibáñez (2014a, 2016). Thus, we expected PD patients to rely less heavily on action- than non-action-related semantic fields. Also, based on evidence from discourse-level studies, we hypothesized that they would favor digressive, clause-peripheral constructions. Third, we expected word repetitions to positively correlate with disease severity.

3. Methods

3.1. Participants

The study included 51 non-demented PD patients (25 female) and 50 healthy controls (25 female) from the PC-GITA database (Orozco-Arroyave, Arias-Londoño, Vargas-Bonilla, González-Rátiva, & Nöth, 2014). All participants were monolingual Spanish speakers from Colombia. The patients had a mean age of 61.45 (*SD* = 9.77), with 10.71 (*SD* = 4.2) years of education. Mean values for these variables in the control sample were 60.9 (*SD* = 9.47) and 10.98 (*SD* = 4.54), respectively. Both groups were matched for age [$t(99) = -0.2878, p = 0.77$], education level [$t(99) = 0.3153, p = 0.75$], and gender [$\chi2\,(1) = 137.9145, p = 0.99$]. Clinical diagnosis of PD was made by an expert neurologist (LM) in accordance with the United Kingdom PD Society Brain Bank criteria (Hughes, Daniel, Kilford, & Lees, 1992). Motor impairments were assessed with Section 3 of the Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS-III) (Goetz et al., 2008). Disease stage was rated with the Hoehn & Yahr (H&Y) scale (Goetz et al., 2004). Mean scores for the PD sample were 38.71 (*SD* = 19.61) in MDS-UPDRS-III and 2.2 (*SD* = 0.7) in H&Y. At the time of testing, the patients' mean years post-diagnosis was 11.18 (*SD* = 9.16). A phoniatric assessment indicated that most patients presented only intermediate levels of dysarthria, some had only very minor signs, and none exhibited severe symptoms. All patients were evaluated during the "on" phase of their medication –i.e., no more than three hours after intake. They were recruited from a larger patient population in Medellín with well-established language disorders (Bocanegra et al., 2015; Cardona et al., 2013; Melloni et al., 2015; Orozco-Arroyave et al., 2016a). None of them presented with other neurological disorders or major psychiatric conditions, which were also absent in controls.

All participants gave written informed consent. The study was carried out in accordance with the Declaration of Helsinki and it was approved by the Ethical Research Committee of Antioquia University's Faculty of Medicine. Additional participant data can be found in Table 1.

3.2. Data collection

3.2.1. Discourse samples

Participants were asked to describe a typical day in their lives, speaking at their normal rate, pitch, and loudness. Their narrations were audio-recorded in a soundproof booth via a Shure SM63L dynamic omnidirectional microphone and a M-Audio Fast-Track computer audio interface, which offers high output for professional applications. All audio files were created on Cool Edit Pro 2.0 and sampled at 44,100 Hz with a resolution of 16 bits. The average duration of the monologues was 45 (*SD* = 24) and 48 (*SD* = 29) seconds for controls and PD patients, respectively.

Table 1
Demographic and clinical data for patients and controls.

	PD patients	Controls	Patients vs. controls
Gender [F/M]	26/25	25/25	$p = 0.99$[a]
Age [F/M]	61.1 (11.4)/60.7 (7.2)	60.4 (11.6)/61.4 (7)	$p = 0.77$[b]
Education [F/M]	10.5 (4.4)/11 (4.1)	10.5 (4.4)/11.4 (4.7)	$p = 0.75$[b]
Years diagnosed [F/M]	9.2 (5.7)/13 (11.6)		
MDS-UPDRS-III [F/M]	38.3 (22)/37.6 (14)		
H&Y [F/M]	2.1 (0.7)/2.2 (0.6)		

Notes: Values are expressed as mean (*SD*). PD = Parkinson's disease; F = female; M = male; MDS-UPDRS-III = Unified Parkinson's Disease Rating Scale, part III; H&Y = Hoehn & Yahr scale.

[a] *p* value calculated through chi-square test ($\chi 2$).

[b] *p* values calculated through *t* tests for independent samples.

The resulting 101 audio monologues were transcribed verbatim on word-processing software and coded to match their corresponding (anonymized) participant. Each recording was replayed on headphones as many times as necessary to maximize transcription accuracy. Transcribed texts were punctuated following standard norms of the Real Academia Española (http://www.rae.es/). Importantly, full stops were used exclusively as inter-sentential separation markers, signaling boundaries between simple, complex, compound or even minor sentences (i.e., brief and oftentimes elliptic phrases lacking a verb). The very few instances of unintelligible words were highlighted and removed from the analysis. For further details regarding the transcription protocol, see Appendix A.

3.2.2. Neuropsychological assessment

A subset of 16 patients accepted our invitation to complete a neuropsychological evaluation tapping executive, semantic, and linguistic domains which may be affected since early disease stages (Goldman, Weis, Stebbins, Bernard, & Goetz, 2012; Ibáñez et al., 2013). Ensuing data were used to estimate the impact of disease in the patients and test our third hypothesis (Section 4.4). For full details, see Appendix B.

3.3. Extraction of language features through automatized analyses

We analyzed the monologues following previously reported methods (Bedi et al., 2014, 2015; Mota et al., 2012). We first preprocessed the transcriptions through lemmatization and tokenization, and then extracted features derived from latent semantic analysis (LSA), part-of-speech tagging (POS-Tag), and graphic embedding, as described below.

3.3.1. Analysis of semantic fields

Textual meaning is characterized by the emergence of semantic fields, that is, conceptual spaces which are distributed throughout discourse and arise from mutual dependencies of words (Cancho & Solé, 2001; Sigman & Cecchi, 2002). We examined these fields in each group via LSA (Deerwester, Dumais, Furnas, Landauer, & Harshman, 1990), a method which generates a linear representation of the words' conceptual associations. The input to LSA is a word-by-document occurrence matrix X, with each row corresponding to a unique word in a corpus (N total words) and each column corresponding to a document (M total documents). We worked with a corpus compiled by Touchstone Applied Science Associates (TASA), featuring a vocabulary of 77,998 different words.

Using Singular Value Decomposition (SVD), we reduced the dimensionality of the matrix to a smaller number of columns, preserving as much as possible the similarity structure between rows. Each word was then projected onto a space. In this space, the meaning of a word is indexed by its corresponding vector. We measured the similarity in meaning between two words (or semantic proximity) by calculating the cosine between the corresponding vectors. Since the vectors were normalized, the range of possible values for the similarity measure was $(-1, 1)$. For each monologue, we computed the proximity between each word and each of the other words in the lexicon, and binarized it to $\{0, 1\}$ depending on whether the distance was above a threshold of 0.15. Each monologue was then represented by a vector of dimension 77,998, in which the value of each coordinate is the mean binarized distance, over the entire monologue, for the corresponding word (Bedi et al., 2014).

The resulting SVD components represent independent combinations of the semantic vectors across all the words in the TASA lexicon. They can thus be considered 'topics', where some words (those with positive weight) are more relevant, while others (those with negative weights) are less relevant. We used SVD to factorize the list of 77,998-dimensional vectors corresponding to all the monologues. We then computed group differences for the projections of each monologue onto a few top SVD factors. For those showing statistical differences, we listed a set of words that contributed strongly to the factor (both positively and negatively).

Also, to obtain a more stringent statistical characterization, we implemented a predictive modeling scheme. We used a Support Vector Machines with Radial Basis Function kernel (SVM-RBF) as classifier, with leave-one-out cross-validation (LOOCV). As in the group analysis, we performed SVD on the training set, retaining the first four components to obtain the best classification accuracy. We thus explored the extent to which a new monologue, not previously identified as belonging to PD patients or controls, could be accurately classified as pertaining to either group. For further details, see Appendix C.

3.3.2. Analysis of grammatical features

Grammatical features were analyzed via the POS-Tag method. We labeled each word in the monologues by its grammatical function, using the Spanish module of the University of Stuttgart's Tree Tagger (Schmid, 1994). For example, the sentence *The prophet cries* would be tagged as [('The', 'DT'), ('prophet', 'NN'), ('cries', 'VBZ')], designating a determiner, a noun, and a verb, respectively. Differences in tag frequency between groups reflected greater or lesser reliance on a given feature. Furthermore, as with semantic features, we utilized a LOOCV scheme for classification purposes. For further details, see Appendix D.

3.3.3. Analysis of word repetitions

The incidence of word repetitions was analyzed via graph-embedding tools. Individual words were considered as nodes in a network, with their links representing grammatical or semantic relationships between nodes. The resulting graphs were analyzed for several topological features. We focused on the number of nodes mediating two occurrences of the same word, namely, loops. In particular, we looked for words or short phrases repeated in succession (L1 loops: e.g., *When, when*...), with one other word in between (L2 loops: e.g., *When I, when*...), or with two other words in between (L3 loops: e.g., <u>When</u> *I see*, <u>when</u>...). We identified differential graph-embedding features between the groups, and explored their correlation with the test scores of patients who underwent a full neuropsychological evaluation. The graph-embedding and clinical/neuropsychological measures yielding the highest correlation were kept to learn an inference model on $N-1$ samples. We tested this model on each left-out sample, repeating the process N times, to calculate the cross-validated inference accuracy of the correlation. For further details, see Appendix E.

4. Results

4.1. Quantitative output

The monologues of each group were compared for basic linguistic attributes, namely, total word count, and number of content words, nouns, verbs, action verbs, non-action verbs, and type/token ratio, indicating that quantitative output was similar for both groups (Table 2).

4.2. Semantic fields

LSA measures revealed significant between-group differences in the second [Wilcoxon: $Z = 2.12$, $p = 0.03$; t-test: t $(99) = 2.7$, $p = 0.008$] and third [Wilcoxon: $Z = 1.94$, $p = 0.05$; t-test: t $(99) = 2.5$, $p = 0.01$] semantic components. As shown by Spearman's rank correlations, neither of those components was associated with age (second component: $r = 0.29$, $p = 0.27$; third component: $r = 0.29$, $p = 0.27$) or education level (second component: $r = 0.27$, $p = 0.32$; third component: $r = 0.11$, $p = 0.69$). We then identified the words that figured more and less prominently (top and bottom words, respectively) in PD patients, labeling the word class of the original Spanish words as follows: noun [n], verb [v], adjective [adj], and adverb [adv]. For the second component, the top words were *read* [v], *reading* [v], *like* [v], *book* [n], *years* [n], *life* [n], and *say* [v], whereas the bottom ones were *play* [v], *game* [n], *get* [v], *well* [adv], *make* [v], *take* [v], and *work* [v]. For the third component, the top words were *home* [n], *help* [v], *around* [adv], *color* [n], *red* [adj], *make* [v], and *day* [n], while the bottom ones were *game* [n], *play* [v], *work* [v], *house* [n], *walk* [v], *read* [v], and *three* [adj]. Taken together, these patterns show that while action-related domains (e.g., PLAY, GET, TAKE, WORK, WALK) figured less prominently in patients than in controls, the opposite was true of non-action domains (e.g., READ, LIKE, SAY, SEE) (Fig. 1).

We further analyzed the semantic component shown in Fig. 1 via two alternative methods. First, we estimated the LSA semantic vectors best and worst aligned with the component (using vector dot product), which yielded PLAY and READ, respectively. This resulted from combining the semantic vectors corresponding to the concepts listed in the figure with their respective weights (we actually used all of the concepts, not just the top ones). Given that PLAY and READ figured less and more prominently in the patients, respectively, this reinforces the dissociation we proposed along the action/non-action distinction.

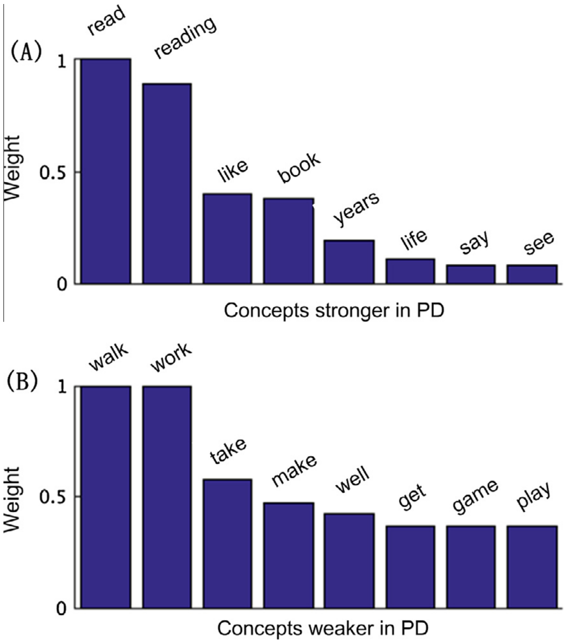

Fig. 1. Most discriminating concepts between Parkinson's disease (PD) patients and controls in the second SVD semantic component. (A) Weights of the eight top (strongest) concepts in PD. (B) Weights of the eight bottom (weakest) concepts in PD. Group discrimination is significant for both the Wilcoxon test and the t-test.

Table 2
Quantitative output measures in patients and controls.

	PD patients	Controls	Patients vs. controls
Total word count	92.75 (46.53)	99.32 (68.86)	$p = 0.57$[a]
Content words	43.76 (19.65)	47.22 (29.25)	$p = 0.49$[a]
Nouns	14.88 (7.41)	16.26 (10.45)	$p = 0.44$[a]
Verbs	15.63 (7.61)	17.24 (10.9)	$p = 0.39$[a]
Action verbs	8.06 (4.78)	8.9 (6.93)	$p = 0.48$[a]
Non-action verbs	7.57 (5.79)	8.34 (5.78)	$p = 0.5$[a]
Type/token ratio	38 (20)	44.5 (27.45)	$p = 0.18$[a,b]

Notes: Values are expressed as mean (*SD*). PD = Parkinson's disease.
[a] p values calculated through t tests for independent samples.
[b] For further details concerning the type/token ratio results, see Appendix F.

Additionally, we measured the similarity of the component to specific concepts that prove relevant to our interpretation, namely PERCEPTION and LOOKING (as prototypical non-action concepts), and ACTION and ACTING (as prototypical action concepts). The similarity, as in the procedure above, is measured through vector dot product, resulting in a value for PERCEPTION and LOOKING of 0.012 and −0.017, respectively, and of 0.065 for both ACTION and ACTING. Given that the expected mean value and standard deviation for the dot product of two random vectors of dimensionality n are 0 and 1/sqrt(n), respectively, and that in this case ($n = 300$) the latter corresponds to 0.057, the semantic component is clearly different from both sets of concepts. As this analysis includes the differential weights shown in Fig. 1, it corroborates that significant differences between patients and controls reflect the weight of action and non-action concepts in their monologues.

To further explore these statistical differences, we implemented a LOOCV scheme. Learning of model parameters was performed on $N-1$ samples ($N = 101$), and the model was then tested on the left-out sample. The process was repeated N times (i.e., each sample was eventually tested) and the resulting average was the expected classification accuracy. To avoid "leakage" of left-out samples, we conducted a calculation over the training set (i.e., without the test sample), and projected the test sample on the resulting SVD components 1–3, or 1–4. The best classifier was SVM-RBF, which yielded an accuracy of 63% using three components, and 66% using four components. Thus, classification accuracy based on differential semantic fields proved only moderately acceptable. For further details, see Appendix G.

4.3. Grammatical features

Three grammatical features significantly discriminated between groups. Patients exhibited greater use of subordinating conjunctions introducing finite clauses, such as *porque* [*because*]

(Wilcoxon: $Z = 3.15$, $p = 0.001$); subordinating conjunctions underspecified for type, such as *aunque* [*although*] (Wilcoxon: $Z = 3.15$, $p = 0.027$); and negation markers, such as *no* [*not*] (Wilcoxon: $Z = 2.29$, $p = 0.021$). Instead, the following top two discriminating features appeared less frequently in patients than in controls, but they showed only a trend toward significance. These were proper nouns (Wilcoxon: $Z = 1.94$, $p = 0.051$) and inter-sentential separation markers, graphically manifested as full stops (Wilcoxon: $Z = 1.86$, $p = 0.062$).

We used the five features above to implement a classification scheme similar to the one based on semantic features. The left-out sample was projected on the components obtained on the training set, and fed into the classifier model for label prediction. We tried several models. The best result, 75% accuracy (over a 50.5% baseline), was obtained with a KNN model with three neighbors and Chebyshev distance. Other models achieved a lower but similar accuracy, indicating that the feature-based classification is robust and to some extent model-independent. The complete list is show in Table 3 (for further details, see Appendix G).

In sum, relative to controls, PD patients used more subordinating conjunctions and negative markers. Also, joint consideration of these elements and two others nearly missing significance afforded a classification accuracy of up to 75%.

4.4. Word and short-phrase repetitions

Between-group comparisons showed no differences in the number of L1 [Wilcoxon: $Z = 1.3742$, $p = 0.17$; $t(99) = 1.2038$, $p = 0.23$], L2 [Wilcoxon: $Z = 0.8278$, $p = 0.40$; $t(99) = 0.6665$, $p = 0.50$], L3 [Wilcoxon: $Z = 0.41292$, $p = 0.68$; $t(99) = -0.17923$, $p = 0.86$], or L4 [Wilcoxon: $Z = 0$, $p = 1$; $t(99) = -0.3678$, $p = 0.71$] loops. Thus, patients and controls produced a similar number of dysfluent word-level repetitions.

However, previous results by Benke et al. (2000) indicated that the frequency of repetitions *within* PD samples could be related to disease severity or level of cognitive dysfunction. To explore this possibility, we considered data from the 16 patients who agreed to complete a clinical and neuropsychological evaluation (see Section 3.2.2). This sub-sample had a mean age of 60.1 ($SD = 11.97$) and 11.6 years of education ($SD = 11.97$). At the time of testing, the patients had been diagnosed for 7.08 years ($SD = 3.6$). The average duration of their monologues was 45 ($SD = 24$) seconds. The patients' scores on each measure are detailed in Appendix H.

Prior to performing the correlations, one patient was detected as an outlier and excluded from the analysis. Out of all clinical and neuropsychological measures, only three showed at least one significant correlation with the loop features (L1, L2, L3, L4) at $p < 0.05$. However, the only one reaching significance at $p < 0.001$ was MDS-UPDRS-III. Statistics for these correlations are provided in Table 4.

As seen in Table 4, the two loop features showing robust correlations with MDS-UPDRS-III scores were L1 and L3. Close inspection of the patients' monologues confirms the dysfluent nature of these word-level repetitions, as seen in instances of both L1 loops (patient 11: *hago <u>el</u>, <u>el</u> desayuno* [literally, *I make <u>the</u>, <u>the</u> breakfast*]), and L3 loops (patient 3: *Hace <u>unos</u> días <u>hacemos unos</u>, estábamos <u>haciendo</u> unos, unos portavasos* [literally, *A few days ago <u>we made</u> some, <u>we</u> /were/ <u>making</u> some, some cup holders*]). Fig. 2a shows the loops involved in the latter example.

Table 3
Classification accuracy based on the top five grammatical features.

Model	Accuracy (%)
KNN with Chebyshev distance	75
SVM-RBF	72
Ada Boost	68
LDA	66
Naïve Bayes	58

Table 4
Significant correlations between loop features and clinical/neuropsychological measures.

Measure	L1 loops	L2 loops	L3 loops	L4 loops
MDS-UPDRS-III	$r = 0.77$ $p < 0.001$	$r = 0.36$ $p = 0.17$	$r = 0.63$ $p = 0.01$	$r = 0.45$ $p = 0.08$
IFS numerical WM	$r = 0.23$ $p = 0.39$	$r = 0.54$ $p = 0.03$	$r = 0.51$ $p = 0.05$	$r = 0.48$ $p = 0.06$
IFS spatial WM	$r = 0.05$ $p = 0.85$	$r = 0.39$ $p = 0.14$	$r = 0.52$ $p = 0.04$	$r = 0.32$ $p = 0.23$

Notes: The r and p values were computed using Pearson's correlation; MDS-UPDRS-III = Unified Parkinson's Disease Rating Scale, part III; IFS = INECO Frontal Screening; WM = working memory.

Given the clinical relevance of the MDS-UPDRS-III as an index of motor dysfunction, we implemented a LOOCV inference scheme. That is, we learned an inference model on $N - 1$ samples ($N = 15$), and tested it on the left-out sample, repeating the process N times. We considered only L1 and L3 features. For each training set, we estimated a linear model as MDS-UPDRS-III = c_1 L1 + c_3 L3, which we then applied to the left-out sample. The Pearson correlation of the inferred values with the actual values of was high ($r = 0.77$, $p = 0.0008$). This indicates that the incidence of dysfluent word-level repetitions allowed inferring the level of motor impairment with an accuracy of 77% (Fig. 2b).

In sum, measures of dysfluent word-level repetitions revealed no difference between patients and controls. However, the patients' level of motor compromise correlated with and could be inferred from the incidence of such dysfluencies.

5. Discussion

5.1. Discourse patterns at the semantic level

Despite moderate predictive success, analysis of semantic fields robustly discriminated between groups. Action-related domains figured less strongly in patients than controls, whereas non-action concepts showed the opposite pattern. Greater impairments in action- than non-action language have been repeatedly observed in PD through controlled, atomistic tasks, including picture naming (Rodriguez-Ferreiro, Menendez, Ribacoba, & Cuetos, 2009), related-word production (Peran et al., 2003), and lexical decision (Boulenger et al., 2008). Importantly, this differential deficit occurs even when action verbs are compared with abstract verbs (Fernandino et al., 2013; Kemmerer, Miller, Macpherson, Huber, & Tranel, 2013), which rules out the possibility that the effect is driven by verbs as a general lexical class. Our data extend these findings by showing diminished reliance on action-related semantic fields *distributed throughout* naturally produced texts.

Action-language impairments in PD and other motor disorders lend support to the embodied cognition framework, which posits that high-level cognitive processes are rooted in lower-level sensorimotor networks (Barsalou, 1999; Gallese & Lakoff, 2005). Following this view, we propose that motor network damage may impact the overall semantic makeup of spontaneous discourse by reducing the relative weight of action-related concepts. Thus, a text's overarching semantic structure may give hints about the integrity of specific embodied mechanisms.

This dissociation was confirmed by a hypothesis-driven comparison between the weight of prototypical action and

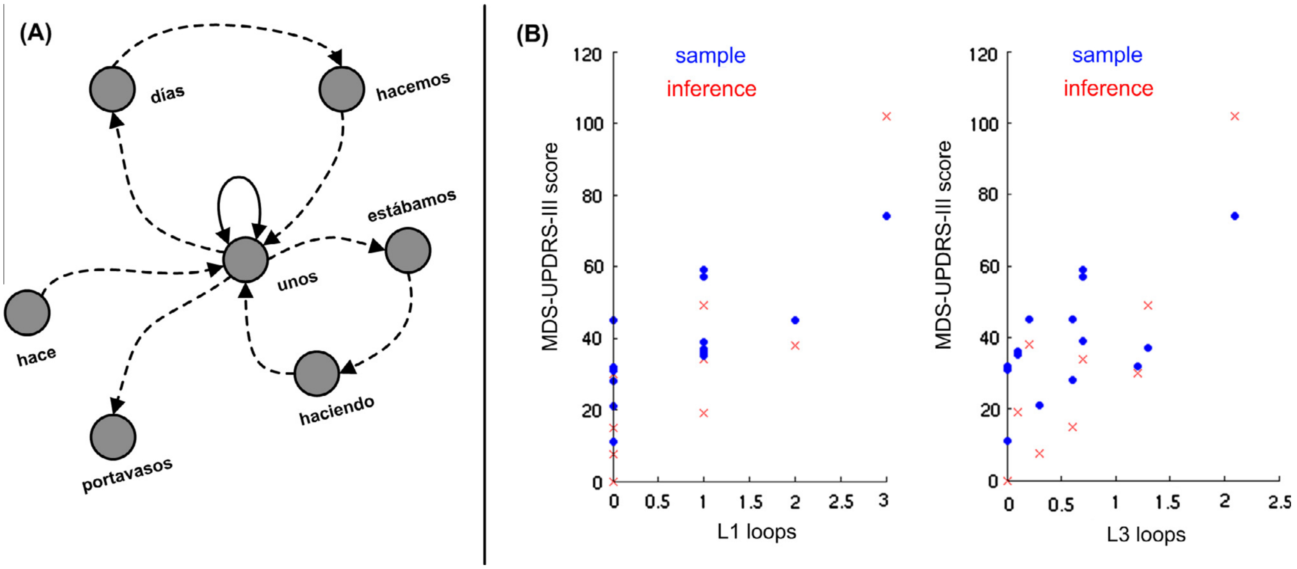

Fig. 2. (A) Example of L1 and L3 loops in a patient's monologue (*Hace unos días hacemos unos, estábamos haciendo unos, unos portavasos*). Bold line: L1 loops; dotted lines: L3 loops. (B) Comparison of inferred and actual values based on the mean model (over all the folds) mapping L1 and L3 loops to the patients' MDS-UPDRS-III scores.

non-action related concepts: whereas PERCEPTION and LOOKING were significantly more prominent in patients than in controls, the opposite was true of ACTION and ACTING. This further indicates that action language is grounded in motor networks (Gallese & Lakoff, 2005), and that damage to such circuits may selectively impair relevant semantic domains, with relative preservation of other domains whose experiential basis is not compromised by the disease (Bak, 2013).

Note, however, that the analysis of semantic fields offered only moderate classification precision. This may partially reflect the fact that the semantic clusters yielding the most robust between-group differences were not *exclusively* rooted in the action vs. non-action distinction; for example, the clusters figuring less prominently in patients also included non-action concepts, which do not typically discriminate PD samples from controls (García & Ibáñez, 2014a). This is not surprising given that we employed an ecological, discourse-level task. While artificial, token-level paradigms can offer contrasting stimulus sets composed entirely of either action or non-action words (Boulenger et al., 2008; Fernandino et al., 2013; Kemmerer et al., 2013; Peran et al., 2003), both types of unit become seamlessly integrated in spontaneous discourse. Indeed, the fact that a broad separation between action and non-action language significantly discriminated between groups and offered considerable classification accuracy even in the absence of pre-controlled experimental manipulations attests to the widespread linguistic impact of disruptions in embodied mechanisms.

There is yet another way in which the nature of our task may have influenced these results. Participants described their activities during a typical day, and it is probable that PD patients engage in fewer motor actions than controls. While this may partially explain the differential presence of action-related semantic fields, the total output of action and non-action verbs (as well as the total word count and type/token ratio) was similar for both groups. Furthermore, most patients were in early disease stages, where motor function is not severely compromised, and they were pharmacologically compensated – a non-trivial consideration, given that levodopa intake in word-level tasks not only favors overall semantic processing (Angwin, Copland, Chenery, Murdoch, & Silburn, 2006; Herrera & Cuetos, 2012), but also leads to differential improvements in processing of action verbs (Boulenger et al., 2008; Herrera, Cuetos, & Ribacoba, 2012). These observations undermine the potential shortcoming just identified, while reinforcing our interpretation. Indeed, in a previous study on spontaneous speech, distance from concepts such as EMPATHY and COMPASSION discriminated individuals on placebo from ecstasy and methamphetamine users (Bedi et al., 2014). By the same token, we propose that the relative weight of action- and non-action-related concepts along distributed semantic fields may capture meaningful aspects of the PD patients' situated experience.

5.2. Discourse patterns at the grammatical level

Our patients made more extensive use of subordinating conjunctions and dependent clauses, introducing varied temporal, adversative, and conditional qualifications to the information realized by the main clause (e.g., *veo televisión, porque a mí me gusta (sic) mucho las manualidades y no lo puedo hacer* [literally, *I watch TV, because I like crafts a lot and I can't do it*]). Discourse in PD patients has been noted to feature a significant increase in the use of "optional phrases which supplement the principal clause [...] with additional information" (Illes et al., 1988: 156). It is also characterized by lack of conciseness (McNamara & Durso, 2003) and an overabundance of irrelevant information (Murray, 2000). In line with Illes et al. (1988), we propose that increased reliance on peripheral information may reflect an unconscious adaptive strategy to keep the flow of communication while compensating for other functional difficulties in working memory or other executive domains (Bocanegra et al., 2015; Lee, Grossman, Morris, Stern, & Hurtig, 2003; Maddox, Filoteo, Delis, & Salmon, 1996). Data from the patients who underwent neuropsychological assessment corroborates this claim. Indeed, the use of subordinators in this subsample negatively correlated with spatial working memory ($r = -0.53$, $p = 0.04$) and global working memory ($r = -0.56$, $p = 0.03$) scores. Thus, the worse the patients' working memory skills, the greater their reliance of subordinators.

Between-group differences were also observed in the use of negative markers. While research on linguistic negation in motor disorders is virtually null, relevant evidence comes from individuals featuring frontal brain lesions and contralateral paresis or hemiplegia. Similar comprehension of negative and affirmative sentences has been reported in non-fluent aphasics (Bebout, 1993) and agrammatic patients (Rispens, Bastiaanse, & van Zonneveld, 2001). The absence of reduced use of negation in our

PD group aligns with such reports. However, the key observation is that patients in the present study produced *more* negative markers than controls. Upon scrutinizing the monologues, we noticed that several of their negative sentences referred to what they were no longer able to do (e.g., *colaboro en la casa a arreglar la cocina, porque no puedo trapear* [literally: *I help at home tidying the kitchen, because I cannot do any mopping*]; see also the excerpt cited in the previous paragraph). This is yet another demonstration of how automatized discourse analysis proves sensitive to disease-related changes in the patients' lives.

Of course, a strictly grammatical analysis does not suffice to show an association between the physiopathology of PD and specific patterns in the use of negations. However, deep brain stimulation of the subthalamic nucleus in PD patients can have a differential effect on positive and negative sentences, suggesting a distinct role of basal ganglia circuits in negation processing (Tomasino et al., 2014). Future studies combining stimulation protocols and naturalistic tasks could shed valuable light on the issue.

Though only marginally significant, differences were also observed in the use of proper nouns. Close inspection of the monologues revealed that the controls' more extensive use of these words mainly involved names of cities, buildings, and companies. In line with our embodied rationale, this pattern arguably reflects distinctive situated features of the subjects' experiences: whereas PD patients tend to be confined to only a few places due to their motor disability, controls tend to commute more often to meet their daily responsibilities.

Another trend concerned inter-sentential separation markers, which figured more frequently in controls. As explained above, these features exclusively signaled separation between sentences of any kind. This implies that PD patients tended to produce fewer sentences than controls, which reasonably ties in with our claim their sentences are longer and less concise – as noted in previous research (Illes et al., 1988; McNamara & Durso, 2003; Murray, 2000).

Note that the patients' discourse was produced during the "on" phase of medication, which enhances basal ganglia signaling to regions specialized for grammatical processing, such as Broca's area (Ullman, 2006). Previous reports on PD have shown that dopamine improves comprehension of sentences (McNamara, Krueger, O'Quin, Clark, & Durso, 1996), even if these include complexities such as subordinate phrases (Grossman, Carvell, Stern, Gollomp, & Hurtig, 1992). While there seems to be no evidence on the effect of dopamine on discourse production, transient enhancement of dopaminergic pathways via deep brain stimulation of the subthalamic nucleus and the pedunculopontine nuclei has been observed to reduce grammatical errors in PD patients during a story generation task (Zanini et al., 2009). Thus, it is likely that our patients' performance was influenced by the bioavailability of dopamine, which could partially explain their preserved quantitative output and vast grammatical repertoire.

Finally, the differences involving these five features allowed predicting the presence of PD with 75% accuracy. This figure is much higher than the one obtained via semantic analyses and does away with the caveats framing the latter. Thus, the discursive profile of PD patients may be more precisely detected by considering grammatical rather than semantic aspects. Methodological and translational implications of this finding are discussed in Section 5.4.

5.3. Discourse patterns at the level of word repetitions

The incidence of word repetitions was similar for the PD group and controls. This result is not surprising. Unlike motor dysfluencies, which are distinctively prevalent in PD (Goberman et al., 2010), word-level repetitions normally occur in healthy individuals (Conture, 2001) and fail to discriminate them from patients (Goberman & Blomgren, 2003; Goberman et al., 2010).

Notwithstanding, L1 and L3 links increased in proportion to motor disability. This finding aligns with evidence that repetitive speech phenomena (including word-level palilalia) in PD become more frequent as disease progresses. In particular, Benke et al. (2000) observed that the prevalence of such iterations jumped from 6.9% in patients with a stable response to levodopa to 54.3% in those who had advanced PD and did not stably respond to medication. In the same vein, dysfluent speech patterns in this population have been observed to recede upon administration of levodopa (Koller, 1983; Leder, 1996) – but see Louis, Winfield, Fahn, and Ford (2001).

While we are unable to rule out articulatory problems as a partial influence of word-level repetitions, the latter may well reflect disturbances in higher-level, non-motoric factors (Benke et al., 2000; Goberman & Blomgren, 2003; Goberman et al., 2010). In fact, word cluttering has been proposed as a form of dysfluency different from stuttering, hallmarked by an irregular speech rate (St. Louis, 1992). In cases of extrapyramidal disease, repetitions of words or phrases may become compulsive and manifest as palilalias (Lebrun, 1996), as also observed in PD (Ackermann, Ziegler, & Oertel, 1989; Lebrun, 1996). More crucially, the absence of between-group differences weakens the possibility that the observed word-level repetitions follow from motor deficiencies.

Dysfluencies during spontaneous production in PD have been proposed to reflect attentional deficits (McNamara et al., 1992) or difficulties in lexical access or semantic and syntactic planning (Goberman et al., 2010). However, in our study, no executive or linguistic measure correlated with the incidence of repetitions. Other language domains are also compromised independently of executive dysfunction in PD. For instance, action-language deficits seem to constitute a *sui generis* disorder following basal ganglia damage (Bocanegra et al., 2015). Similarly, word-level dysfluencies in unfolding discourse may depend on the level of basal ganglia deterioration, above and beyond the patients' neuropsychological profile. Indeed, baseline dysfluency levels are altered upon stimulation of the subthalamic nucleus in PD patients (Burghaus et al., 2006; Thiriez et al., 2013; Toft & Dietrichs, 2011) and of the globus pallidus in patients with dystonia (Nebel, Reese, Deuschl, Mehdorn, & Volkmann, 2009).

Finally, the amount of word repetitions afforded an inference accuracy of 77% on MDS-UPDRS-III scores, revealing an intimate relation with the degree of motor disability – for similar findings based on articulatory measures, see Orozco-Arroyave et al. (2016b). This is an interesting result, especially since it was obtained with a LOOCV based on one-minute monologues. Much higher patient classification accuracy has been obtained in other populations with ten-minute speech samples (Mota et al., 2012). Still, the fact that word repetitions predicted motor compromise well above chance based on limited linguistic data highlights the potential of spontaneous discourse measures as a proxy of movement impairments in PD.

5.4. Methodological implications and potential applications

So far, language research on PD has markedly prioritized decontextualized atomistic tasks (for reviews, see García & Ibáñez, 2014a; Cardona et al., 2013). In addition, most discourse-level studies have focused on aggregate or proportional calculations of individual units (e.g., total words, communication units, cohesive markers) – e.g., Ellis, Crosson, Gonzalez Rothi, Okun, and Rosenbek (2015), Illes (1989), Illes et al. (1988), Murray (2000), Vanhoutte et al. (2012). However, there is a dearth of research on how PD affects the deployment of multilevel linguistic relations in unfolding discourse. Our study highlights the potential benefits of such an approach. For instance, while token-level counts of action and non-action verbs showed no differences between patients and controls, the assessment of semantic fields distributed throughout their texts discriminated both groups. The study of relationships among linguistic units can reveal informative patterns which are absent in the examination of the units themselves.

Automated analyses of speech alterations have significant advantages. First, they bypass the biases and bottlenecks of human-based text analysis. Second, they allow handling massive amounts of data without added financial or temporal costs. Third, they could be applied remotely and repeatedly to complement traditional clinical and neuropsychological assessment, offering a chance to monitor the progression of discourse patterns associated with medication dosage, psychiatric comorbidness, or brain stimulation procedures. This is not a trivial consideration given the economic burden implied by the worldwide growth of PD (de Rijk et al., 2000; Samii et al., 2004).

Finally, our findings have theoretical implications for neurolinguistics. Specifically, they underscore the role of basal ganglia circuits in language processing at large. Those structures seem to be related to the normal deployment of discursive relations in spontaneous speech. Accordingly, the functional contributions of the basal ganglia to language may reach further than acknowledged in extant models – see, for example, (Ardila, Bernal, & Rosselli, 2015; Grossman, Lee, Morris, Stern, & Hurtig, 2002; Hagoort, 2013, 2014; Ullman, 2004).

Previous accounts have separately highlighted the role of basal ganglia circuits in action semantics (Cardona et al., 2013), grammar (Ullman, 2004), fluency, and sequencing (Ardila et al., 2015). Our study integratively corroborates these associations, highlighting the central role of these networks in situated language processing. Above and beyond performance in atomistic tasks, basal ganglia integrity seems fundamental for the normal deployment of multidimensional textual relationships in unfolding discourse.

5.5. Limitations and avenues for further research

Our work features a number of limitations and prospects for further research. First, the accuracy of our predictive analysis, though above chance, is not sufficiently high and is probably not better than that achievable through other standard tools. However, analysis of longer speech samples may yield much better predictions (Bedi et al., 2014, 2015; Mota et al., 2012), provided sessions are not so long that they induce fatigue in the patients. Second, a replication of the study with story-retelling paradigms could circumvent the potential caveat introduced by our task instructions – also, throughout repeated testing, describing a typical day could become learned and repetitive, which may skew the results; thus, in longitudinal studies, different topics could be contemplated for each recording session. Third, beyond our current emphasis on strictly linguistic domains, further research should also explore whether alterations in these and other discourse-level patterns are related to non-linguistic dysfunctions, such as general deficits in hierarchical sequencing and processing of durational patterns (Kotz, Schwartze, & Schmidt-Kassow, 2009). Fourth, given previous demonstrations that boosting dopaminergic pathways enhances performance on certain language tasks, it would be interesting to explore the impact of levodopa or basal ganglia stimulation on both discourse comprehension and production measures. Also, our protocol did not include measures to differentiate patients in terms of motor symptomatology. Future studies should assess how this factor impacts present results (in particular, those concerning word repetitions). Moreover, in the quest of increased ecological validity, future studies should also examine whether the observed monologue-based patterns generalize to dialogue, the most naturalistic discourse situation (García & Ibáñez, 2014b). Finally, specific biomarkers could be identified by correlating any of our automatized measures with volumetric studies of basal ganglia atrophy, via voxel-based morphometry or other techniques –see Melloni et al. (2015).

6. Conclusion

The study of discourse phenomena in spontaneous speech offers an ecological window into language mechanisms. Here, using automatized tools, we found evidence for distinctive patterns in PD patients, as manifested in semantic fields, grammatical features, and word-level repetitions. Thus, the basal ganglia seem crucial for the deployment of multidimensional textual relationships in naturalistic discourse production. These insights could hardly have been reached via decontextualized atomistic tasks or through "armchair" text analysis. Future applications of our approach (ideally, with longer speech samples) could contribute to the characterization of communication profiles in different clinical populations, reveal the role of specific brain structures in naturalistic verbal processing, and inform situated models of language. In sum, we propose it is high time to complement experiments on how certain linguistic units are individually processed with computerized research on how language unfolds in the creation of texts.

Conflict of interest

None to declare.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandl.2016.07.008.

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