Parkinson's Disease Subtypes Identified from Cluster Analysis of Motor and Non-Motor Symptoms

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Abstract

Parkinson's disease is now considered a complex, multi-peptide, central and peripheral nervous system disorder with considerable clinical heterogeneity. Non-motor symptoms play a key role in the trajectory of Parkinson's disease, from prodromal premotor to end stages. To understand the clinical heterogeneity of Parkinson's disease, this study used cluster analysis to search for subtypes from a large, multi-centre, international, and well-characterized cohort of Parkinson's disease patients across all motor stages, using a combination of cardinal motor features (bradykinesia, rigidity, tremor, axial signs) and, for the first time, specific validated rater-based non-motor symptom scales. Two independent international cohort studies were used: (a) the validation study of the Non-Motor Symptoms Scale ($n = 411$) and (b) baseline data from the global Non-Motor International Longitudinal Study ($n = 540$). *k*-means cluster analyses were performed on the non-motor and motor domains (domains clustering) and the 30 individual non-motor symptoms alone (symptoms clustering), and hierarchical agglomerative clustering was performed to group symptoms together. Four clusters are identified from the domains clustering supporting previous studies: mild, non-motor dominant, motor-dominant, and severe. In addition, six new smaller clusters are identified from the symptoms clustering, each characterized by clinically-relevant non-motor symptoms. The clusters identified in this study present statistical confirmation of the increasingly important role of non-motor symptoms in Parkinson's disease heterogeneity and take steps towards subtype-specific treatment packages.

1 Introduction

Parkinson's disease (PD) is classically considered a motor disorder, with resting tremor, rigidity, and bradykinesia as its core features. However, the concept of PD has changed considerably in the last

few years, now prompting a revision of its diagnostic criteria to include non-motor symptoms (NMS) in the core parameters (Postuma *et al.*, 2015; Marras and Chaudhuri, 2016). There has been growing recognition that NMS in PD are caused by neurotransmitter pathway dysfunctions which involve both the central and peripheral nervous systems (Jellinger, 2012; Gjerløff *et al.*, 2015). The significant clinical heterogeneity of NMS in PD suggests the existence of specific non-motor subtypes (Marras and Chaudhuri, 2016; Sauerbier *et al.*, 2016).

Previous cluster analyses have already identified motor- and non-motor-based clusters in PD patients (e.g. van Rooden *et al.*, 2011; Erro *et al.*, 2013; Ma *et al.*, 2015; Pont-Sunyer *et al.*, 2015). Recently, it has been argued that the recent concept of non-motor endophenotypes of PD provides a stronger basis for subtyping, since these relate to the central pathophysiology of specific neurotransmitter systems and are therefore likely to remain stable over time (Marras and Chaudhuri, 2016). As such, several studies have explored PD subtypes while considering motor subtypes and their association with non-motor aspects of the disease such as psychopathology and cognition (Graham and Sagar, 1999; Reijnders *et al.*, 2009; Selikhova *et al.*, 2009; Burn *et al.*, 2012; Flensborg Damholdt *et al.*, 2012), REM sleep behavior disorder (Romenets *et al.*, 2012), and daily visual activities (Seichepine *et al.*, 2011). To our knowledge, however, no studies have used cluster analysis techniques to examine subtypes present in NMS only.

In this study, we used cluster analysis techniques to search for PD subtypes from a large, multi-centre, international, and well-characterized cohort of patients across all stages, using a combination of motor cardinal features (bradykinesia, rigidity, tremor, axial signs) and comprehensive NMS assessed using specific validated rater-based scales. We believe this is the largest study of its size with these characteristics, and the first to focus on exclusively NMS-based phenotyping.

2 Materials and methods

2.1 Design

Data from two independent international studies were used in the analysis: the validation study of the Non-Motor Symptoms Scale (NMSS) ($n = 411$) (Martinez-Martin *et al.*, 2009a) and baseline data from the global Non-Motor International Longitudinal Study (NILS) ($n = 540$) (Ray Chaudhuri *et al.*, 2013). NILS has been adopted as a national study by the National Institute of Health Research in the UK (UKCRN No: 10084) and is a 5-year follow-up study addressing the range, nature, and natural history of NMS in PD across all motor stages. All data in NMSS and NILS have been anonymized and entered into a secure database at the National Center of Epidemiology, Carlos III Institute of Health, Madrid, Spain.

2.2 Patients

PD patients diagnosed according to internationally recognized criteria (Gibb and Lees, 1988; Lees *et al.*, 2009) across all disease stages were included. For the NMSS study, patients were older than 30 years, but for inclusion of NILS patients there was no age limit. Exclusion criteria were: inability to read, understand, or answer written questionnaires; comorbidity, sequelae, or any disorder interfering with the assessment of PD; and inability to give informed consent. Patient recruitment was carried out across 15 countries in America, Asia, and Europe from 2007 to 2011.

2.3 Assessments

For all patients, socio-demographic and historical data were recorded and the following assessments were applied:

1. The Scales for Outcomes in Parkinson's Disease-Motor (SCOPA-Motor), a scale with three dimensions: A. Examination (10 items); B. Activities of daily living (7 items); and C. Complications (4 items). Each item scores from 0 (normal) to 3 (severe), the total score ranging from 0 to 75. This scale was derived from the Unified Parkinson's Disease Rating Scale and showed high correlation with the original scale ($r > 0.85$) and satisfactory clinimetric attributes in validation studies (Marinus *et al.*, 2004; Martinez-Martin *et al.*, 2005).
2. The Non-Motor Symptoms Scale (NMSS), a 30-item scale with nine domains: cardiovascular (2 items), sleep/fatigue (4 items), mood/apathy (6 items), perceptual problems/hallucinations (3 items), attention/memory (3 items), gastrointestinal tract (3 items), urinary function (3 items), sexual function (2 items), and miscellaneous (4 items). Each item scores from 0 to 12 (severity, 0 to 3, multiplied by frequency, 1 to 4) and the total NMSS score varies from 0 to 360, a value representing the total non-motor symptomatic burden (Chaudhuri *et al.*, 2007; Martinez-Martin *et al*., 2009a).
3. The Hoehn and Yahr (HY) scale (Hoehn and Yahr, 1967).
4. The Clinical Impression of Severity Index for PD (CISI-PD), a global evaluation of motor signs, disability, motor complications, and cognitive status. Items are rated from 0 (normal) to 6 (very severe), the total score ranging from 0 to 24 (Martinez-Martin *et al*., 2006, 2009b).

2.4 Standard protocol approvals, registrations, and patient consent

The NMSS validation study received ethical approval from the Carlos III Institute of Health, Madrid, Spain and local research ethics committees (Martinez-Martin *et al.*, 2009a). The NILS is included in the UK Department of Health portfolio of approved studies (UK CRN portfolio Nr. 10084) and has been approved at all relevant institutions and corresponding ethics committees/institutional review boards. All patients gave written informed consent before inclusion in accordance with the Declaration of Helsinki.

2.5 Statistical analysis

SCOPA-Motor examination items were aggregated to obtain four "cardinal motor signs": tremor (items 1 and 2), bradykinesia (item 3), rigidity (item 4), and axial signs (items 5 to 10). Additionally, an aggregate "motor complications" variable was obtained from the sum of items 18 to 21 (dyskinesias and motor fluctuations). All variables were standardized before clustering, and unstandardized afterwards for interpretation. Analyses were conducted in R version 3.2.4 (www.r-project.org) and Stata version 14 (http://www.stata.com/).

2.5.1 Cluster analysis

k-means was used for cluster analysis. We performed two analyses on the data: the first clustering on the nine aggregate non-motor symptom domains, the four cardinal motor signs (tremor, bradykinesia, rigidity, axial), and motor complications, henceforth the "domains clustering", and the second on the 30 individual non-motor symptoms of the NMSS only, henceforth the "symptoms clustering". Average-linkage hierarchical agglomerative clustering on the 30 non-motor symptoms, 4 motor signs, and motor complications was also performed to observe the grouping of the variables.

Various formal measures were used to determine the optimal number of clusters for the dataset. For the domains clustering, the optimal k according to the Gap Statistic and the 1-standard-error method (Tibshirani *et al.*, 2001) was $k = 4$ (Supplementary Figure 1A). Other cluster determination methods suggested $k = 2, 3, 4$, where $k = 2, 3$ simply divided the data uninformatively into groups with varying levels of overall disease severity. Thus $k = 4$ was selected to offer a good combination of model fit and parsimony. The same method was applied for the symptoms clustering, where the number of clusters was $k = 6$ (Supplementary Figure 1B).

2.5.2 Comparative subgroup analysis

For each variable in both clusterings, we used one-way ANOVA and χ^2 tests to respectively check the equality of variable means and proportions across the clusters found, using Bonferroni correction for multiple testing with corrected $p < 0.05$ considered significant. Differences among pairwise clusters were tested post-hoc using Tukey's range test for continuous means, or pairwise χ^2 tests for proportions, with Bonferroni correction both for the within-variable pairwise tests and the multiple variable comparisons.

To compare the domains and symptoms clusterings, we depicted cluster alignment with a contingency table, and computed the adjusted rand index (ARI) (Hubert and Arabie, 1985) to evaluate similarity between the two clusterings.

Lastly, to explore the relationship between symptom severity and disease duration, we computed the correlation of each variable with disease duration and fitted smoothed loess curves to the data both globally and for each cluster in the domains clustering.

3 Results

3.1 Study sample

Out of the 951 patients in the study, we used listwise deletion to exclude 47 patients due to missing measurements, resulting in 904 remaining patients. There were no significant differences between the included and excluded groups with respect to age, sex, disease duration, and HY ($\chi^2 \geq 0.19$). The characteristics of the sample included for analysis ($n = 904$) are displayed in Table 1. Patients were predominantly male (62.17%). 13.38% were in HY stage 1; 43.36% in stage 2; 29.65% in stage 3; 11.50% in stage 4; and 2.10% in stage 5.

3.2 Domains clustering

Results from the *k*-means clustering on the nine non-motor domains, the four cardinal motor signs, and motor complications are reported in Table 2 along with additional variables not used in the analysis (heatmap in Figure 1; boxplots in Supplementary Figure 2). Cluster means for all variables were found to be statistically significantly different except for age at disease onset and sex (adjusted $p < 0.05$). Specific pairwise differences are noted in the table.

Cluster D1 ($n = 428$) patients were mildly affected in all domains. This cluster was characterized by relatively lower disease durations and ages.

Cluster D2 ($n = 180$) patients were severely affected in non-motor domains but mildly affected in motor domains. This cluster had a severity of motor variables relatively similar to the cluster D1 (mild) subtype especially in tremor, but expressed significantly higher scores for non-motor domains than clusters D1 and D3, especially in the sleep/fatigue, mood/apathy, urinary, and miscellaneous

domains. Except for motor complications, scores for every variable were statistically significantly different from those in cluster D3.

Cluster D3 ($n = 232$) patients were severely affected in motor domains but mildly affected in non-motor domains. Mean motor scores were greater than the means of clusters D1 and D2, with the exception of motor complications. Additionally, mean motor scores were less than D4, with the exception of tremor, which was especially high. Importantly, CISI-PD scores of clusters D2 and D3 were not statistically significantly different, and no differences were observed in cluster D2 and cluster D3 age or disease duration.

Cluster D4 ($n = 64$) patients were severely affected in all domains, having the greatest symptom mean out of all four clusters with the exception of tremor. Consequently, patients in cluster D4 had the longest average disease duration and oldest ages, but did not have a significantly different age of disease onset.

3.3 Symptoms clustering

k-means performed on the 30 individual non-motor symptoms found 6 clusters ordered according to increasing CISI-PD score (Table 3, heatmap in Figure 2). Means of all symptoms were found to differ across clusters except for disease onset, sex, and tremor, with pairwise differences again noted in the table.

Cluster S1 ($n = 456$), the largest cluster representing 50% of the group, was similar to domains cluster D1, and was composed of patients relatively mildly affected in all NMS. Cluster S2 ($n = 201$) had higher mean symptom scores than cluster S1's in several cases, including restless legs syndrome (RLS), swallowing, and the miscellaneous domain, but could nonetheless be classified as a mild/moderate cluster.

Although clusters S3-S6 increased in motor and overall disease severity, they varied significantly in their non-motor expression and each expressed a unique subset of NMS. These groups of non-motor symptoms aligned well with the established non-motor domains. Cluster S3 ($n = 100$) mainly expressed domain 7 (urinary), while cluster S4 ($n = 73$) was affected severely in domain 3 (mood/apathy). Cluster S5 ($n = 54$) showed severe impact in most non-motor symptoms but especially in domain 5 (attention/memory). Similarly, cluster S6 ($n = 20$) had severe scores across all non-motor symptoms and motor features, but was most severely affected in the cardiovascular, perception/hallucination, and gastrointestinal NMSS domains. Overall, the symptoms clustering fragmented the domains clusters into smaller groups, as explored in the next section.

3.4 Comparison between clusterings

Alignment of the D and S clusters is visualized in Table 4. While S1 grouped patients from D1 (mild) and D3 (motor-dominant), and D4 (severe) showed a dominant contribution from S5 (severe non-motor) and S6 (severe motor and non-motor), the remaining clusters were fragmentarily distributed, as indicated by the low similarity between the clusterings (ARI $= 0.32$) For the domains clustering, patients in clusters mildly affected in non-motor domains (D1, D3) were distributed among the milder symptoms clusters (S1-S4, skewed left). Conversely, patients in clusters with severe non-motor symptoms (D2, D4) were split among the various specific non-motor-dominant clusters (S2-S6), suggesting that the symptoms clustering is clinically more specific than the domains clustering.

3.5 Hierarchical clustering on variables

Hierarchical clustering on the 30 non-motor symptoms and the four cardinal motor signs is depicted in Figure 3. Symptoms belonging to the same domain of the NMSS tended to cluster together, with some exceptions. Diplopia (domain 4) was grouped loosely with domain 8 (sexual) symptoms. RLS (domain 2) was grouped loosely with domain 9 (miscellaneous) symptoms. Similarly, drowsiness (domain 2) was grouped with domain 5 (attention/memory) symptoms. Notably, tremor was the most isolated symptom, occupying a single branch at the top of the tree.

3.6 Correlation analysis

Due to high variance, most variables had little to no correlation with disease duration (Supplementary Figure 3). In Figure 4, we plotted 4 variables especially relevant to the domains clustering against disease progression: CISI-PD, Tremor, Anxiety, and Depression. Notable differences in disease progression for each cluster can be seen in the scatterplots: for example, patients in NMS dominant cluster D2 actually tended to have higher scores for anxiety and depression at disease onset, decreasing with increasing disease duration.

4 Discussion

We believe that this is the largest cluster analysis-based study of PD-related motor and non-motor symptoms from a large, international, multi-centre cohort. Previous cluster-analysis based studies have either focused on early/untreated Parkinson's disease (Erro *et al.*, 2013; Pont-Sunyer *et al.*, 2015) or lack detailed assessments based on the severity and frequency of non-motor domains and symptoms (van Rooden *et al.*, 2011). Additionally, we believe this is the first study to perform cluster analysis exclusively on NMS to reveal NMS-specific subtypes.

The domains clustering's 4 clusters closely correspond with several previous studies (van Rooden *et al.*, 2011; Erro *et al.*, 2013; Ma *et al.*, 2015; Pont-Sunyer *et al.*, 2015), especially those reported by van Rooden *et al*. (2011). Both clusters D1 (mild) and D4 (severe) are groups which are present in most analyses, but unlike van Rooden *et al.*, our data show that mean differences in disease duration *do* exist between mild and severe subtypes. Clusters D2 and D3 represent a divergence in symptomatic expression: D2 representing a non-motor dominant phenotype also described in many clinical phenotype-driven studies (Sauerbier *et al*., 2016), and D3 corresponding to the traditional motor-dominant view of PD. Due to these clusters' similar overall PD severity (CISI-PD) and duration, differences in disease progression do not explain the differences between D2 and D3. Finally, the high incidence of tremor in D3, even higher than D4, is interesting and reflects not only the motor-dominant subtype of van Rooden *et al.* but also the tremor-dominant/slow-progression cluster described by Ma *et al.* (2015).

Our correlation analysis demonstrates notable differences in disease progression among these clusters. The high initial depression and anxiety scores for cluster D2 suggests that patients susceptible to NMS-dominant PD can be identified by high NMS scores early after disease onset. Furthermore, the general improvement in depression and anxiety scores for this cluster matches recent results found in a 2-year follow-up study of an untreated PD cohort (Mollenhauer *et al*., 2016).

From the symptoms clustering (Figure 2), six smaller clusters were identified. S1 was similar to D1. S2 to S6, while increasing in motor severity, expressed specific NMS, thus supporting the clinical concept of NMS-based subtyping. Cluster S2, with principal components including RLS, swallowing, pain, and others, may be a new finding from this study. Cluster S3, with significant urinary dysfunction, fits the descriptions by Erro *et al*. (2013), highlighting the relevance of this symptom as a specific marker in non-motor dominant clusters and disease progression. Cluster S4,

characterized by high mood/apathy symptoms, is consistent with the sleep and apathy clinical phenotypes described by other studies (Sauerbier *et al.*, 2016). Clusters S5 and S6 are of clinical interest, as in these clusters NMS dominate, overshadowing motor symptoms with an emphasis on cognitive impairment in S5 and autonomic (cardiovascular and gastrointestinal) symptoms in S6. Overall, many of these subtypes are newly reported and their characteristics support clinical endophenotyping of non-motor subtypes not reported in previous studies.

The comparison between the domains and symptoms clustering shown in the contingency table (Table 4) suggests that the broader subset of cluster S1, a mild non-motor dominant cluster, essentially expresses two NMS subtypes, one of them with motor symptoms. The low numbers observed in some cells do not allow consistent clinical interpretation. The hierarchical clustering (Figure 3) indicates that the symptoms grouping in the NMSS dimensions works as expected, as most items in each domain group together, with the exception of tremor.

What are the clinical implications of these clusterings? First, our analysis represents statistical conformation of NMS-dominant presentation of PD. The specific expression of several NMS domains such as mood/anxiety, sleep/fatigue, cognition, and urinary function suggests that these subgroups may have different patterns of neurodegeneration involving the brain's various non-dopaminergic pathways, possibly in excess of dopaminergic degeneration, as suggested by several authors (Jellinger, 2012). Second, clinical recognition of subtypes using ad hoc criteria would allow for the development of truly subtype-specific treatment packages for PD (Marras and Chaudhuri, 2016). Third, clinical characterization of these groups will allow studies of natural history of specific subtypes.

The clinical non-specificity of D1, S1, D4, and S6, with extremely diverse disease durations and severities, contrasts with the precisely characterized clusters S3, S4, and S5, with dominant expression of urinary, mood/apathy and attention/memory symptoms, respectively, at intermediate stages of the disease. This pattern is in line with the notion of "phenotypic convergence" proposed by Warren *et al*. (2013) as a key clinical feature of the spread of neurodegenerative disorders due to abnormal protein aggregates. The identified clusters may represent distinct footprints of large-scale network disintegration which necessitates translation to clinical management.

Like any cohort-based, cluster-analysis driven study, there are several limitations of this analysis. Due to the data collection methods of the two studies used, selection due to prevalence bias, i.e. sample overrepresentation of patients with higher survival, is unlikely to explain this clustering; however, clustering at early PD stages may have been undermined by poorly recorded symptoms prior to diagnosis. Furthermore, we did not report a control group, although our intention was not to describe the symptoms as discriminant from normal subjects. Lastly, NMS profiles in advanced PD could also be influenced by patterns of dopaminergic therapy, particularly hallucinations and orthostatic problems. However, these symptoms did not emerge as key drivers of any of the domains identified in either of our clusterings. Conversely, our study has several notable strengths: (1) the sample size, which to our knowledge is the largest international sample in this kind of study; (2) the inclusion of patients in all disease stages; and (3) the use of detailed assessments both for motor and non-motor symptoms.

In conclusion, we present statistical confirmation of the growing recognition of NMS-dominant presentation of PD and its heterogeneity. The clinical recognition of these subtypes could allow for subtype-specific treatment packages for PD, and in the future, clinical characterization of these groups will allow for studies of natural history of the various non-motor dominant clusters identified

in this paper. Translating results to clinical management or experimental designs would require the identification of inclusion and exclusion criteria of patients into specific subgroups.

5 Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6 Author contributions

JM conducted the statistical analysis and interpretation of the data, drafted the methods and results section of the paper, and revised the manuscript for content. KC obtained the data, designed the study, and drafted and revised the introduction and conclusion sections of the paper. CB, JC, and PL revised the manuscript for content and contributed to the analysis and interpretation of data. PM obtained the data, designed the study, and drafted and revised the introduction and conclusion sections of the paper.

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390 **10 Tables**

391 **Table 1.** Description of the sample.

	Mean	SD	Median	Range
Age at study	64.28	9.86	65	34 - 89
Age at onset of Parkinson's disease (PD onset)	56.27	10.72	57	25 - 89
Duration of the disease (PD duration)	8.01	5.80	7	0 - 40
Non-Motor Symptoms Scale total score	50.45	41.72	39	0 - 225
Cardiovascular	1.74	3.26	0	0 - 24
Sleep/Fatigue	8.76	8.71	6	0 - 48
Mood/Apathy	8.67	11.54	4	0 - 60
Perceptual problems/Hallucinations	1.64	3.86	0	0 - 33
Attention/Memory	5.40	7.42	2	0 - 36
Gastrointestinal	5.53	6.78	3	0 - 36
Urinary	8.07	8.93	5	0 - 36

Sexual function	3.53	5.98	0	0 - 24
Miscellaneous	7.12	7.78	4	0 - 48
Cardinal motor features *				
Tremor	2.59	2.58	2	0 - 12
Bradykinesia	2.40	1.41	2	0 - 6
Rigidity	2.23	1.36	2	0 - 6
Axial	3.25	2.67	3	0 - 12
SCOPA-Motor Total score	21.07	12.06	19	1 - 72
A. Examination	11.54	6.56	10	0 - 41
B. Activities of daily living	6.80	4.19	7	0 - 21
C. Complications	2.73	3.01	2	0 - 12
Clinical Impression of Severity Index	8.29	4.61	8	0 - 24

SD: Standard deviation. SCOPA: Scales for Outcomes in Parkinson's Disease.

* Scores derived from items of the SCOPA-Motor A. Examination.

Table 2. Domains clustering summary. Unless otherwise specified, statistics are reported as mean (sd).

	Cluster	D1	D2	D3	D4
	n (%)	428 (47%)	180 (20%)	232 (26%)	64 (7%)
Non-motor	1. Cardiovascular	0.7 (1.5)^{2,4}	3.2 (3.7)^{1,3,4}	1.1 (2.1)^{2,4}	6.9 (6.4)^{1,2,3}
domains	2. Sleep/fatigue	4.5(5.0)^{2,3,4}	16 (8.7)^{1,3,4}	7.5 (6.6)^{1,2,4}	21.7 (9.7)^{1,2,3}
	3. Mood/apathy	3.4 (4.8)^{2,3,4}	19.2 (15.0)^{1,3}	6.6 (8.0)^{1,2,4}	21.7 (13.5)^{1,3}
	4. Perception/hallucination	0.5 (1.7)^{2,4}	2.7 (4.3)^{1,3,4}	0.8 (1.8)^{2,4}	9.7 (6.9)^{1,2,3}
	5. Attention/memory	3.0 (4.5)^{2,4}	10.5 (9.2)^{1,3,4}	3.3 (4.4)^{2,4}	14.5 (11.0)^{1,2,3}
	6. Gastrointestinal	2.9 (4.1)^{2,3,4}	8.5 (7.1)^{1,3,4}	4.7 (5.3)^{1,2,4}	17.4 (9.2)^{1,2,3}
	7. Urinary	4.7 (6.2)^{2,4}	14.0 (9.9)^{1,3,4}	6.2 (6.7)^{2,4}	20.3 (9.7)^{1,2,3}

	8. Sexual function	1.7 (3.4)[2,3,4]	7.3 (7.8)[1,3]	2.4 (4.1)[1,2,4]	9.0 (9.9)[1,3]
	9. Miscellaneous	4.0 (4.8)[2,3,4]	13.2 (8.7)[1,3]	6.2 (6.8)[1,2,4]	14.5 (10.1)[1,3]
Motor symptoms	Axial	1.7 (1.5)[2,3,4]	3.6 (2.2)[1,3,4]	4.5 (2.3)[1,2,4]	8.2 (2.7)[1,2,3]
	Bradykinesia	1.6 (0.9)[2,3,4]	2.2 (1.1)[1,3,4]	3.5 (1.0)[1,2,4]	4.5 (1.3)[1,2,3]
	Rigidity	1.5 (0.9)[2,3,4]	1.8 (1.2)[1,3,4]	3.3 (1.0)[1,2,4]	4.2(1.2)[1,2,3]
	Tremor	2.0 (1.9)[3,4]	1.5 (1.8)[3,4]	4.1 (2.8)[1,2]	4.1 (4.1)[1,2]
	Motor complications	1.4 (2.1)[2,3,4]	3.1 (2.9)[1,4]	3.7 (2.9)[1,4]	7.0 (3.6)[1,2,3]
Variables not	Sex (% male)	64	54	67	58
used in analysis	CISI-PD total	5.5 (3.0)[2,3,4]	9.6 (3.8)[1,4]	10.1 (3.5)[1,4]	16.4 (4.6)[1,2,3]
	Age	62.5 (9.7)[4]	65.2 (9.4)[4]	64.9 (10.1)[4]	71.1 (7.9)[1,2,3]
	PD onset	56 (10.5)	56.6 (10.6)	56.3 (11.3)	56.7 (10.6)
	PD duration	6.5 (4.7)[2,3,4]	8.6 (5.7)[1,4]	8.6 (5.7)[1,4]	14.4 (8.0)[1,2,3]

[1] Significant difference with cluster D1 (corrected $p < 0.05$)

[2] Significant difference with cluster D2 (corrected $p < 0.05$)

[3] Significant difference with cluster D3 (corrected $p < 0.05$)

[4] Significant difference with cluster D4 (corrected $p < 0.05$)

Table 3. Symptoms clustering summary. Unless otherwise specified, statistics are reported as mean (sd).

	Cluster	S1	S2	S3	S4	S5	S6
	n(%)	456 (50%)	201 (22%)	100 (11%)	73 (8%)	54 (6%)	20 (2%)
1.	Lightheadedness	0.5 (1.1)[2,3,4,5,6]	1.7 (2.5)[1,5,6]	2.5 (3.4)[1,6]	1.9 (2.5)[1,6]	3.3 (3.7)[1,2,6]	7.7 (3.6)[1,2,3,4,5]
Cardiovascular	Fainting	0.1 (0.6)[6]	0.3 (1)[6]	0.1 (0.5)[6]	0.5 (1.2)[6]	0.1 (0.5)[6]	6.3 (2.9)[1,2,3,4,5]

2. Sleep/	Drowsiness	0.9 (1.8)[2,3,4,5,6]	2.4 (2.9)[1,5,6]	2.3 (2.9)[1,5,6]	2.2 (3)[1,5,6]	6.6 (4.2)[1,2,3,4]	5.2 (3)[1,2,3,4]
fatigue	Fatigue	1.2 (1.9)[2,3,4,5,6]	4.2 (3.7)[1,4,5]	4.5 (4)[1,5]	5.9 (4.2)[1,2]	8 (3.5)[1,2,3]	6.9 (3.1)[1]
	Insomnia	1.1 (2.2)[2,3,4,5,6]	3 (3.8)[1,4]	3.1 (4.2)[1,4]	5.3 (4.8)[1,2,3]	4.7 (4.8)[1]	5 (2.4)[1]
	RLS	0.5 (1.3)[2,4,5,6]	2.4 (3.5)[1,3,6]	1 (2.4)[2,5,6]	1.8 (3.2)[1,6]	3.2 (4.2)[1,3]	4.9 (2.6)[1,2,3,4]
3. Mood/	Loss interest	0.4 (0.9)[2,4,5,6]	1.1 (1.8)[1,4,5,6]	0.6 (1.3)[4,5,6]	6.6 (3.9)[1,2,3,5]	4.5 (3.7)[1,2,3,4]	5.3 (2.8)[1,2,3]
apathy	Loss activities	0.6 (1.3)[2,4,5,6]	1.9 (2.7)[1,4,5,6]	1 (2)[4,5,6]	7.8 (3.5)[1,2,3,5,6]	6 (4.5)[1,2,3,4]	4.7 (2.9)[1,2,3,4]
	Anxiety	0.8 (1.6)[2,4,5,6]	2.2 (2.9)[1,4,5,6]	1.6 (2.9)[4,5,6]	5.8 (4.3)[1,2,3]	6.4 (4.4)[1,2,3]	4.7 (3)[1,2,3]
	Depression	0.7 (1.4)[2,4,5,6]	2.7 (3.2)[1,3,4,5,6]	1.4 (2.3)[2,4,5,6]	7.4 (4)[1,2,3]	5.8 (4.3)[1,2,3]	5.3 (3.2)[1,2,3]
	Flat affect	0.3 (1)[2,4,5,6]	1.1 (2.1)[1,4,5]	0.8 (2.1)[4,5,6]	4.8 (4.3)[1,2,3,5]	2.9 (3.7)[1,2,3,4]	3 (2.1)[1,3]
	Loss pleasure	0.3 (1.1)[4,5,6]	1 (1.8)[4,5,6]	0.8 (1.8)[4,5,6]	7.3 (3.8)[1,2,3,5,6]	4.6 (4.2)[1,2,3,4]	3.6 (2.8)[1,2,3,4]
4. Perception/	Hallucination	0.2 (0.9)[5,6]	0.6 (1.7)[5,6]	0.7 (1.9)[5,6]	0.6 (1.8)[5,6]	2.7 (3.3)[1,2,3,4,6]	4.8 (3.3)[1,2,3,4,5]
hallucination	Delusion	0.1 (0.6)[4,5,6]	0.3 (1.4)[4,5,6]	0.1 (0.6)[4,5,6]	1.3 (3)[1,2,3,6]	2 (3.5)[1,2,3,6]	4.7 (3.4)[1,2,3,4,5]
	Diplopia	0.2 (0.8)[5,6]	0.6 (1.4)[5,6]	0.4 (1.6)[5,6]	0.8 (2.2)[5,6]	3.1 (4.4)[1,2,3,4]	3.6 (2.7)[1,2,3,4]
5. Attention/	Loss concentration	0.7 (1.5)[2,3,4,5,6]	2.6 (2.9)[1,5,6]	2.2 (3.4)[1,5,6]	2.9 (2.9)[1,5]	7.5 (3.9)[1,2,3,4]	5.1 (2.8)[1,2,3]
memory	Forget explicit	0.7 (1.3)[2,3,4,5,6]	2.2 (2.7)[1,5,6]	2.2 (3)[1,5,6]	2.1 (2.5)[1,5,6]	8.5 (3.2)[1,2,3,4,6]	4.8 (2.9)[1,2,3,4,5]
	Forget implicit	0.5 (1.2)[2,3,4,5,6]	1.9 (2.6)[1,5,6]	1.5 (2.7)[1,5,6]	1.8 (2.2)[1,5,6]	7.6 (4.1)[1,2,3,4,6]	5.1 (3.2)[1,2,3,4,5]
6.	Drooling	0.6 (1.5)[2,3,4,5,6]	2.3 (3.3)[1,5,6]	3.3 (4.1)[1,6]	3.3 (4.2)[1,6]	4.2 (4.8)[1,2]	6.2 (3.3)[1,2,3,4]
Gastrointestinal	Swallowing	0.3 (0.8)[2,3,5,6]	2 (3)[1,6]	1.2 (2)[1,6]	1.2 (2)[6]	2.3 (2.9)[1,6]	6.5 (4.2)[1,2,3,4,5]

	Constipation	1.5 (2.7)[2,3,4,5,6]	3 (3.8)[1,6]	3.8 (4.4)[1,6]	3.7 (4.4)[1,6]	4.5 (4.9)[1,6]	8.8 (4.4)[1,2,3,4,5]
7. Urinary	Urinary urgency	0.9 (1.7)[2,3,4,5,6]	1.8 (2.4)[1,3,5,6]	6.6 (3.8)[1,2,4]	2.4 (3.4)[1,3,5,6]	7.7 (4.3)[1,2,4]	6.2 (3.5)[1,2,4]
	Urinary frequency	0.9 (1.8)[3,4,5,6]	1.3 (1.9)[3,4,5,6]	7.7 (3.5)[1,2,4]	3.1 (3.6)[1,2,3,5,6]	6.2 (4.5)[1,2,4]	6.7 (3.1)[1,2,4]
	Nocturia	1.7 (2.3)[3,4,5,6]	2.6 (2.9)[3,4,5,6]	8.5 (3.5)[1,2,4]	4.6 (4.2)[1,2,3,5]	6.9 (4.4)[1,2,4]	7.1 (3.4)[1,2]
8. Sexual	Sex drive	0.7 (1.7)[2,3,4,5,6]	1.9 (3.4)[1,5]	3 (4.1)[1,5]	3.6 (4.4)[1,5]	6 (5.3)[1,2,3,4]	3.9 (5.3)[1]
	Sex dysfunction	0.7 (2)[3,4,5,6]	1.8 (3.3)[3,5]	3.4 (4.3)[1,2]	2.3 (4.2)[1,5]	5 (5.2)[1,2,4]	3.8 (5.6)[1]
9.	Unexplained pain	0.7 (1.8)[2,3,4,5,6]	2.6 (3.9)[1]	2.4 (4)[1]	2.3 (3.6)[1]	4.3 (5)[1]	4.3 (2.2)[1]
Miscellaneous	Gustation/olfaction	1.2 (2.5)[2,4,5,6]	4 (4.2)[1]	2.5 (3.6)	3 (3.9)[1]	4 (4.7)[1]	5.5 (4.7)[1]
	Weight change	0.8 (1.4)[2,4,5,6]	1.9 (3.1)[1,5]	1.8 (3)[5]	2.1 (2.8)[1]	3.6 (4.3)[1,2,3]	4 (3.9)[1]
	Sweating	0.6 (1.6)[2,3,4,5,6]	2.5 (3.9)[1]	2.4 (3.9)[1]	2.1 (3.6)[1]	2.8 (3.9)[1]	3.9 (3.4)[1]
Motor	Axial	2.3 (2)[2,3,4,5,6]	3.5 (2.6)[1,5,6]	4 (2.8)[1,6]	4.4 (2.7)[1,6]	5.3 (3.3)[1,2,6]	8.5 (2.3)[1,2,3,4,5]
symptoms	Bradykinesia	2.1 (1.2)[4,5,6]	2.5 (1.4)[6]	2.5 (1.4)[6]	2.9 (1.4)[1,6]	3 (1.6)[1,6]	4.5 (1.7)[1,2,3,4,5]
	Rigidity	2 (1.2)[6]	2.3 (1.5)[6]	2.3 (1.4)[6]	2.5 (1.3)[6]	2.6 (1.5)[6]	4.7 (1)[1,2,3,4,5]
	Tremor	2.6 (2.4)[6]	2.5 (2.4)[6]	2.1 (2.5)[6]	2.5 (2.6)[6]	2.4 (2.8)[6]	5.8 (5.3)[1,2,3,4,5]
	Motor comp	1.9 (2.5)[2,4,5,6]	3.5 (3)[1,6]	2.7 (2.7)[6]	3.7 (3.3)[1,6]	3.9 (3.7)[1,6]	8 (3.7)[1,2,3,4,5]
Variables not	Sex	67	57	64	49	63	50
used in analysis	CISI PD total	6.4 (3.5)[2,3,4,5,6]	9.3 (4.1)[1,5,6]	9.4 (4.1)[1,6]	10.7 (4.6)[1,6]	11.8 (5.5)[1,2,6]	18.4 (4.2)[1,2,3,4,5]
	Age	62.8 (10)[3,5,6]	63.8 (10)[5]	68.3 (7.5)[1]	63.1 (9.2)	69.7 (9.2)[1,2]	72.1 (7.7)[1]

PD onset	56.2 (10.8)	55 (10.7)	58.2 (10)	54.8 (10.3)	58.8 (11.7)	59.2 (8.6)
PD duration	6.6 (4.8)[2,3,5,6]	8.8 (5.9)[1]	10.1 (6.7)[1]	8.3 (4.9)	11 (8.5)[1]	12.8 (6.5)[1]

[n] Significant difference with cluster S*n* (corrected $p < 0.05$)

Table 4. Contingency table describing cross-categorization of individuals in the domains and symptoms clusters.

Domains clusters \ Symptoms clusters	S1	S2	S3	S4	S5	S6	Total
D1	335	64	26	3	0	0	428
D2	0	54	46	49	31	0	180
D3	121	77	22	12	0	0	232
D4	0	6	6	9	23	20	64
Total	456	201	100	73	54	20	904

11 Figure legends

Figure 1. Heatmap of variables for each cluster in the domains clustering, separated by white lines according to 9 non-motor domains, 4 cardinal motor features, motor complications, and 4 general variables not included in the analyses. Since symptoms have different scales, cluster means for each symptom are displayed as standardized scores relative to each overall symptom mean.

Figure 2. Heatmap of variables for each cluster in the symptoms clustering, separated by white lines according to 30 individual non-motor symptoms and variables not included in the analysis (cardinal motor features, motor complications, and other general variables). Since symptoms have different scales, cluster means for each symptom are displayed as standardized scores relative to each overall symptom mean.

Figure 3. Average-linkage hierarchical clustering of motor (blue) and non-motor (black) symptoms. Symptoms are labeled with their name and corresponding domain number. The tree is colored with 5 clusters.

Figure 4. Scatterplots of selected symptoms against disease duration. For clarity, scatterplot points are colored according to cluster and jittered slightly. Smoothed loess curves for each cluster are drawn in their respective cluster colors. The black curve is the curve for the entire population, and the global mean score is marked with a dotted line.