

Excessive burden of lysosomal storage disorder gene variants in Parkinson's disease

Laurie A. Robak,^{1,2,*} Iris E. Jansen,^{3,4,*} Jeroen van Rooij,^{5,6,7} André G. Uitterlinden,^{5,6,8} Robert Kraaij,^{5,6,8} Joseph Jankovic,⁹ International Parkinson's Disease Genomics Consortium (IPDGC),[#] Peter Heutink³ and Joshua M. Shulman^{1,2,9,10}

*These authors contributed equally to this work.

[#]See Appendix 1 and Supplementary material.

Mutations in the glucocerebrosidase gene (*GBA*), which cause Gaucher disease, are also potent risk factors for Parkinson's disease. We examined whether a genetic burden of variants in other lysosomal storage disorder genes is more broadly associated with Parkinson's disease susceptibility. The sequence kernel association test was used to interrogate variant burden among 54 lysosomal storage disorder genes, leveraging whole exome sequencing data from 1156 Parkinson's disease cases and 1679 control subjects. We discovered a significant burden of rare, likely damaging lysosomal storage disorder gene variants in association with Parkinson's disease risk. The association signal was robust to the exclusion of *GBA*, and consistent results were obtained in two independent replication cohorts, including 436 cases and 169 controls with whole exome sequencing and an additional 6713 cases and 5964 controls with exome-wide genotyping. In secondary analyses designed to highlight the specific genes driving the aggregate signal, we confirmed associations at the *GBA* and *SMPD1* loci and newly implicate *CTSD*, *SLC17A5*, and *ASAH1* as candidate Parkinson's disease susceptibility genes. In our discovery cohort, the majority of Parkinson's disease cases (56%) have at least one putative damaging variant in a lysosomal storage disorder gene, and 21% carry multiple alleles. Our results highlight several promising new susceptibility loci and reinforce the importance of lysosomal mechanisms in Parkinson's disease pathogenesis. We suggest that multiple genetic hits may act in combination to degrade lysosomal function, enhancing Parkinson's disease susceptibility.

- 1 Department of Molecular and Human Genetics, Baylor College of Medicine, Houston TX USA
- 2 Jan and Dan Duncan Neurologic Research Institute, Texas Children's Hospital, Houston TX USA
- 3 German Center for Neurodegenerative Diseases (DZNE) and Hertie Institute for Clinical Brain Research, University of Tübingen, Tübingen 72076, Germany
- 4 Department of Clinical Genetics, VU University Medical Center, Amsterdam 1081HZ, The Netherlands
- 5 Department of Internal Medicine, Erasmus MC, Rotterdam, The Netherlands
- 6 Netherlands Consortium for Healthy Ageing (NCHA), Rotterdam, The Netherlands
- 7 Department of Neurology, Erasmus MC, Rotterdam, The Netherlands
- 8 Department of Epidemiology, Erasmus MC, Rotterdam, The Netherlands
- 9 Department of Neurology, Baylor College of Medicine, Houston, TX, USA
- 10 Department of Neuroscience and Program in Developmental Biology, Baylor College of Medicine, Houston, TX, USA

Correspondence to: Joshua M. Shulman, MD, PhD
Jan and Dan Duncan Neurological Research Institute
1250 Moursund St., Suite N.1150
Houston, TX 77030, USA
E-mail: Joshua.Shulman@bcm.edu

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Correspondence may also be addressed to: Peter Heutink, PhD
 German Center for Neurodegenerative Diseases (DZNE)
 Otfried-Müller-Str. 23
 72076 Tübingen
 Germany
 E-mail: Peter.Heutink@dzne.de

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Abbreviations: CADD = combined annotation dependent depletion; IPDGC = International Parkinson's Disease Genomics Consortium; LSD = lysosomal storage disorder; MAF = minor allele frequency; PPMI = Parkinson's Progression Markers Initiative; RSX-1 = Rotterdam Study exome dataset version 1; SKAT-O = sequence kernel association test – optimized; WES = whole exome sequencing

Introduction

Parkinson's disease is a common neurodegenerative disorder with evidence for a substantial genetic aetiology (Kalia and Lang, 2015). Studies in families and large population-based cohorts have implicated more than 30 genes (Singleton *et al.*, 2013; Bras *et al.*, 2015; Verstraeten *et al.*, 2015); however, the risk alleles identified to date explain only a fraction of Parkinson's disease heritability estimates (Hamza and Paymi, 2010; Do *et al.*, 2011; Keller *et al.*, 2012), suggesting the involvement of additional loci. Beyond discovering the responsible genes, a major challenge remains to understand the mechanisms by which these factors alter disease onset and/or progression, including whether they act independently or interact within coherent biological pathways.

Substantial evidence highlights the importance of lysosomal mechanisms in Parkinson's disease susceptibility and pathogenesis (Vekrellis *et al.*, 2011; Kalia and Lang, 2015; Moors *et al.*, 2016; Wong and Krainc, 2016). Prior to its discovery as a Parkinson's disease risk locus, the glucocerebrosidase gene, *GBA*, was known to cause Gaucher disease, an autosomal recessive lysosomal storage disorder (LSD). Increased risk for Parkinson's disease in heterozygous carriers of *GBA* loss-of-function alleles was first recognized in families of individuals with Gaucher disease (Tayebi *et al.*, 2003; Goker-Alpan *et al.*, 2004). Follow-up studies in large, case-control samples confirmed that heterozygous *GBA* variants confer at least a 5-fold increased risk of Parkinson's disease (Aharon-Peretz *et al.*, 2004; Sidransky *et al.*, 2009). *GBA* variants may also modify Parkinson's disease clinical manifestations (Clark *et al.*, 2007; Winder-Rhodes *et al.*, 2012; Brockmann *et al.*, 2015; Davis *et al.*, 2016), causing earlier age of onset, higher risk of cognitive impairment, and accelerated progression. LSDs—of which there are more than 50—are strictly Mendelian-inherited, metabolic disorders collectively caused by dysfunction in lysosomal biogenesis or function, and similarly characterized by the abnormal accumulation of non-degraded metabolites in the lysosome (Filocamo and Morrone, 2011; Boustany, 2013). The strong genetic evidence linking Gaucher disease and Parkinson's disease risk leads to the intriguing, generalized hypothesis

that LSDs and Parkinson's disease may share a common genetic mechanism. Other LSD genes have therefore become attractive candidate risk factors for Parkinson's disease (Shachar *et al.*, 2011; Deng *et al.*, 2015). Several studies have consistently supported a role for *SMPD1* (Foo *et al.*, 2013; Gan-Or *et al.*, 2013, 2015; Wu *et al.*, 2014; Clark *et al.*, 2015), which causes Niemann-Pick disease, type A/B. Initial reports evaluating other LSD genes, including *NPC1*, *NPC2*, *MCOLN1*, *NAGLU* and *ARSB*, have either shown conflicting results or await further replication (Winder-Rhodes *et al.*, 2012; Klunemann *et al.*, 2013; Zech *et al.*, 2013; Clark *et al.*, 2015; Jansen *et al.*, 2017). LSDs are individually quite rare in populations of European ancestry, as are the known genetic variants established to cause these disorders (Filocamo and Morrone, 2011; Boustany, 2013). However, with the exception of *GBA*, most studies of LSD gene candidates have been small and therefore likely underpowered to detect the effects of rare alleles or those with more modest effect sizes. Genome-wide association studies in large Parkinson's disease case-control cohorts have independently implicated more common risk alleles at two other LSD genes, *SCARB2* and *GALC* (Do *et al.*, 2011; Nalls *et al.*, 2014; Chang *et al.*, 2017). *SCARB2* encodes a membrane protein required for correct targeting of glucocerebrosidase to the lysosome. *GALC*, encoding galactosylceramidase, participates in ceramide metabolism, similar to *GBA*. Besides this growing genetic evidence, studies in cellular and animal models also implicate the lysosome in the clearance of α -synuclein (Cuervo *et al.*, 2004; Lee, 2004; Vogiatzi *et al.*, 2008), which aggregates to form Lewy body pathology in Parkinson's disease. Reciprocally, α -synuclein disrupts neuronal vesicle trafficking and lysosomal function (Cooper *et al.*, 2006; Mazzulli *et al.*, 2011; Moors *et al.*, 2016; Wong and Krainc, 2016).

In this study, we leverage the largest Parkinson's disease whole exome sequencing (WES) dataset currently available to systematically examine the overlap between genes responsible for LSDs and Parkinson's disease. Our results reveal an aggregate burden for genetic variants among 54 genes established to cause LSDs and suggest that many genes besides *GBA* likely contribute to susceptibility for Parkinson's disease.

Materials and methods

Subjects

Clinical and demographic features for our study cohorts, which have also been described in other recent reports (Giri *et al.*, 2017; Jansen *et al.*, 2017), are shown in Supplementary Table 1. The International Parkinson's Disease Genomics Consortium (IPDGC) WES discovery dataset used for this study consists of 2835 samples of Northern and Western European ancestry, including 1156 Parkinson's disease cases and 1679 controls not known to have Parkinson's disease. Subjects were recruited from academic medical centres across the USA and Europe. Cases were recruited at a mean age of 51.5 years [standard deviation (SD) = 11.5] and diagnosed with Parkinson's disease at a mean age of 41.2 years (SD = 10.8); 40.4% reported a positive family history. Control subjects were on average 63.7 years of age (SD = 17.1). The majority of control exomes ($n = 1201$ of 1679) originated from the Rotterdam Study exome dataset version 1 (RSX-1) (Giri *et al.*, 2017; van Rooij *et al.*, 2017). The Rotterdam Study is a prospective population-based cohort study based in Rotterdam, The Netherlands. WES was performed on DNA from participants from the RSX-I subcohort, enrolled in 1990, with an average age at baseline of 68.6 years (SD = 8.6, 54.4% female) (Hofman *et al.*, 2015). All IPDGC and RSX-1 subjects gave written informed consent for participation in genetic research, which was approved by relevant oversight committees and institutional review boards. Subjects with pathogenic variants in established Mendelian Parkinson's disease genes (*SNCA*, *LRRK2*, *VPS35*, *PARK2/parkin*, *PARK7/DJ-1*, or *PINK1*) were excluded from analysis (Jansen *et al.*, 2017). Following quality control filters, the Parkinson's Progression Markers Initiative (PPMI) replication dataset (Parkinson Progression Marker Initiative, 2011) includes 436 cases and 169 controls of Northwest European descent. Cases were recruited at a mean age of 61.7 years (SD = 9.7) and diagnosed with Parkinson's disease at an average age of 59.8 years (SD = 10.0); 27.1% reported a positive family history. PPMI controls were an average of 61.8 years of age (SD = 10.1) at the time of evaluation. Data used in the preparation of this article were obtained from the PPMI database (www.ppmi-info.org/data); up-to-date information on the study is available online (www.ppmi-info.org). Samples analysed for both the IPDGC and PPMI cohorts were derived from whole blood. The NeuroX cohort has also been previously described in detail (Nalls *et al.*, 2015; Jansen *et al.*, 2017). A minority of subjects overlapping with the IPDGC WES discovery sample were removed, such that the NeuroX replication cohort was a completely independent sample, including 6713 individuals with Parkinson's disease and 5964 controls. NeuroX cases were diagnosed at an average age of 61.6 (SD = 12.4) and controls were evaluated at an average age of 64.1 (SD = 14.3).

Sequencing, genotyping and quality control

Data generation and detailed quality control procedures for the IPDGC and RSX-1 samples have recently been reported (Giri *et al.*, 2017; Jansen *et al.*, 2017; van Rooij *et al.*, 2017).

WES was performed using the Roche Nimblegen SeqCap v2 or Illumina exome capture kits to prepare sample libraries, followed by paired-end sequencing with Illumina HiSeq2000. The generation of the PPMI WES dataset are described elsewhere (www.ppmi-info.org). Although the datasets originate from different consortia, the same algorithms were used for read processing. The Burrows-Wheeler Aligner-MEM algorithm (Li and Durbin, 2010) was used for alignment of sequencing reads to the human reference genome (hg19). Using Picard tools (<http://broadinstitute.github.io/picard>), Binary Alignment/Map files were generated in a sorted and indexed manner. Alignments were Base-Quality score recalibrated and indels realigned using the Genome Analysis Toolkit (McKenna *et al.*, 2010) v3.3-0, after which single nucleotide variants and small insertions/deletions were called with the HaplotypeCaller to one genomic Variant Call Format file per individual. The IPDGC and RSX-1 WES datasets (hereafter referred to as simply the IPDGC discovery dataset) were merged by joint variant calling from the individual genomic Variant Call Format files. Variants that were not assigned with the standard Genome Analysis Toolkit quality annotation 'PASS' were excluded for subsequent analyses. 94.4% and 98.0% of the IPDGC and PPMI exomes, respectively, achieved a minimum of $10\times$ coverage.

As previously described (Giri *et al.*, 2017; Jansen *et al.*, 2017), for individual quality control, samples were excluded for ambiguous gender, deviating heterozygosity/genotype calls, low genotype call rates, or cryptic relatedness following identity-by-descent analyses. Population structure was further evaluated using multi-dimensional scaling component analysis based on linkage disequilibrium-pruned, genome-wide common variant markers. Prior to these calculations, our datasets were merged with available genotypes from 1000 Genomes Project (1000GP) ancestry-based population samples, including African (AFR), East Asian (EAS), European (EUR) and the Americas (AMR) (1000 Genomes Project Consortium, 2012). Using the European samples as a reference, population outliers were excluded, resulting in the removal of 39 or 9 individuals from the IPDGC and PPMI datasets, respectively. All remaining samples cluster tightly with European ancestry subjects on multi-dimensional scaling plots (Supplementary Fig. 1). Genotype and variant quality control was accomplished by removal of low-quality genotypes (Phred-scaled genotype quality score < 20 , depth < 8) and variants with low call rates or departure from Hardy-Weinberg equilibrium. Furthermore, for the IPDGC discovery dataset, variants were only considered when located within the overlapping targeted regions of the applied library preparation capture kits. Post-quality control procedures, a total of 462 946 and 192 421 variants were called for the IPDGC and PPMI datasets, respectively.

Data generation and quality control for the NeuroX cohort has also previously been described in detail (Nalls *et al.*, 2015; Jansen *et al.*, 2017). NeuroX consists of 242 901 exonic variants from the Illumina Infinium HumanExome BeadChip and 24 706 custom variants related to neurological disease. For individual quality control, as above, samples were excluded for gender ambiguity, dubious heterozygosity/genotype calls, evidence of relatedness, or poor clustering on multi-dimensional scaling plots (Supplementary Fig. 1). We similarly excluded variants for low call rates, departure from Hardy-Weinberg equilibrium, or for significant differences in

Table 1 LSD genes and variants in the IPDGC cohort

Disease	Gene	Variants ^a
Aspartylglucosaminuria	AGA	13 (10)
Metachromatic leukodystrophy	ARSA	5 (5)
Maroteaux-Lamy disease	ARSB	11 (10)
Farber Lipogranulomatosis	ASAH1	20 (17)
Kufor-Rakeb syndrome	ATP13A2	24 (18)
Neuronal ceroid lipofuscinosis (CLN3)	CLN3	18 (17)
Neuronal ceroid lipofuscinosis (CLN5)	CLN5	-
Neuronal ceroid lipofuscinosis (CLN6)	CLN6	10 (7)
Neuronal ceroid lipofuscinosis (CLN8)	CLN8	9 (4)
Cystinosis	CTNS	13 (12)
Galactosialidosis	CTSA	14 (11)
Neuronal ceroid lipofuscinosis (CLN10)	CTSD	7 (4)
Neuronal ceroid lipofuscinosis (CLN13)	CTSF	11 (9)
Pycnodysostosis	CTSK	6 (5)
Neuronal ceroid lipofuscinosis (CLN4B)	DNAJC5	5 (5)
Fucosidosis	FUCA1	15 (12)
Pompe disease	GAA	15 (10)
Krabbe disease	GALC	36 (30)
Morquio A disease	GALNS	22 (14)
Gaucher disease	GBA	39 (32)
Fabry disease	GLA	9 (7)
GM1-gangliosidosis/Morquio B	GLB1	8 (4)
GM2-gangliosidosis	GM2A	1 (1)
I-Cell disease	GNPTAB	39 (31)
Sanfilippo D syndrome	GNS	20 (11)
Neuronal ceroid lipofuscinosis (CLN11)	GRN	19 (12)
Sly disease	GUSB	17 (10)
Tay-Sachs disease	HEXA	20 (18)
Sandhoff disease	HEXB	8 (6)
Sanfilippo C syndrome	HGSNAT	18 (15)
Mucopolysaccharidosis type IX	HYAL1	13 (9)
Hunter syndrome	IDS	9 (8)
Hurler syndrome	IDUA	8 (4)
Neuronal ceroid lipofuscinosis (CLN14)	KCTD7	4 (3)
Danon disease	LAMP2	9 (7)
Wolman disease	LIPA	14 (10)
Alpha-mannosidosis	MAN2B1	12 (11)
Beta-mannosidosis	MANBA	18 (15)
Mucopolidosis type IV	MCOLN1	19 (14)
Neuronal ceroid lipofuscinosis (CLN7)	MFSD8	18 (14)
Schindler disease/Kanzaki disease	NAGA	9 (8)
Sanfilippo B syndrome	NAGLU	10 (9)
Sialidosis	NEU1	-
Niemann-Pick disease type C1	NPC1	43 (35)
Niemann-Pick disease type C2	NPC2	2 (2)
Neuronal ceroid lipofuscinosis (CLN1)	PPT1	9 (7)
Sphingolipid-activator deficiency	PSAP	22 (16)
Action mycolonus-renal failure syndrome	SCARB2	10 (7)
Sanfilippo A syndrome	SGSH	10 (8)
Salla disease	SLC17A5	18 (17)
Niemann-Pick disease type A/B	SMPD1	25 (21)
GM3-gangliosidosis	ST3GAL5	11 (11)
Multiple sulfatase deficiency	SUMF1	-
Neuronal ceroid lipofuscinosis (CLN2)	TPPI	15 (13)

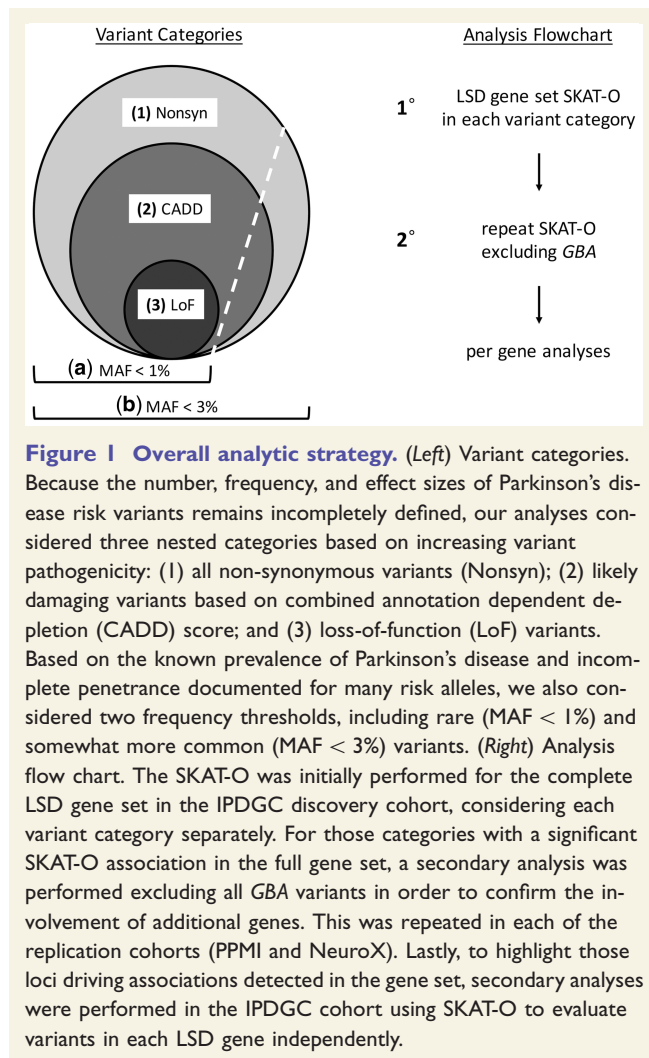
^aThe number of variants (MAF < 3%) in each LSD gene is shown for the IPDGC discovery cohort, including total number of non-synonymous variants and likely damaging variants based on CADD (in parentheses). Of the 54 LSD genes considered, no exonic variants in *CLN5* or *NEU1* passed quality control filters (see 'Materials and methods' section), and no non-synonymous variants were identified in *SUMF1*.

missingness rate between cases and controls. Post-quality control, we called 177028 exonic variants from the NeuroX dataset.

Where allowable based on individual consents and institutional review board approval, the datasets used in this study, including WES and NeuroX data from the IPDGC, are publicly available. Data availability is detailed in Jansen *et al.* (2017) and at <http://pdgenetics.org/resources>. Data from PPMI is also available for download at <http://www.ppmi-info.org/access-data-specimens/download-data/>.

Variant selection

Our analyses initially considered 54 LSDs (Table 1), defined based on widely accepted clinical, pathological, and metabolic criteria (Filocamo and Morrone, 2011; Boustany, 2013; Amberger *et al.*, 2015). All variants within the LSD gene set were extracted from the three datasets. For the IPDGC WES dataset, no variants in the genes *CLN5* and *NEU1* passed the prespecified maximum missingness criteria of 15%, yielding 1136 total exonic variants for consideration in these analyses. In addition, there were no non-synonymous variants identified in *SUMF1*. Variants were categorized in nested groups (Fig. 1) including (i) non-synonymous ($n = 760$ variants in 51 genes); (ii) likely damaging ($n = 596$ variants in 51 genes); or (iii) loss-of-function ($n = 69$ variants in 27 genes) (Table 1 and Supplementary Table 2). Loss-of-function variants included stop gain/loss, frameshift, and splicing mutations falling within two base pairs of exon-intron junctions. Predictions of variant pathogenicity were obtained from ANNOVAR (Wang *et al.*, 2010), based on the Combined Annotation Dependent Depletion (CADD) algorithm (v1.3, <http://cadd.gs.washington.edu>) (Kircher *et al.*, 2014). CADD integrates predictions from numerous bioinformatic algorithms into a single 'C-score' and ranks all possible nucleotide changes in the genome based on potential to disrupt gene/protein function. In accordance with prior work (Amendola *et al.*, 2015), we selected a stringent CADD C-score ≥ 12.37 , representing the top ~2% most damaging of all possible nucleotide changes in the genome—this subset is enriched for known pathogenic alleles. For descriptive purposes, all putative damaging variants within the IPDGC discovery cohort were further cross-referenced with ClinVar (Landrum *et al.*, 2016) to identify those previously established with pathogenicity for LSDs (Supplementary Table 3). For the PPMI cohort, no variants were called in *DNAJC5*, resulting in a dataset of 515 total exonic variants, of which 256 variants from 49 genes were non-synonymous and 187 variants in 47 genes met the CADD criteria for putative damaging changes (Supplementary Table 2). For the NeuroX cohort, all genes in the 54-gene set were represented, resulting in 467 non-synonymous variants, of which 348 were classified as likely damaging (Supplementary Table 2). Within these categories, variants were filtered based on two minor allele frequency (MAF) thresholds: (i) <1%; and (ii) <3% (Fig. 1). The latter, more relaxed frequency threshold is based on the population prevalence (de Lau and Breteler, 2006; Pringsheim *et al.*, 2014) and known incomplete penetrance of Parkinson's disease risk alleles (Anheim *et al.*, 2012; Rana *et al.*, 2013; Trinh *et al.*, 2014; Marder *et al.*, 2015). For a subset of individuals in the IPDGC ($n = 572$) and PPMI ($n = 566$) WES cohorts, array-based genotyping data were also available, allowing us to compute concordance rates for genotyping calls present in both datasets



using two independent assays (Supplementary Table 4). We observe complete concordance for *GBA* variants as well as nearly perfect concordance (>>99%) for variant genotype calls in the full LSD gene set.

Statistical analysis

The sequence kernel association test – optimal (SKAT-O) (Lee *et al.*, 2012, 2016) was implemented in R using SKAT v1.0.9 to determine the difference in the aggregate burden of rare LSD gene variants between Parkinson's disease cases and controls. SKAT-O aggregates genetic information across defined genomic regions to test for associations. Covariates were included to adjust analyses for gender and WES coverage (pre-quality control missingness). Twenty multi-dimensional scaling components were also included to account for other possible confounding factors (four components for analyses of the NeuroX genotyping cohort). An empirical *P*-value (*P*) was derived from the distribution of null results based on 10 000 permutation trials in which case/control assignment was randomized. As shown in Fig. 1, SKAT-O analysis was initially performed for the complete LSD gene set, considering each class of variants defined based on frequency and

functional characteristics. To adjust for multiple comparisons, we applied the Bonferroni-Holm stepwise procedure to control for the familywise error rate and establish a corrected statistical significance threshold and adjusted *P*-value (P_{adj}) based on a significance level, α of 0.05 (Holm, 1979). For those categories with a significant SKAT-O association in the full gene set, a secondary analysis was performed excluding all *GBA* variants to confirm the involvement of additional genes. For example, in the IPDGC discovery cohort, we adjusted for $k = 5$ or $k = 2$ comparisons for the number of variant categories evaluated in the primary and secondary analyses, respectively. Due to the nested variant categories (Fig. 1) and the highly interdependent nature of the respective burden tests, we separately considered those results with an empirical SKAT-O *P*-value < 0.05, but not surviving the Bonferroni-Holm correction, as 'suggestive'. Unadjusted, empirical SKAT-O *P*-values for all gene set analyses are included in Supplementary Table 5. Lastly, to highlight those loci driving associations detected in the gene set, secondary analyses were also performed using SKAT-O to evaluate variants in each LSD gene independently. For these per gene analyses, which we considered exploratory due to limited statistical power, we report all findings with an empirical unadjusted *P*-value < 0.05.

To estimate statistical power, we performed 1000 SKAT simulations of causal subregions within the discovery or replication datasets. We assumed a Parkinson's disease prevalence of 0.0041 and 0.0017 for the IPDGC and PPMI datasets, respectively, based on their distinct ages of onset (Supplementary Table 1) (Pringsheim *et al.*, 2014). For gene set simulations, subregion length was defined as the sum of individual LSD gene coding region lengths (169.5 kb and 170.4 in IPDGC and PPMI, respectively). For single gene simulations, the average gene length was used (3.5 kb and 3.2 kb, respectively). The MAF cut-off for causal variants was set to 0.00035 (based on the frequency of rare *GBA* loss-of-function alleles in the IPDGC dataset) or 0.03 for the rare or more common variant models, respectively, and penetrance was assumed to be either 100% or 10%. Because we predict that LSD gene variants associated with Parkinson's disease will have a damaging effect, all causal variants were assumed to have a positive coefficient (risk rather than protective alleles).

Results

Variants were extracted from 54 genes responsible for LSDs, defined based on widely accepted criteria (Table 1), and filtered into nested categories based on two frequency thresholds and three tiers of functional criteria (Fig. 1A). Our overall analytic approach is illustrated in Fig. 1B. To test our hypothesis that an aggregate burden of variants in the LSD gene set contributes to Parkinson's disease, we first implemented SKAT-O within the IPDGC WES discovery cohort (Table 2). Following adjustment for multiple comparisons (see 'Materials and methods' section), significant associations were detected for the LSD gene set considering either all non-synonymous variants (Category 1b, $P_{adj} = 0.014$) or likely damaging variants (Category 2b, $P_{adj} = 0.0055$), when using the more relaxed frequency

Table 2 Analyses of LSD variant burden in Parkinson's disease

Cohort	Cases (n)	Controls (n)	Variants ^a	(a) MAF < 1%		(b) MAF < 3%	
				n ^b	P _{LSD} ^c	n ^b	P _{LSD} (P-GBA) ^c
Discovery							
IPDGC	1167	1685	(1) Nonsyn	746 (709)	0.056	760 (721)	0.014 (0.026)
			(2) CADD	585 (555)	0.066	596 (564)	0.0055 (0.0198)
			(3) LoF	69 (65)	0.464	— ^d	—
Replication							
PPMI	436	169	(1) Nonsyn	243 (237)	0.096	256 (248)	0.320
			(2) CADD	179 (174)	0.294	187 (180)	0.281
NeuroX	6713	5964	(1) Nonsyn	452 (443)	0.068	467 (456)	0.0004 (0.002)
			(2) CADD	338 (331)	0.057	348 (339)	0.0003 (0.020)

^aVariants were classified into nested categories (Fig. 1A) based on two frequency thresholds, (a) MAF < 1% or (b) MAF < 3%, and three functional filters, all non-synonymous (1), CADD likely damaging (2), and loss-of-function (3).

^bn = total number of LSD variant (number of variants excluding *GBA*). In parentheses, the number of variants excluding those in *GBA* are shown.

^cEmpirical SKAT-O *P*-values are based on 10 000 permutations following randomization of case/control status, and adjusted for multiple comparisons using the Bonferroni-Holm method (see 'Materials and methods' section). As shown in Fig. 1, primary analyses consider the variant burden among 54 LSD genes (*P*_{LSD}). For significant SKAT-O results, secondary analyses were performed excluding all variants in *GBA* (*P*_{-GBA}). Unadjusted *P*-values are reported in Supplementary Table 5.

^dNo additional LoF variants met the relaxed frequency threshold (MAF < 3%).

LoF = loss of function variants; NeuroX = NeuroX exome array cohort; Nonsyn = non-synonymous variants.

threshold of MAF < 3%. When considering only the subset of rare (MAF < 1%) non-synonymous or likely damaging variants, the SKAT-O result was attenuated and no longer significant (Category 1a, *P*_{adj} = 0.056 and category 2a, 0.066, respectively). No association was observed when considering only loss-of-function alleles (Category 3, *P*_{adj} = 0.464), possibly due to the relative paucity of such variants limiting statistical power (Supplementary Table 2). We next repeated analyses with significant results, but excluding all *GBA* variants. As expected, the strength of the associations was attenuated; however, both SKAT-O results, including either all non-synonymous variants (MAF < 3%) or the subset of likely damaging variants, were robust to the exclusion of *GBA* and remained significant (Category 1b, *P*_{adj} = 0.026 and Category 2b, *P*_{adj} = 0.0198). Our results indicate that the association between variant burden and Parkinson's disease risk in the IPDGC discovery cohort is mediated, at least in part, by the effects of LSD genes other than *GBA*, an established Parkinson's disease susceptibility locus.

To replicate our findings, we leveraged two independent cohorts, including an additional WES dataset from PPMI (436 Parkinson's disease cases and 169 controls) (Parkinson Progression Marker Initiative, 2011) and the NeuroX exome-wide genotyping dataset from IPDGC (6713 Parkinson's disease cases and 5964 controls) (Nalls *et al.*, 2015). We again implemented SKAT-O to detect a potential variant burden in Parkinson's disease cases versus controls. In the smaller PPMI replication cohort, we discovered suggestive evidence for an excessive LSD variant burden in Parkinson's disease (Table 2 and Supplementary Table 5); however, this finding was not significant following adjustment for multiple comparisons (Category 1a, *P*_{adj} = 0.096). The association signal—which appeared independent of *GBA*—was detected exclusively among rare

alleles (MAF < 1%) and only when considering all non-synonymous variants. It is possible that SKAT-O is sensitive to cohort differences between PPMI and the IPDGC, including both sample size and pertinent demographic features (e.g. age of onset and family history; Supplementary Table 1). However, in the substantially larger NeuroX dataset, significant burden associations were detected for the same two variant categories implicated by SKAT-O in the IPDGC discovery cohort (Table 2), despite the less comprehensive genotyping coverage compared to WES. A major driver for the robust LSD gene set association in NeuroX (Category 1b, *P*_{adj} = 0.0004 and Category 2b, *P*_{adj} = 0.0003) appears to be the more common *GBA*^{E326K} variant (Freq_{Cases} = 0.021, Freq_{Controls} = 0.011), which has been reported to be associated with Parkinson's disease risk in several large studies (Duran *et al.*, 2012; Pankratz *et al.*, 2012). Importantly, consistent with our findings in the IPDGC discovery cohort, the LSD gene set burden association for both of these variant categories remained significant in NeuroX following exclusion of *GBA* (Category 1b, *P*_{adj} = 0.002 and Category 2b, *P*_{adj} = 0.020). When considering only the subset of rare (MAF < 1%) variants in the NeuroX dataset, the SKAT-O result for the LSD gene set was attenuated and no longer significant; although, the association in the non-synonymous variant group remained suggestive, and this association was independent of *GBA* (Supplementary Table 5). In sum, based on analyses in three independent Parkinson's disease case-control datasets, we demonstrate a burden of variants in LSD genes associated with Parkinson's disease risk, and this signal is at least partially independent of *GBA*.

To determine which additional LSD genes/variants may be responsible for the observed association with Parkinson's disease risk, we performed exploratory analyses using SKAT-O to assess for potential contribution of

variants within each gene considered independently. For these analyses, we returned to the IPDGC discovery dataset, and again focused on likely damaging variants, which showed the strongest association signal in our primary analysis (Category 2b). In these gene-based analyses, besides the expected result for *GBA* ($P = 0.0001$) and confirmation of *SMPD1* ($P = 0.029$), we discover evidence of novel aggregate associations for variants in *CTSD* ($P = 0.002$), *SLC17A5* ($P = 0.005$), and *ASAH1* ($P = 0.031$). The specific variants implicated for each of these genes are included in Supplementary Table 3, along with all other putative damaging variants considered in our full LSD gene set analysis. While our datasets are underpowered to definitively assess the contributions of a particular rare variant in any single gene (see 'Discussion' section), these results identify the most likely specific loci driving the aggregate LSD gene set association signal detected in the IPDGC discovery sample.

Lastly, we examined the distribution of putative damaging LSD gene variants (MAF < 3%, Category 2b) within the IPDGC WES cohort (Fig. 2). Consistent with our finding of an excessive variant burden in Parkinson's disease, the distribution of variants appeared modestly right-skewed in cases. The average variant burden among IPDGC cases was 0.9 alleles per individual, which was slightly higher than that seen in controls (0.8 alleles per individual). Given their commonality, the majority of IPDGC cases (56%) have at least one putative damaging variant in an

LSD gene, and 21% carry multiple alleles. Notably, only 22 of 1156 total Parkinson's disease cases are homo- or hemizygous for putative damaging LSD variants (Supplementary Table 6), suggesting that Mendelian recessive or X-linked inheritance may contribute minimally to the overall burden association. As discussed further below, our findings are consistent with a hypothetical model in which multiple LSD gene variants may interact to influence Parkinson's disease risk.

Discussion

This study reveals an important connection between the genetic factors broadly responsible for LSDs, which are predominantly paediatric Mendelian disorders, and Parkinson's disease, an adult-onset neurodegenerative disorder with complex genetic aetiology. Specifically, among 54 genes that cause LSDs, we find evidence for a burden of damaging alleles in association with Parkinson's disease risk. This association persisted after excluding *GBA*, consistent with a contribution from additional LSD genes. More than half of Parkinson's disease cases in our cohort harbour one or more putative damaging variants among the LSD genes. Thus, our results implicate several promising new Parkinson's disease susceptibility loci and reinforce the importance of lysosomal mechanisms in Parkinson's disease pathogenesis.

The strengths of this study include a large Parkinson's disease case/control discovery cohort as well as two independent datasets for replication of our findings. The IPDGC WES discovery sample is characterized by younger-onset Parkinson's disease cases (mean age ~41 years) and those with a positive family history, thereby enriching for individuals with a potential genetic contribution. Recruitment of a substantially older IPDGC control group (mean age ~64), reduces the possibility of latent, unrecognized Parkinson's disease (i.e. with minimal or absent symptoms), likely further increasing power for genetic discovery. By contrast, our PPMI and NeuroX replication cohorts include older cases (mean age ~62 years) and age-matched controls, making them more broadly representative of the older adult population commonly affected by Parkinson's disease. Consistent findings of an excessive LSD variant burden across these three datasets, especially the large NeuroX sample ($n \sim 12\,677$), strongly enhances the generalizability of our conclusions. To minimize the possibility of population stratification, stringent quality control filters were implemented to ensure a homogeneous European ancestry sample in all study cohorts (Supplementary Fig. 1). Nevertheless, it will also be important to examine other ethnic populations in the future, especially those potentially enriched for LSD-causing variants due to genetic bottlenecks.

Since our understanding of the characteristics of causal alleles—including in both Parkinson's disease and LSDs—is incomplete, our initial analyses systematically considered

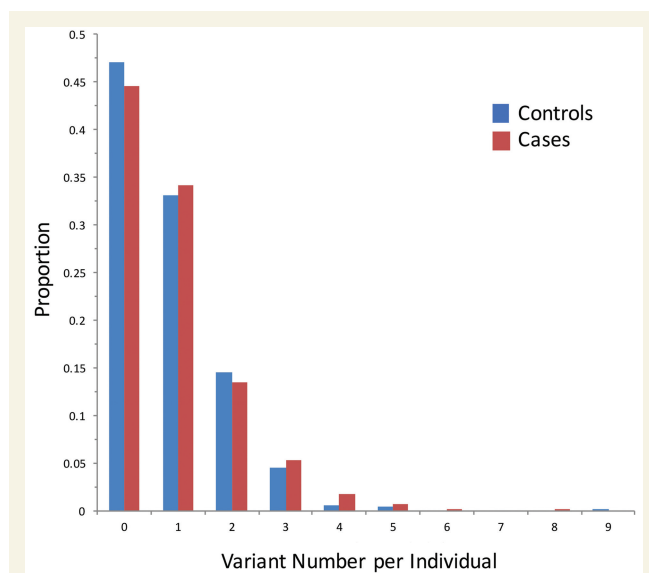


Figure 2 Distribution of LSD variants in the IPDGC cohort. The number of likely damaging LSD variants (MAF < 3%, CADD C-score ≥ 12.37) per individual is shown versus the proportional representation in the IPDGC discovery cohort. Cases (red) and controls (blue) are plotted separately. Many individuals harbour multiple LSD alleles, and the distribution is right-skewed among Parkinson's disease cases. The analysis considers variants in all 54 LSD genes. Supplementary Fig. 2 shows a similar plot restricted to the five top driver genes.

multiple variant classes binned into categories based on frequency and putative functional impact. In the IPDGC and PPMI cohorts, WES offers comprehensive characterization of LSD gene variants. By contrast, since the NeuroX data are restricted to those variants included on the genotyping array, it is possible that many potential pathogenic variants would be missed. Nevertheless, a total of 348 putative damaging variants were detected, including alleles for all LSD genes (Supplementary Table 2). Importantly, the selected analytic tool, SKAT-O, is robust to a wide frequency spectrum, including rare and more common alleles, and to variants with different magnitudes and directions of effect (Lee *et al.*, 2012, 2016). Our results suggest that consideration of likely damaging alleles based on bioinformatic predictions, including more common LSD variants (MAF < 3%), appeared to offer optimal sensitivity for detection of a significant aggregate variant association. Many of these variants are known to be pathogenic for LSDs (Supplementary Table 3). For example, of the *GBA* variants considered in our analyses, 27% of those with annotations available in ClinVar (Landrum *et al.*, 2016) are rated as likely or definitively pathogenic. Critically, the implementation of burden association tests for joint consideration of LSD genes significantly improves statistical power over single gene and variant tests (Zuk *et al.*, 2014). In populations of European ancestry similar to our study cohorts, loss-of-function alleles, including those established to cause LSDs, are individually rare (Supplementary Table 2), and based on *post hoc* simulations (see ‘Materials and methods’ section), we estimate poor power for discovery of rare Parkinson’s disease risk alleles at single loci. For example, assuming a rare variant model (MAF = 0.035%, as for *GBA* loss-of-function alleles in our sample) and even assuming full penetrance, the IPDGC discovery cohort has only 30% power to discover an association for a single gene. However, a similar simulation considering the full set of 54 LSD genes was fully powered (100%). Our consideration of higher frequency variants further enhances power for both discovery and replication, especially when coupled with filtering based on potential pathogenicity. For example, allowing for more common variants (MAF < 3%) and assuming 10% of such alleles are causal, we estimate that the smaller PPMI cohort achieves 95% power for replication of a gene set association, whereas negligible power (1%) is available for interrogation of a single gene candidate. We anticipate that larger WES datasets will significantly improve power, including for per gene analyses.

We also performed analyses in the IPDGC cohort to pinpoint the specific drivers from the LSD gene set responsible for increasing Parkinson’s disease risk. Our results (i) recapitulate the established association with *GBA*; (ii) strengthen the emerging evidence in support of *SMPD1*; and (iii) newly implicate *SLC17A5*, *ASAH1*, and *CTSD* as candidate Parkinson’s disease susceptibility genes. Recessive mutations in *SMPD1* cause Niemann-Pick type A/B disease and this locus has been independently implicated in Parkinson’s disease risk based on several published

studies (Lee *et al.*, 2012; Foo *et al.*, 2013; Gan-Or *et al.*, 2013, 2015; Clark *et al.*, 2015). While our analysis identified 21 candidate, putative damaging *SMPD1* risk alleles (Supplementary Table 3), most appear distinct from those reported in other studies of Parkinson’s disease. One notable exception, *SMPD1* p.L304P, was previously implicated in a study of Ashkenazi Jewish subjects (Gan-Or *et al.*, 2013). Another non-synonymous variant identified in the IPDGC sample, p.P332L, is at the same amino acid position as a different substitution, p.P332R, which was previously implicated in a Chinese Parkinson’s disease cohort (Foo *et al.*, 2013). Among the novel candidate genes, *SLC17A5*, *ASAH1*, and *CTSD*, most of the implicated variants are rare (MAF < 1%). Only two of these variants (rs16883930 and rs141068211 in *SLC17A5* and *ASAH1*, respectively) are present in the 1000 Genomes reference (The 1000 Genomes Project Consortium, 2012), having been previously examined in genome-wide scans, and both were non-associated with Parkinson’s disease risk ($P > 0.05$) based on available data (Lill *et al.*, 2012). Mutations in *SLC17A5*, *ASAH1*, and *CTSD* cause the rare LSDs, Salla disease, Farber lipogranulomatosis, and neuronal ceroid lipofuscinosis (CLN10), respectively. Whereas sialin (the protein product of *SLC17A5*) is a lysosomal membrane transporter for sialic acid, acid ceramidase (*ASAH1*) participates in ceramide metabolism, similar to glucocerebrosidase and sphingomyelinase (*SMPD1*). In addition to promoting lysosomal stress, glucosylceramide, which accumulates in Gaucher disease, has been suggested to directly promote the aggregation of α -synuclein (Mazzulli *et al.*, 2011; Moors *et al.*, 2016). Interestingly, *CTSD* encodes a lysosomal aspartyl proteinase that has been independently implicated in α -synuclein degradation (Cullen *et al.*, 2009; McGlinchey and Lee, 2015). In sum, the LSD genes and variants implicated by our studies are excellent candidates for further replication, including resequencing and/or genotyping in the largest available Parkinson’s disease case/control samples. Although we used standard quality control procedures for calling variants from WES and genotyping data, definitive confirmation of specific variants will require additional studies.

There is a growing recognition of the importance of lysosomal biology in Parkinson’s disease pathogenesis (Moors *et al.*, 2016; Wong and Krainc, 2016). First, the lysosome is an important route for α -synuclein degradation (Cuervo *et al.*, 2004; Lee, 2004; Vogiatzi *et al.*, 2008). Genomic variants that elevate α -synuclein protein levels—such as rare locus multiplication (Singleton *et al.*, 2003) or a common polymorphism that enhances promoter activity (Soldner *et al.*, 2016)—also increase Parkinson’s disease risk. Knockdown of selected LSD genes, including *GBA* or *SCARB2*, in neuronal cells or in mouse models impairs α -synuclein clearance (Cooper *et al.*, 2006; Sardi *et al.*, 2011; Rothaug *et al.*, 2014), whereas increasing glucocerebrosidase activity has the opposite effect (Sardi *et al.*, 2011; Mazzulli *et al.*, 2016b; Migdalska-Richards *et al.*,

2016). Second, lysosomal autophagy plays a critical role in mitochondrial quality control, and substantial evidence, including from genetics, highlight mitochondrial dysfunction in Parkinson's disease (Haelterman *et al.*, 2014). Third, there is accumulating evidence from numerous experimental models that α -synuclein interferes with endoplasmic reticulum-to-Golgi vesicle trafficking, inducing reciprocal disruptions in lysosomal biogenesis (Cooper *et al.*, 2006). Expression of α -synuclein impeded trafficking of multiple hydrolases linked to LSDs, including GBA, within human dopaminergic neurons (Mazzulli *et al.*, 2016a). In one recent study, subjects with idiopathic Parkinson's disease, in which GBA carriers were excluded, were found to have modest but significantly reduced glucocerebrosidase enzymatic activity based on peripheral blood testing (Alcalay *et al.*, 2015). Fourth, besides GBA and the other LSD genes implicated in our study, genome-wide association studies of Parkinson's disease have recently identified common variants at the GALC locus, which causes Krabbe disease (Chang *et al.*, 2017). Further, mutations in ATP13A2, a rare cause of recessive juvenile-onset parkinsonism and dementia, have been independently implicated to cause the LSD neuronal ceroid lipofuscinosis (Bras *et al.*, 2012). Lastly, many other common and rare Parkinson's disease risk alleles, including at RAB7L1, GAK, LRRK2, and VPS35 have strong functional links to vesicle trafficking, including for lysosomal biogenesis and function. Together, these findings support a model in which partial loss-of-function in genes regulating lysosomal activity, such as those that cause LSDs, may increase vulnerability to α -synuclein-mediated mechanisms in Parkinson's disease.

While our analyses reveal a robust and replicable LSD variant burden in Parkinson's disease cases, the overall magnitude of the difference between variant frequencies in cases and controls appears modest (Fig. 2). We speculate that this is probably an underestimate of the true difference due to several assumptions. Specifically, only a subset of the 54 LSD genes and 760 non-synonymous variants considered in our burden analyses are likely to be truly involved in Parkinson's disease risk. Further, as noted above, while the CADD framework allowed us to prioritize 596 variants as putative damaging alleles, larger Parkinson's disease exome datasets with improved statistical power will be required to resolve the specific LSD genes and variants that contribute to Parkinson's disease risk. Lastly, similar to GBA (Anheim *et al.*, 2012; Rana *et al.*, 2013), we expect that many of the other LSD gene variants contributing to Parkinson's disease risk may have individually modest and therefore incompletely penetrant effects, perhaps modified by alleles at other loci (Cooper *et al.*, 2013). In sum, the likely (i) incomplete penetrance of many pathogenic variants; along with (ii) contamination of our analyses by many benign variants would be expected to inflate estimates for the LSD variant burden among controls and attenuate the overall SKAT-O association.

Parkinson's disease heritability remains incompletely explained by the genes and variants identified to date (Hamza and Paymi, 2010; Do *et al.*, 2011; Keller *et al.*, 2012; Verstraeten *et al.*, 2015). Besides the likelihood of yet undiscovered loci, alternative explanations for familial aggregation of disease include epigenetic changes due to shared environmental exposures or even false positive diagnoses due to phenocopies (Pihlström and Toft, 2011; Mullin and Schapira, 2015). In complex genetic disorders such as Parkinson's disease, the cumulative impact of common and rare variants at multiple genomic loci, as well as non-additive interactions among alleles, likely also play an important role (Lupski *et al.*, 2011; Cooper *et al.*, 2013). Polygenic modelling approaches have previously demonstrated how common risk alleles can cumulatively impact Parkinson's disease risk and age-of-onset (Nalls *et al.*, 2014; Escott-Price *et al.*, 2015). In addition, a recently published analysis in the IPDGC WES and NeuroX cohorts identified evidence for oligogenic interactions underlying Parkinson's disease risk, including alleles for GBA and those for established Mendelian Parkinson's disease genes (Lubbe *et al.*, 2016). In the IPDGC, WES reveals a substantial proportion of Parkinson's disease cases (21%) carrying two or more likely damaging variants in LSD genes. Consistent with other reports (Clark *et al.*, 2015), our observation suggests the possibility that LSD gene variants may interact in a multi-hit, combinatorial manner to degrade lysosomal function, causing the accumulation of α -synuclein and potentially other toxic substrates, and increasing susceptibility for Parkinson's disease. Oligogenic interactions such as those proposed here may be an important source for 'missing heritability' in Parkinson's disease (Pihlström and Toft, 2011; Mullin and Schapira, 2015). Recent work has also implicated oligogenic inheritance in other neurological disorders, including amyotrophic lateral sclerosis (van Blitterswijk *et al.*, 2012; Kenna *et al.*, 2013; Cady *et al.*, 2015) and idiopathic peripheral neuropathy (Gonzaga-Jauregui *et al.*, 2015), and further reveals how pleiotropic genes causing early-onset, monogenic disorders may act in combination to additionally trigger late-onset, complex genetic disorders (Lupski *et al.*, 2011; Cooper *et al.*, 2013). Future studies, including even larger, case-control cohorts with WES and complementary experiments in Parkinson's disease cellular or animal models, are needed to further investigate whether a variant burden in LSD genes, perhaps in combination with other susceptibility loci, underlies oligogenic risk and contributes substantially to Parkinson's disease heritability.

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Supplementary material

Supplementary material is available at *Brain* online.

Appendix I

See Supplementary material for details of authors and affiliations.

IPDGC Consortium members

Mike A. Nalls, Vincent Plagnol, Dena G. Hernandez, Manu Sharma, Una-Marie Sheerin, Mohamad Saad, Javier Simón-Sánchez, Claudia Schulte, Suzanne Lesage, Sigurlaug Sveinbjörnsdóttir, Sampath Arepalli, Roger Barker, Yoav Ben-Zion, Henk W. Berendse, Daniela Berg, Kailash Bhatia, Rob M. A. de Bie, Alessandro Biffi, Bas Bloem, Zoltan Bochdanovits, Michael Bonin, Jose M. Bras, Kathrin Brockmann, Janet Brooks, David J. Burn, Elisa Majounie, Gavin Charlesworth, Codrin Lungu, Honglei Chen,

Patrick F. Chinnery, Sean Chong, Carl E. Clarke, Mark R. Cookson, J. Mark Cooper, Jean Christophe Corvol, Carl Counsell, Philippe Damier, Jean-François Dartigues, Panos Deloukas, Günther Deuschl, David T. Dexter, Karin D. van Dijk, Allissa Dillman, Frank Durif, Alexandra Dürr, Sarah Ekins, Jonathan R. Evans, Thomas Foltynie, Jing Dong, Michelle Gardner, J. Raphael Gibbs, Alison Goate, Emma Gray, Rita Guerreiro, Clare Harris, Jacobus J. van Hilten, Albert Hofman, Albert Hollenbeck, Janice Holton, Michele Hu, Xuemei Huang, Isabel Wurster, Walter Mätzler, Gavin Hudson, Sarah E. Hunt, Johanna Huttenlocher, Thomas Illig, Pálmi V. Jónsson, Jean-Charles Lambert, Cordelia Langford, Andrew Lees, Peter Lichtner, Patricia Limousin, Grisel Lopez, Delia Lorenz, Codrin Lungu, Alisdair McNeill, Catriona Moorby, Matthew Moore, Huw R. Morris, Karen E. Morrison, Valentina Escott-Price, Ese Mudanohwo, Sean S. O'Sullivan, Justin Pearson, Joel S. Perlmutter, Hjörvar Pétursson, Pierre Pollak, Bart Post, Simon Potter, Bernard Ravina, Tamas Revesz, Olaf Riess, Fernando Rivadeneira, Patrizia Rizzu, Mina Ryten, Stephen Sawcer, Anthony Schapira, Hans Scheffer, Karen Shaw, Ira Shoulson, Joshua Shulman, Ellen Sidransky, Colin Smith, Chris C. A. Spencer, Hreinn Stefánsson, Francesco Bettella, Joanna D. Stockton, Amy Strange, Kevin Talbot, Carlie M. Tanner, Avazeh Tashakkori-Ghanbaria, François Tison, Daniah Trabzuni, Bryan J. Traynor, André G. Uitterlinden, Daan Velseboer, Marie Vidailhet, Robert Walker, Bart van de Warrenburg, Mirdhu Wickremaratchi, Nigel Williams, Caroline H. Williams-Gray, Sophie Winder-Rhodes, Kári Stefánsson, Maria Martinez, Nicholas W. Wood, John Hardy, Peter Heutink, Alexis Brice, Thomas Gasser, Andrew B. Singleton.

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