WDR26 Haploinsufficiency Causes a Recognizable Syndrome of Intellectual Disability, Seizures, Abnormal Gait, and Distinctive Facial Features

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We report 15 individuals with de novo pathogenic variants in *WDR26*. Eleven of the individuals carry loss-of-function mutations, and four harbor missense substitutions. These 15 individuals comprise ten females and five males, and all have intellectual disability with delayed speech, a history of febrile and/or non-febrile seizures, and a wide-based, spastic, and/or stiff-legged gait. These subjects share a set of common facial features that include a prominent maxilla and upper lip that readily reveal the upper gingiva, widely spaced teeth, and a broad nasal tip. Together, these features comprise a recognizable facial phenotype. We compared these features with those of chromosome 1q41q42 microdeletion syndrome, which typically contains *WDR26*, and noted that clinical features are consistent between the two subsets, suggesting that haploinsufficiency of *WDR26* contributes to the pathology of 1q41q42 microdeletion syndrome. Consistent with this, *WDR26* loss-of-function single-nucleotide mutations identified in these subjects lead to nonsense-mediated decay with subsequent reduction of RNA expression and protein levels. We derived a structural model of WDR26 and note that missense variants identified in these individuals localize to highly conserved residues of this WD-40-repeat-containing protein. Given that *WDR26* mutations have been identified in ~1 in 2,000 of subjects in our clinical cohorts and that *WDR26* might be poorly annotated in exome variant-interpretation pipelines, we would anticipate that this disorder could be more common than currently appreciated.

Characterizing and identifying syndromic forms of intellectual disability can be difficult for both clinicians and scientists. This is typically due to variability in the severity, associated features, and rarity of these disorders. Several of these challenges have improved with the advent of genome-wide sequencing coupled with careful standardized phenotyping and highly collaborative networks, which have markedly facilitated the identification, characterization, and recognition of rare syndromic disorders with intellectual disability. However, limitations often related to poor annotation or understanding of gene function continue to hinder the identification of disease-related genes. Here, we report the recognition of a role for *WDR26* (WD40 repeat protein 26 [MIM: 617424]) in human syndromic intellectual disability. This recognition was dependent upon the presence of de novo variants, the utilization of broad reference datasets that included this variably annotated gene, and a concerted effort of international collaborators to identify individuals and characterize the clinical features.

In the evaluation of two individuals (1 and 2) with mildly dysmorphic features and intellectual disability at different institutions (GeneDx, Children's Hospital of Philadelphia, and University Medical Center Utrecht),

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http://dx.doi.org/10.1016/j.ajhg.2017.06.002.

Table 1. Pathogenic *WDR26* Variants

Individual	cDNA Notation (GenBank: NM_025160.6)	Predicted Effect on Protein (GenBank: NP_079436.4)	Inheritance
1	c.1276G>T	p.Glu426*	de novo
2	c.1161_1162del	p.His389Profs*6	de novo
3	c.1457del	p.Val486Glufs*9	de novo
4	c.644T>C	p.Leu215Pro	de novo
5	c.904_905del	p.Gln302Aspfs*22	de novo
6	c.850G>A	p.Asp284Asn	de novo
7	c.137C>A	p.Ser46*	de novo
8	c.1570C>T	p.Gln524*	de novo
9	c.762T>G	p.Ser254Arg	de novo
10	c.1284G>A	p.Trp428*	de novo
11	c.1419+2dupT	splice site	de novo
12	c.835C>T	p.Arg279*	de novo
13	c.574dupA	p.Ile192Asnfs*8	de novo
14	c.514T>A	p.Trp172Arg	de novo
15	c.1149_1158+1del	p.Val384fs	de novo

each was noted to have a de novo nonsense mutation in the minimally characterized gene *WDR26*. Although this gene was not included in the OMIM gene set until recently (added March 31, 2017), it is included in Agilent v.4 and later exome capture sets (Agilent) as part of the RefSeq gene set.[1] The probability of loss-of-function intolerance (pLI)[2] for *WDR26* in the Exome Aggregation Consortium (ExAC) Browser was 1.00, strongly supporting that these variants are pathogenic. Subsequently, *WDR26* was included in lab gene annotation datasets that enabled the identification of additional de novo loss-of-function and missense variants (ExAC missense Z score for 68 observed and 175 expected: $Z = 3.94$[2]). Identification of additional subjects with *WDR26* variants was subsequently facilitated by the use of GeneMatcher,[3] PhenomeCentral,[4] and DECIPHER[5] as part of the Matchmaker Exchange Repositories.[6] We consequently identified 15 subjects with pathogenic variants of *WDR26*. All mutations were de novo, identified via trio exome sequencing, and included five frameshift, five nonsense, one splice site, and four missense mutations (Table 1). Individuals were identified in cohorts of 28,700 exomes for all indications and in 21,400 exomes for individuals with intellectual disability, giving a frequency of ~1 in 2,000 for all exome analyses and ~1 in 1,500 for individuals with intellectual disability.

To compare and characterize the clinical features of these individuals, we obtained consent and collected clinical information. Consent for publication was obtained for all photographs included in this manuscript. All individuals for whom evaluation or analysis beyond routine clinical care was performed were enrolled in a protocol with informed consent approved by the institutional review board of the Children's Hospital of Philadelphia, the Commissie Mensgebonden Onderzoek Regio Arnhem-Nijmegen, the Rouen University Hospital, the Health and Disability Ethics Committee of New Zealand, the East of England – Cambridge South of the National Research Ethics Service for the Deciphering Developmental Disorders (DDD) UK study, or the UK research ethics committee (REC) (10/H0305/83 granted by the Cambridge South REC and GEN/284/12 granted by the Republic of Ireland REC). A clinical case report for each subject is included in the Supplemental Note. Detailed molecular and clinical features for each individual have been compiled in Table S1.

The 15 subjects (10 females and 5 males) range in age from 24 months to 34 years. Consistent phenotypic features of these individuals include variable developmental delay, seizures, and similar facial features (Tables 2 and S1). Developmental delay ranges from mild to severe, and all individuals have delayed speech; four individuals had absent speech at the time of assessment (two at 4 years, one at 5.5 years, and one at 8 years). Individual 2, the oldest individual in the cohort, is described as having dysarthric speech as an adult. Motor delay is also common, such that the emergence of walking was reported from 17 months to 3 years. Of the ten individuals with available descriptions, all were described as having a wide-based, spastic, hemiparetic, and/or stiff-legged gait. Several subjects have stereotypies, including rocking behavior and abnormal hand movements or posturing, and overall, individuals are described as happy and socially engaging. Neurologic abnormalities are also common among the subjects. All individuals have a history of seizures, including febrile and/or non-febrile seizures, and several required antiepileptic medications for a period of time. The reported non-febrile seizure types include tonic-clonic, absence, and Rolandic, and age of onset ranges from the newborn period to 7 years. Minor structural brain malformations are present in 9 of 13 individuals. One female (individual 14) had a markedly abnormal left supratentorial hemispheric structure and has now had a left hemispherectomy with resulting hemiparesis. Hypotonia, often noted to be mild, was described in 9 of 12 individuals for whom information was available.

Individuals with mutations in *WDR26* also share a set of identifiable facial features (Figures 1 and S1). Common features include a prominent maxilla and upper lip (13/15), wide mouth (10/15), abnormal gingiva (9/15), widely spaced teeth (13/15), mildly coarse facial features (12/15), and a broad or full nasal tip (11/15). The gingival display represents a relatively unique finding (see individual 10 in Figure 1), but with the current relatively small number of individuals, it's unclear whether this represents increased vertical height of the maxilla or an inferiorly displaced attachment of the maxillary gingiva. This feature is an isolated finding in 7/15 individuals and manifests with overt gingival hyperplasia in an additional two individuals. Other facial features include anteversion of the nares

Table 2. Common Facial Features of Individuals with *WDR26* Mutations and 1q41 Microdeletions

Features	*WDR26* (n = 15)	1q41q42 Microdeletions Including *WDR26* (n = 17)
Developmental delay or intellectual disability	15/15	15/15
Seizures	15/15	13/14
CNS structural anomalies	10/14	11/15
Hypotonia	9/12	5/15
Abnormal gait	9/9	1/15
Happy and/or friendly personality	10/11	2/2
Autistic and/or repetitive behaviors or posturing	5/9	1/1
Coarse facial features	12/15	12/16
Full cheeks as a child	11/13	7/8
Abnormal eyebrows	6/15	5/12
Depressed nasal root	5/15	11/15
Anteverted nares	8/15	9/13
Full nasal tip	11/15	9/14
Prominent maxilla and protruding upper lip	13/15	7/12
Decreased cupid's bow	11/15	10/12
Widely spaced teeth	13/15	7/8
Abnormal gums	9/15	6/6

Fractions indicate the number observed over the number reported or ascertained. The following abbreviation is used: CNS, central nervous system.

(8/15), a tendency toward full cheeks in childhood (11/13), sparse lateral eyebrows (6/15), subjectively large irises often with rounded palpebral fissures (10/15), a depressed nasal bridge (5/15), mild micrognathia (5/15), and a partially flattened or decreased Cupid's bow of the upper vermillion border (11/15). Ophthalmologic abnormalities include strabismus and/or amblyopia (9/14) and Marcus Gunn jaw winking (1/15). Two individuals have small structural cardiac defects (one with a right sided aortic arch and one with a ventricular septal defect). One individual (individual 10) has a cleft palate. No subjects have major structural defects of the respiratory or gastrointestinal systems. Six individuals have been described as having feeding difficulties and/or failure to thrive. Although skeletal findings were ascertained in only a minority of subjects, one (individual 8) was found to have osteopathia striata of the distal femurs, two have pes cavus (individuals 9 and 11), one has moderate forefoot varus and mild left hip dysplasia (individual 13), and two have mild contractures of the lower extremities (knees in individual 8 and knees and hips in individual 10).

WDR26 is located in chromosomal region 1q42, which is proposed to be implicated in 1q41q42 microdeletion syndrome.[7] The findings of individuals with 1q42 deletions are characterized by consistent facial features, developmental delay, and a predisposition for seizures. Other clinical features in some individuals include short stature, microcephaly, and multiple structural anomalies including cleft palate, clubfoot, congenital heart disease, and congenital diaphragmatic hernia.[7–14] Deletions for these subjects range in size from 300 kb to 10 Mb and include varied subsets of genes. However, somewhat strikingly, a comparison of the clinical and facial features of subjects with minimal microdeletions, as noted in additional photos of individual 16 (Figure 1) from Au et al.[15] and the subject reported in Cassina et al.,[16] and of subjects with isolated *WDR26* mutations demonstrates a nearly complete overlap.

This overlap between clinical features of individuals with *WDR26* variants and those seen with 1q4142 microdeletions suggests that both result from haploinsufficiency of *WDR26*. However, it is formally possible that the missense, nonsense, and frameshift variants identified could lead to a dominant-negative protein. Furthermore, very little is known about the regulation of *WDR26* mRNA, which raises the possibility that *WDR26* nonsense or truncating mutations could occur in a stable mRNA and lead to the formation of a truncated, dominant-negative protein. To rigorously test these possibilities, we performed several experiments. First, because nonsense and frameshift mutations often lead to nonsense-mediated decay of mutant mRNA,[17,18] we tested the stability of mutant mRNA in each of three available lymphoblastoid cell lines derived from subjects with de novo *WDR26* mutations (individuals 2, 5, and 6), along with two control samples. In comparison to the equal presence of mutant and wild-type alleles in genomic DNA (Figure 2A, top row), the mutant allele was markedly reduced in cDNA derived from untreated cell lines with frameshift mutations (Figure 2A, middle row, two left panels). Because

Figure 1. Clinical Features of Individuals with Pathogenic *WDR26* Variants
Each individual is noted with a number that corresponds to that used throughout the manuscript. Images are clustered for each individual. Included on the top left of each cluster is the variant identified, the sex, and an additional study identifier, also noted in Table S1 at the right.

cycloheximide (CHX) is an inhibitor of nonsense-mediated decay of mRNA, we also treated the cell lines with cycloheximide before production of cDNA. With this treatment, we observed stabilization of the mutant mRNA allele (Figure 2A, bottom row, two left panels), consistent with nonsense-mediated decay in cycloheximide-untreated cells. We also observed no truncated WDR26 in any of the cell lines with western blotting (data not shown). We noted that, in contrast to the frameshift alleles, the missense mutation (c.850G>A, predicted to encode p.Asp284Asn) did not exhibit loss of expression of the mutant allele in the absence of cycloheximide, consistent with the expected absence of nonsense-mediated decay and suggesting an alternative mechanism of pathogenicity. Second, to assess whether this nonsense-mediated decay leads to a reduction in *WDR26* mRNA, as would be expected for haploinsufficiency, we performed quantitative RT-PCR of total *WDR26* mRNA levels from these same cell lines. These data demonstrated significant reductions for the frameshift mutations but only a

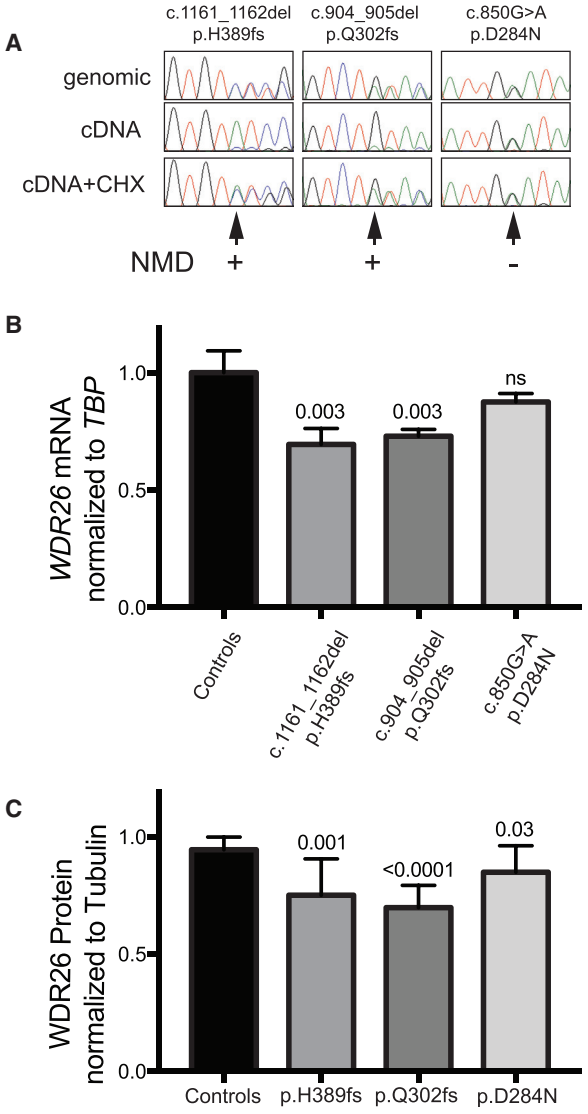

Figure 2. Effect of *WDR26* Mutations on Nonsense-Mediated RNA Decay and Protein Levels

(A) Nonsense-mediated mRNA decay (NMD) analysis. Epstein-Barr-virus-immortalized lymphoblastoid cell lines (LCLs) from subject 2 (c.1161_1162del [p.His389Profs*6], labeled p.H389fs), subject 4 (c.644T>C [p.Gln302Aspfs*22], labeled p.Q302fs), and subject 6 (c.850G>A [p.Asp284Asn], labeled p.D284N) were cultured in the presence of 1 mg/mL cycloheximide (CHX) for 6 hr and analyzed by RT-PCR and sequencing for the presence of wild-type and mutant alleles. Sequencing chromatograms for heterozygous genomic DNA as reference, untreated, and CHX-treated conditions are shown, demonstrating the reduced presence of the frameshift alleles but not the missense allele, denoted by an arrow at the location of the mutation and summarized result of the NMD assay (+ or −).

(B) *WDR26* RNA expression levels. Consistent with (A), digital droplet-based quantitative RT-PCR of *WDR26* mRNA expression normalized to TBP mRNA demonstrated a statistically significant reduction of expression for the frameshift alleles (69% for c.1161_1162del and 73% for c.644T>C) but not for the c.850G>A missense allele (88%).

(C) WDR26 levels were quantified by fluorescent western blotting and normalized to tubulin. Significantly lower WDR26 levels than control levels were noted for each pathogenic allele tested (75% for p.His389Profs*6, 70% for p.Gln302Aspfs*22, and 85% for p.Asp284Asn). The mean and SEM, along with unpaired two-tailed p values comparing multiple biological replicates (three for RNA and seven for protein) with controls, are demonstrated for each condition.

non-significant trend for the c.850G>A missense mutation (Figure 2B), suggesting a possible alternative pathogenic mechanism for missense variants. Lastly, to assess the effect of these variants on total protein levels, we performed quantitative western blotting with normalization to tubulin (Figure 2C). This demonstrated strongly significant reductions in WDR26 levels for the frameshift alleles and a mild reduction for the p.Asp284Asn missense variant (Figure 2C). Together, these data confirm that clinical features most likely arise from WDR26 haploinsufficiency and suggest that WDR26 missense variants could alter protein stability and also lead to reduced function in a manner consistent with deletion and loss-of-function alleles.

To further explore the mechanism of pathogenicity for the de novo *WDR26* missense variants, we assessed their conservation and localization within the protein. WDR26, typical for this protein class, contains WD-40 repeats (Figure 3A) and conserved LisH (LIS1 homology) and CTLH (C-terminal LIS homology) domains.[19,20] Each of the de novo missense WDR26 variants is located within a region of high sequence phylogenetic conservation (Figure 3B) and in one of these key motifs. Residues Trp172 and Leu215 are identical phylogenetically through *Drosophila*, whereas more notably, both Ser254 and Asp284 are identically conserved through yeast. This suggests that even subtle changes at these sites would be poorly tolerated. Consistent with this, the ExAC Residual Variance Intolerance Score (ExAC RVIS) for WDR26 is 18.1%,[21] and the subRVIS for the domains containing amino acids 172, 215, 254, and 284 is 9.2% (guidelines state that less than 35% is not tolerated[22]). Also consistently, the residue-specific prediction algorithms SIFT, PROVEAN, PolyPhen-2, and MutationTaster all predict the p.Trp172Arg, p.Leu215Pro, and p.Ser254Arg variants to be damaging. Finally, although there are mixed results for the informatics assessment of p.Asp284Asn, which alters the charge for a residue identically conserved through yeast, it is predicted to be damaging by PROVEAN and MutationTaster.

To better understand the potential effect of the missense variants identified in these subjects, we modeled a structure for WDR26 on the solved crystal structure for *Drosophila* WDS (PDB: 4CY3),[23] a homolog of human WDR5 in humans and a closely related WDR protein. In contrast with previous primary-sequence-based domain calling approaches, which suggest that WDR26 contains five, six, or seven WD-40 repeats,[19,20,24–26] our model for WDR26 suggests that it contains 14 variably perfect WD-40 repeats, each of which forms four-stranded anti-parallel β sheets or blades, and together they all compose two seven-bladed complete β propeller structures (Figures 3A and 3C). WD-40 domains 1–7 (WD1–WD7, amino acids 1–353) comprise an N-terminal β propeller,

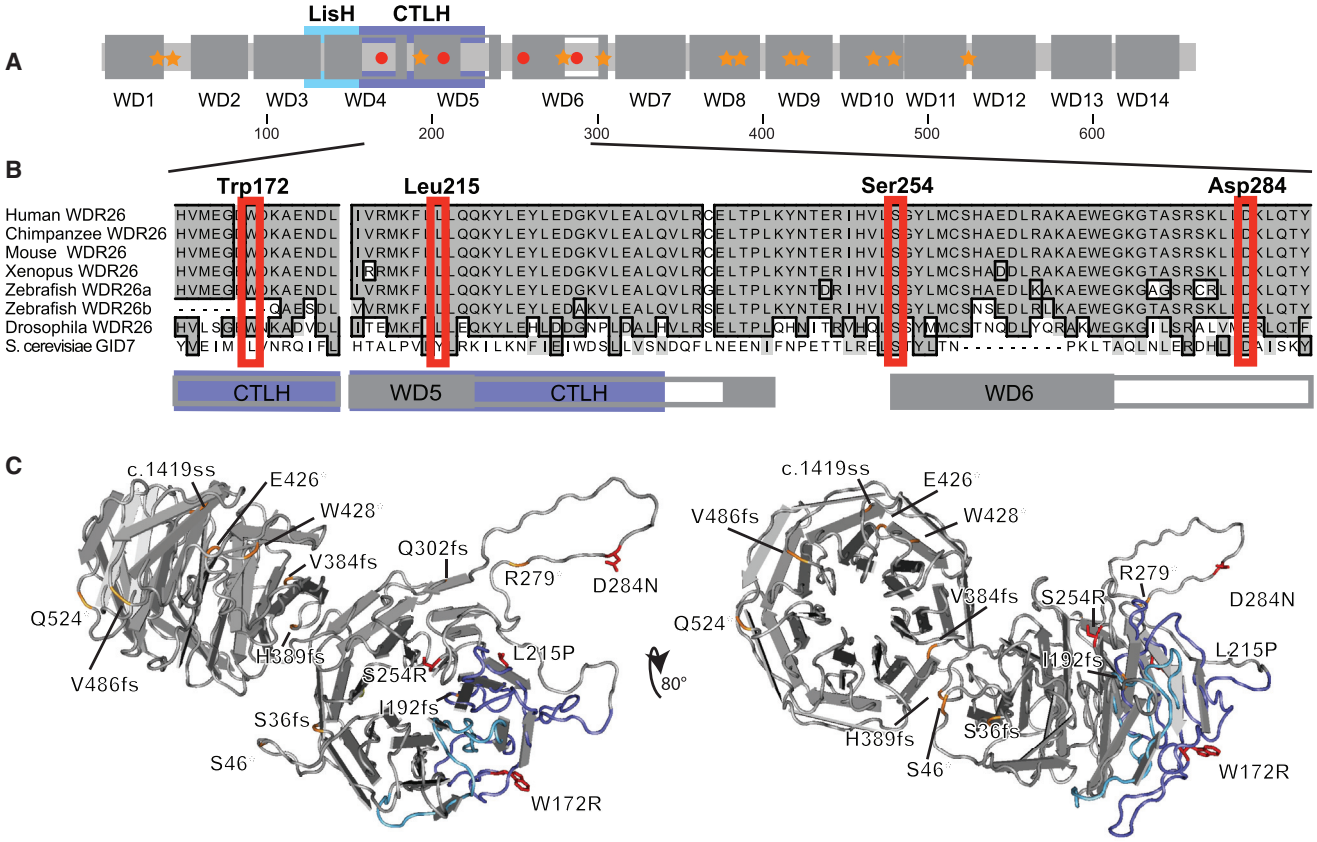

Figure 3. Localization of WDR26 Variants

(A) Schematic domains of WDR26. Illustrated are the key domains of WDR26, which include the 14 deduced WD repeats (larger dark-gray boxes labeled WD1–WD14; insertions in the domains are noted by unfilled gray bordered segments), the LisH and CTLH homology domains (in aqua and purple, respectively), and the location of loss-of-function (orange stars) and missense (red circles) variants. Scale numbers demonstrating amino acid residues are indicated beneath.

(B) Localization of WDR26 missense variants to highly conserved residues in WD repeats near the CTLH domain. ClustalW homology alignments for human WDR26a (UniProtKB: Q9H7D7; GenBank: NP_079436.4), Chimpanzee (*Pan troglodytes*) WDR26 (UniProtKB: K7CSM5), mouse (*Mus musculus*) WDR26 (UniProtKB/Swiss-Prot: Q8C6G8.3), frog (*Xenopus laevis*) WDR26 (UniProtKB: A0A0H5BJW1), zebrafish (*Danio rerio*) WDR26a (GenBank: NP_001189371.1) and predicted WDR26b (GenBank: XP_001921656.4), fruit fly (*Drosophila melanogaster*) WDR26 (UniProtKB/Swiss-Prot: Q7K0L4.1), and yeast (*Saccharomyces cerevisiae* S288c) GID7 (UniProtKB/Swiss-Prot: P25569.2) are shown. Identical residues are in dark gray with a black outlined border. Similar residues are indicated with light-gray shading and no border. Mutated residues are noted above, and red boxes denote the position in all species. Gray and purple boxes beneath denote the WD and CTLH domain boundaries, respectively.

(C) Structural model of WDR26 with variants. Illustrated are structural models of WDR26 with a direct view of the N-terminal β propeller domain (left) and an ~80° rotation toward the viewer to directly show the C-terminal β propeller domain (right). β sheets are illustrated as flat directional arrows. Note the organization of four β sheets into WD modules. The LisH and CTLH domains are noted by aqua and purple shading, respectively, of the protein backbone. Locations of variants are labeled and indicated; missense mutations are indicated by red shading of the residue and sidechain, and the relative position of loss-of-function alleles is noted by orange shading of the protein backbone.

and WD8–WD14 (amino acids 354–645) comprise a C-terminal β propeller. The C-terminal β propeller is ~80° off-axis from the N-terminal β propeller and contains the conserved LisH and CTLH domains (Figure 3C shows two views to illustrate each β propeller). Consistent with key functional roles, p.Trp172Arg (individual 14) and p.Leu215Pro (individual 4) lie within the CTLH domain, and p.Leu215Pro lies in the WD5 repeat in a key β sheet residue. Similarly, p.Ser254Arg (individual 9) lies in the neighboring WD6 repeat at the edge of a β sheet. The locations of these variants suggest that alterations in β sheets, which comprise essential components of the WD repeats, result in peptides with abnormal function and/or instability of the β propeller motif. In comparison, p.Asp284Asn (individual 6) lies within a predicted loop that is less well structured and extends from the surface of the protein to lie outside of the β propeller structure. In combination with the localization of this variant, the very high conservation of this region (Figure 3B), along with data suggesting that functional specificity of WD-40 proteins is determined by domains that extend from the β propeller,[27] suggests that the Asp284 residue could be involved in key extrinsic interactions. This also suggests that protein stability might be more tolerant of alteration at this site, a finding noted above by western blotting of WDR26 from the lymphoblastoid cells from this

Table 3. Growth Parameters for Individuals with *WDR26* Mutations

Parameter	n	Average (*Z* Score)	Range (*Z* Score)	No. Abnormal (No. < *Z* Score)
Birth weight	13	−0.9	−2.0 to 1.8	4/13 ≤ −1.5
Later Time Point				
Length	15	−0.6	−4.0 to 1.4	2/15 ≤ −1.5
Weight	14	−0.9	−5.0 to 4.3	6/14 ≤ −1.5
OFC	14	−0.9	−3.0 to 1.1	3/14 ≤ −1.5

Fractions indicate the number observed over the number reported or ascertained. The following abbreviation is used: OFC, occipital-frontal circumference.

individual (Figure 2C). The finding of similar clinical features of individuals with 1q41q42 microdeletions, loss-of-function nonsense and frameshift mutations, and missense mutations suggests that the missense variants identified in these individuals disrupt a key function of WDR26.

In total, we have identified 15 subjects with mutations that result in haploinsufficiency of *WDR26*. Because of the location of *WDR26* within the 1q41q42 deletion syndrome region, it might have been considered a candidate gene for causing the similar clinical features noted in these individuals. Of note, these microdeletions range in size from 300 kb to 10 Mb and include a varied subsets of genes; in fact, several attempts have been made to identify potential candidate genes for the clinical features seen in these individuals.[7–16] More recently, two papers[15,16] described individuals with intellectual disability, seizures, and dysmorphic features with 590 and 286 kb deletions on 1q41q42 that included *FBXO28* (MIM: 609100) and *WDR26*, along with *DEGS1* (MIM: 615843), *NVL* (MIM: 602426), *MIR320B2*, *CNIH4* (MIM: 617483), *MIR4742*, and *CNIH3* (Figure S2). Each concluded that, along with previously published cases, this narrowed the region of overlap to include a single candidate gene, *FBXO28*. However, these and previous analyses relied on the observation by Shaffer et al.[7] that *WDR26* was excluded from the smallest region of overlap by a single individual (subject 5). When reviewing this case in light of our current recognition of a facial phenotype associated with isolated *WDR26* mutations (Figures 1 and S1 and Tables 2, 3, and S1), we found that this individual lacks the characteristic facial features. Given that he has a large (5.1 Mb) deletion, it is likely that his associated features are due to haploinsufficiency of other genes. Furthermore, the ExAC pLI of 1.0 and constraint for missense variants of $Z = 3.94$ for *WDR26* are consistent with a very strong effect if deleted, whereas the pLI for *FBXO28* is less significant at 0.93, and all other genes in this interval demonstrate pLIs less than these. Together, when assessing both neurocognitive and facial phenotypes, these genetic data support that *WDR26* is the likely candidate gene whose haploinsufficiency is the cause of 1q41q42 deletion syndrome.

Assessment of the mechanism by which *WDR26* haploinsufficiency leads to human developmental disorders has yet to be elucidated. *WDR26* is expressed in most human tissues, including the brain and skeletal muscle at both fetal and adult stages,[19] consistent with the tissues involved in individuals with *WDR26* mutations. However, multiple roles have been proposed for WDR26. Data from relatively few studies suggest that it could play wide-ranging roles in regulation of MAPK, Wnt, and PI3K signaling; neuronal and cardiomyoblast proliferation; apoptosis signaling; and leukocyte activation and signaling.[19,20,24–26,28–30] We have tested cell lines derived from heterozygous subjects for evidence of altered Wnt signaling but have not noted any changes in lymphoblastoid or fibroblast cell types (data not shown).

Similarly, additional understanding of the biological function of WDR26 could indeed benefit from insight gained from clinical features of individuals with *WDR26* mutations. For example, the observed common features (including intellectual disability more prevalently involving speech; seizures; wide-based, spastic, and/or stiff-legged gait; a prominent maxilla and upper lip; and widely spaced teeth; Tables 2 and S1) could underlie the reasons that several alternative diagnoses were considered for individuals in this cohort. Considered diagnoses included Angelman syndrome (MIM: 105830; individuals 4, 7, 10, and 11) and Pitt-Hopkins syndrome (MIM: 610954; individual 4), suggesting a disorder of neuronal development.[31] In addition, atypical Cornelia de Lange syndrome (MIM: 122470; individuals 1 and 6), Coffin-Siris syndrome (MIM: 135900; individual 1), Floating-Harbor syndrome (MIM: 136140; individual 6), X-linked alpha-thalassemia/mental retardation syndrome (MIM: 301040; individuals 7, 9, and 15), Kabuki syndrome (MIM: 147920; individual 13), and Kleefstra syndrome (MIM: 610253; individuals 12 and 15) were considered. These diagnoses suggest that additional possible pathogenic mechanisms for *WDR26* haploinsufficiency might be related to chromatin regulation.[32–37] This would be consistent with an overlap between the clinical features in these subjects and those of the recently denoted "transcriptomopathies."[38,39]

In summary, we coupled exome sequencing with variant annotation and interpretation via pipelines including broadly annotated gene sets, along with global collaborative tools, to identify human mutations in *WDR26*. This cohort of individuals demonstrates a recognizable phenotype of intellectual disability, developmental delay, seizures,

abnormal gait, and characteristic facial features that include a prominent maxilla and upper lip that readily reveal the upper gingiva and widely spaced teeth. Notably, this gene, although included in most exome capture sets, it is not included in some database gene analysis sets. We would suggest that if a *WDR26* mutation is suspected in an individual on the basis of clinical features, previous exome data could be reanalyzed. Given the phenotypic and mechanistic overlap of haploinsufficiency, *WDR26* is most likely the major contributory gene in 1q41q42 deletion syndrome as a major factor in the neurocognitive and facial phenotypes. Finally, although little is known to date about its function, we anticipate that reduced expression of *WDR26* alters multiple signaling pathways and cellular mechanisms to result in this recognizable human phenotype.

Supplemental Data

Supplemental Data include a Supplemental Note, two figures, and one table and can be found with this article online at http://dx.doi.org/10.1016/j.ajhg.2017.06.002. Detailed experimental methods are available upon request.

Conflicts of Interest

M.T.C., A.B., G.D., J.J., and R.P. are employees of GeneDx.

Acknowledgments

We are exceptionally grateful to the individuals and families who participated in this study; colleagues who contributed samples and clinical information, including Dr. John Tolmie; and Harriet Saunders for technical assistance. This work was supported by institutional funds from the Children's Hospital of Philadelphia Research Institute to C.M.S. and M.A.D. and from CureKids New Zealand to S.P.R. The authors would like to thank the Exome Aggregation Consortium and the groups that provided exome variant data for comparison. We acknowledge the Deciphering Developmental Disorders study, which presents independent research commissioned by the Health Innovation Challenge Fund (grant HICF-1009-003), a parallel funding partnership among the Wellcome Trust, Department of Health, and Wellcome Trust Sanger Institute (grant WT098051). The views expressed in this publication are those of the authors and not necessarily those of the Wellcome Trust or the Department of Health. The research team acknowledges the support of the National Institute for Health Research through the Comprehensive Clinical Research Network.

Received: January 24, 2017
Accepted: May 30, 2017
Published: July 6, 2017

Web Resources

BLASTP, https://blast.ncbi.nlm.nih.gov/Blast.cgi?PAGE=Proteins
Combined Annotation Dependent Depletion (CADD), http://cadd.gs.washington.edu/home
DECIPHER, https://decipher.sanger.ac.uk
Elements of Morphology: Human Malformation Terminology, https://elementsofmorphology.nih.gov/
Exome Aggregation Consortium (ExAC) Browser, http://exac.broadinstitute.org
GenBank, https://www.ncbi.nlm.nih.gov/genbank/
GeneMatcher, https://genematcher.org/
Human Phenotype Ontology Browser, http://www.human-phenotype-ontology.org
Mutation Taster, http://www.mutationtaster.org/
OMIM, http://www.omim.org/
PolyPhen-2, http://genetics.bwh.harvard.edu/pph2/
PROVEAN, http://provean.jcvi.org/index.php
RCSB Protein Data Bank, http://www.rcsb.org/pdb/home/home.do
Residual Variation Intolerance Score (RVIS), http://genic-intolerance.org
SIFT, http://sift.jcvi.org
SubRVIS, http://www.subrvis.org
UniProtKB, http://www.uniprot.org/help/uniprotkb

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Supplemental Data

WDR26 Haploinsufficiency Causes a Recognizable Syndrome of Intellectual Disability, Seizures, Abnormal Gait, and Distinctive Facial Features

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Supplemental Note: Case Reports

Individual 1 (PPMD01P, GEA055P, USA)
Individual 1 was initially evaluated at 20 months of age due to concern for short stature and developmental delay. She was the product of a fraternal twin gestation conceived via in-vitro fertilization to a then 32-year-old G4P030 -> P2 mother. Mom had three prior first trimester miscarriages of unknown etiology. Family history is otherwise unremarkable. The pregnancy was uncomplicated and prenatal ultrasounds were normal. Prenatal screening was declined. She was born at 35 weeks gestation via spontaneous vaginal delivery. Birth weight was 4 lbs. 10 oz. (<10% for gestational age); twin brother birth weight 6 lbs. 2 oz. Her neonatal history was unremarkable. Her development has been delayed: she sat at 10 months, crawled at 15 months, and walked at 2.5 years. Language began to develop at 16-17 months, however, at 5 years she has only six words and some inconsistent signs. She has made slow developmental progress without regression. She exhibits some stereotypical behaviors including hand flapping and teeth grinding. She is playful and affectionate. Her medical history includes hypotonia, torticollis with positional plagiocephaly, strabismus, Marcus Gun jaw winking, recurrent otitis media s/p tympanostomy tubes, gastroesophageal reflux, and constipation. She developed febrile seizures at 17 months and subsequent EEG showed multifocal sharps and slow wave discharges. Brain MRI at 13 months showed a prominent sulcal pattern with dilation of the lateral ventricles and mild diminished white matter volume.

Growth parameters at 20 months showed head sparing failure to thrive: height <5% (50% for 10.5 months), weight 2% (50% for 9 months), and head circumference at 21%. At follow-up evaluation at 27 months of age, her growth parameters were similar: height <5% (50% for 16 months), weight 2% (50% for 12 months), and head circumference 12%. Growth parameters at 4 years were significant for height <5% (50% for 28 months) and weight <5% (50% for 23.5 months)(head circumference not obtained). Physical exam at that time was significant for a full dark hair, mildly coarse features, full cheeks, full brows with long lashes, large appearing irises, mildly depressed and slightly short nasal bridge, mildly anteverted nares, bulbous nasal tip, slightly long philtrum, widely spaced teeth, thin upper lip with decreased cupid's bow, prominent maxilla, mild micrognathia, mildly low tone, and mildly spastic gait.

Her genetic evaluation included normal female karyotype and normal chromosomal microarray (Quest-Affymetrix CytoScan HD 2.6M probes). She had negative sequencing and deletion/duplication analysis for the following genes: NIPBL, SMC3, RAD21, HDAC8, and SMC1A. Russell-Silver testing (11p15 methylation and UPD7 analysis) was normal and X-inactivation analysis was uninformative. Clinical whole exome sequencing identified a de novo heterozygous variant of unknown significance p.Glu426* (c.1276 G>T) in *WDR26*. No additional suspicious variants were reported.

Individual 2 (UNEZ01P, Netherlands)
Individual 2 is a 34-year old female at the time of evaluation. Her medical history is significant for severe mental retardation, spastic diplegia (left side most pronounced), febrile seizures at age 17 months, suspicion of seizures from age 7-8 years, dysarthric speech, constipation, sleep disturbances, double arch of teeth (primary and permanent dentition), exotropia/amblyopia, and vascular disturbances in the left foot (purple discoloration). Brain MRI showed enlarged lateral ventricles and thin corpus callosum. Her height is 10%, weight <3%, and head circumference 16%. Physical exam is

significant for coarse facial features, proptosis, full nasal tip, small nares, short philtrum, full lips, wide mouth with decreased cupid's bow, prominent maxilla, widely spaced teeth, and mild micrognathia. She had full cheeks, anteverted nares, and a short depressed nasal root in childhood. Clinical whole exome sequencing revealed a *de novo* variant p.His389Profs*6 (c.1161_1162del) in *WDR26*. In addition, *de novo* variants in *CDC7* c.1070A>G, p.Asp357Gly) and *NTNG2* (c.1426G>A, p.Ala476Thr) were noted, but were less suspicious, based on predictions and were subsequently felt less likely with the identification of additional individuals with *WDR26* pathogenic variants.

Individual 3 (OFPW01P, USA)
Individual 3 was 2.5 years at initial evaluation. She was the product of a full term, uncomplicated pregnancy. She was born via repeat C-section. Birth weight was 6 pounds and 4 ounces and birth length 18 inches. She was observed in the NICU for 3 days due to initial breathing issues, briefly requiring oxygen. Hypotonia was noted at a few weeks of age, eventually prompting evaluation by Neurology at 10 months of age. Previous evaluation included normal basic metabolic studies, normal karyotype, normal microarray analysis, and normal Prader-Willi/Angelman methylation studies. She had initial difficulty with solid foods, but now does well with a variety of foods. She developed prolonged febrile seizures at 2 yo and still has episodes of intermittent body stiffening. EEG immediately after the start of the seizures was abnormal, but more recent EEG was much improved. Brain MRI was normal. At 3 years 2 months she has no words used appropriately but can follow several step commands. She is always very happy and smiling. She started walking at 3 years of age and has a stiff gait. She has mild hypotonia and head nods when concentrating or tired. Growth parameters at 3 years 2 months of age were as follows: head circumference is 15%, her length is 29%, and her weight is 5%. Physical exam is significant for mildly coarse facial features with full cheeks, mild proptosis, large appearing irises, depressed nasal root, mild anteversion of nares, small nares, mild micrognathia, prominent maxilla, low set attached gingiva, and hypotonia. Clinical whole exome sequencing revealed a de novo variant p.Val486Glufs*9 (c.1457delT) in *WDR26.* No additional suspicious variants were reported.

Individual 4 (UNNV01P, Netherlands)
Individual 4 was a 2 year 1 month old female at the time of evaluation and is currently 6 yo. She developed febrile seizures at 11 months that continued until 5.5 years (3-4 episodes). She was later evaluated at 6 years for possible seizures, but does not carry a definitive diagnosis. Brain MRI and EEG were normal. Her medical history is also significant for congenital abducens paralysis requiring surgical intervention and mixed myopia and hyperopia. She has mild hypotonia and a mildly wide ataxic gait. She has significant developmental delay with first words at 24 months, sitting at 12 months, and walking at 2 years. She is described as happy and smiling. Growth parameters at 2 years 1 month were significant for height +0.5 SD, weight -1.5 SD, and head circumference -1 SD. Physical exam is significant for mildly coarse facies, full cheeks, proptosis, sparse lateral brows, full nasal tip, wide mouth with decreased cupid's bow, full lips, maxillary prominence, short philtrum, widely spaced teeth, gingival hyperplasia, mild prognathism, pes planus, sandal gap, and hypotonia. Whole exome sequencing revealed a de novo variant p.Leu215Pro (c.644T>C) in *WDR26.* No other suspicious variants were identified.

Individual 5 (IILW01P, USA)
Individual 5 was a 3 year 4 month old female at the time of evaluation. She was the product of a 37.5 week twin gestation. She had two episodes concerning for seizures at

2.5 years. EEG was normal. Brain MRI showed an arachnoid cyst, white matter volume loss, periventricular leukomalacia, and pineal cyst. She has hypotonia and a mildly wide gait. Her development has been delayed. She crawled at 18 months and walked between 2 and 2.5 years. Her first words were at 18 months and she has 4-5 words at 3 years 4 months. She has abnormal social interactions with some stereotypies on exam (clapping and hand flapping). Growth parameters at 3 years and 2 months were weight 3%, height just below 3%, and head circumference 10% for age. Physical exam is significant for large appearing irises, depressed nasal bridge, mild anteversion of the nares, full nasal tip, prominent smile, full cheeks, prominent maxilla, decreased cupid's bow, low set attached gingiva, pectus excavatum, and wide based gait. Williams syndrome and, to some extent, Angelman syndrome were considered at initial evaluation. Following normal chromosome microarray and Rett/Angelman syndrome disorders panel, clinical exome sequencing was pursued, which revealed a de novo variant p.Gln302Aspfs*22 (c.904_905delCA) in *WDR26.* A paternally heterozygous paternally inherited variant in *RNASEH2D* (c. 529G>A, p.Ala177Thr) was also noted but felt to be less consistent with clinical features and inheritance.

Individual 6 (PPMD02P, GEA131P, USA)
Individual 6 was a 24 month old female at the time of her last evaluation. She was the product of a full term, spontaneous gestation. Family history is significant for her biological mother having learning differences resulting in adoption by foster parents. Pregnancy was complicated by lack of prenatal care and multiple maternal drug exposures, requiring a 90 day NICU stay for withdrawal. There were concerns for seizures in the newborn period, requiring Phenobarbital. EEG was normal. Brain MRI showed a pineal cyst and FLAIR abnormality in the bilateral medial temporal lobes (artifact vs. delayed myelination). She has a history of elevated transaminases (ALT >1000) of unknown etiology that resolved spontaneously. Liver biopsy showed non-specific inflammation. Her medical history is also significant for a wandering left eye, hypotonia, sacral dimple, g-tube dependence, failure to thrive, and gastroesophageal reflux. She has had mild developmental delay. Early milestones are unclear, but she walked at 17 months. At 24 months she had about 15-20 words. She has some stereotypical behaviors including rocking and abnormal hand movements. She has made slow developmental gains without regression.

Growth parameters at her first genetics evaluation at our institution were significant for height 6%, weight 21%, and head circumference 4% for age. Growth parameters at her last visit (24 months of age) were significant for height 13%, weight 7%, and head circumference 8%. Physical exam from that time was significant for fuller cheeks, mildly upslanting palpebral fissures, large appearing irises, prominent nasal tip with mild anteversion of the nares, thin upper lip, shorter philtrum, maxillary prominence, mildly wide spaced teeth, wider mouth, decreased cupid's bow, sacral dimple, bilateral fifth finger clinodactyly, and a wide based and intermittently crouched gait.

Genetic evaluation included the following normal studies: genome wide SNP array, karyotype, chromosomal breakage studies, and multiple single gene analysis (*NIPBL, SMC1A, SMC3, RAD21, HDAC8, SRCAP*, and *EP300*). Exome sequencing revealed three variants of uncertain significance in the following genes: *ARID1B* (c.1016_1021dupTGGCGG; p.Val339_Ala340dup; maternally inherited), *ZMYND11* (c.470A>G; p.Glu157Gly; maternally inherited), and *WDR26* (c.850G>A; p.Asp284Asn; de novo). The variants in *ARID1B* and *ZMYND11* were felt to be less likely as causative

based on inheritance, pathogenic mechanism, poor conservation of residue and/or poor clinical correlation with previously reported phenotypes.

Individual 7 (SCLB01P, USA)
Individual 7 was a 4 year old male at the time of his last evaluation. He was the product of a 34 week gestation that was complicated by placenta previa, treated with bedrest starting at 22 weeks gestation, and diet-controlled gestational diabetes. He was delivered at 34 weeks due to maternal hemorrhage and spent 10 days in the NICU. Parental concern was first raised at 8 months of age due to poor weight gain. At a year of age he started developmental services due to delay. He sat at 11 months, army crawled at 14 months, 4-pt crawled at 16-17 months, and started walking at 22 months. His initial gait was wide-based and stiff-legged. At 4 years he has no words. Brain MRI showed a pineal cyst and area of signal intensity in cerebellum, ventricular size asymmetry with contour abnormality along the left lateral ventricle and associated mild white matter signal abnormality suggesting a prior insult, well-circumscribed focus non-enhancing T2 signal abnormality in the right cerebellar hemisphere, mild thinning of corpus callosum, mild vermian and left cerebellar hemisphere hypoplasia. He had a history of febrile seizures (one episode at 2 years and one at 3 years) and an episode of body stiffening concerning for a seizure at 3.5 years. EEG showed spike and wave discharges over the vertex and he was started on Depakote. Medical history is also significant for a right-sided aortic arch, eustachian tube dysfunction, and hypotonia. He has some abnormal behaviors (biting, hair pulling) and mimicking behaviors, but is typically friendly with new people.

Growth parameters at 4 years of age were significant for height 9%, weight 9%, and head circumference 1% for age. Physical exam is significant for slender build with little subcutaneous fat, mildly coarse features, midface retrusion, large appearing irises with inferior scleral reveal, abnormal lateral brows, depressed nasal root, prominent maxilla, widely spaced teeth, open mouth posture, full lips with decreased cupid's bow, fused and broad secondary alveolar ridges, low set attached gingiva, and bilateral fifth finger clinodactyly.

Genetic evaluation included a normal microarray, fragile X testing, *ATRX* analysis, and Angelman syndrome methylation testing. Whole exome sequencing (GeneDx) revealed three maternally inherited variant of uncertain significance in *CHD7* (c.5995 G>A, p.Ala1999Thr), *EFHC1* (c.520 A>G, p.Ile174Val), and *MBD5* (c.139T>G, p.Leu47Val) as well as a *de novo* variant in *WDR26* (c.137 C>A, p.Ser46*).

Individual 8 (DNCW01P, France)
Individual 8 is a 21 year old male. Pregnancy was complicated by IUGR (birth weight 2800g, length 47 cm, head circumference 33 cm). His medical history is significant for seizures, ventricular septal defect, failure to thrive, short stature, scoliosis, knee contractures, gastroesophageal reflux, left hemiparesis, inguinal hernia, cryptorchidism, gingival hypertrophy, conjunctival problems, chalazions, and delayed primary dental eruption. X-rays showed osteopathia striata. Brain MRI showed opercular dysplasia and pachygyria. His developmental milestones were delayed with sitting at 12 months and walking at 26 months. He had less than 10 words at 9 years of age. He has severe intellectual disability. Growth parameters at 19 years of age were globally small (weight -5SD, height -4SD, and head circumference <-3SD). Physical exam was significant for mild temporal narrowing, mildly coarse facies, abnormal lateral brows, short nasal bridge, mild anteversion of the nares, full nasal tip, prominent maxilla, full cheeks in

childhood, widely spaced teeth, gingival hyperplasia, open mouth posture, scoliosis, and knee contractures. Whole exome trio sequencing revealed de novo variants in two genes with a SnpEff impact of moderate or greater confirmed by Sanger sequencing. A missense variant *INTS12* c.887T>C (p.Phe296Ser), which had a nonsignificant ExAC missense constraint probability (p=0.312; z-score=0.49), and was considered an unlikely causal candidate. In contrast, a de novo nonsense variant was noted in *WDR26* (c.1570C>T, p.Gln524*), which had a pLI=0 and was considered a strong causal candidate.

Individual 9 (DDD273958, GSEK01P, GEA212P, UK)
Individual 9 is a 14 year old boy, the second child to healthy non-consanguineous Scottish parents. He was born at term by emergency section due to fetal distress with a birth weight of 4.33kg and there were no neonatal problems. He was described as difficult to feed with a poor suck. He had febrile convulsions until the age of 2 years. He has not had brain imaging. He was noted at the age of 3 years to have global developmental delay and marked speech delay. He has asthma and eczema but is in good health. He attends a special school and at the age of 14 years, speaks in short sentences but is difficult to understand. He is a happy, friendly boy who is sociable and well liked. He has some anxiety and hand clasping. He walks with a stiff gait and has tight achilles tendons and high arches of the feet and brisk knee and ankle reflexes. Growth parameters at 14 years were appropriate for age. Physical exam was significant for mildly coarse facial features, bright blue large appearing irises, sparse lateral brows, short nasal bridge with full tip, full cheeks, prominent maxilla with short philtrum, full lips, wide spaced teeth with low set attached gingiva, wide mouth with decreased cupid's bow, fifth finger clinodactyly, and pes cavus. Whole exome sequencing revealed a de novo variant in *WDR26* (c.762T>G; p.Ser254Arg).

Individual 10 (EUCT01P, DDD273377, UK)
Individual 10 is a 7 year old female, the second child of non-consanguineous parents. She was the product of a full term uncomplicated pregnancy; birth weight 2700g and head circumference 34 cm. She was noted to have a cleft soft palate on newborn exam. She had some early issues with poor feeding (recurrent aspiration pneumonia) and poor growth (requiring nasogastric and then long term PEG feeds). In early life she had puffy feet, constipation and recurrent otitis media. She developed tonic-clonic and absence seizures at the age of 3 years and was treated with valproate. EEG showed intermittent discrete spike/sharp wave discharges over the occipital area. Brain MRI showed left sided middle cranial fossa arachnoid cyst, relatively prominent cerebral ventricles and subarachnoid spaces, generalized thinning of the corpus callosum, and generalized lack of brain bulk. She has intellectual disability and developmental delay. Her first words were at 2 years and at age 7 she has around four words and also communicates using Makaton signs She sat at 11 months, bottom shuffled at 17 months, and walked at 24 months. She is described as being happy and affectionate. Growth parameters at 7 years were appropriate for age. Physical exam was significant for mildly coarse facies, brachycephaly, hypertelorism, large appearing irises with inferior reveal, upslanting palpebral fissures, sparse lateral brows, posteriorly rotated ears, mild anteversion of nares, full nasal tip, full lips with decreased cupid's bow, wide mouth, low set attached gingiva, decreased range of motion in hips and knees, inverted nipples, and hypertonic limbs with brisk reflexes. She walks with a wide-based gait. Stickler syndrome and Angelman syndromes were considered. Whole exome sequencing revealed a de novo variant in *WDR26* (c.1284G>A; p.Trp428*).

Individual 11 (OKAS01P; USA)
Individual 11 is an 8-year old female, the second child of non-consanguineous parents. The pregnancy was complicated by oligohydramnios and IUGR, prompting induction of labor at 35.5 weeks gestation. She had hypotonia, feeding difficulties, and failure to thrive in infancy and has since been found to have an excessive appetite and high metabolic demand. She was diagnosed with absence seizures at about 8 years. EEG showed generalized as well as multifocal epileptiform activities and is currently on Zonisamide and Keppra. Brain MRI showed a diminutive vs. hypoplastic corpus callosum. She has an abnormal gait, ADHD, and a tic disorder that is exacerbated by stimulants. Her medical history is also significant for chronic otitis media s/p tympanostomy tubes, gastroesophageal reflux, food allergies, and eczema. She has intellectual disability and developmental delay. She sat at 11 months, crawled at 14 months, and walked at 20 months. Her first words were at 13 months. She was putting two words together by 5 years and talking in short sentences at 8 years. She is in regular classes with a full time aid and has had great success with ABA therapy. She is described as happy and friendly, but anxious at times. Growth parameters at 8 years were appropriate for age. Physical exam revealed mildly coarse facial features, mild bitemporal narrowing, large appearing irises, mildly upslanting palpebral fissures, penciled brow, mild posteriorly rotated ears, full nasal tip, prominent maxilla, short philtrum, widely spaced teeth, full lips, wide mouth with decreased cupid's bow, low set attached gingiva, and pes cavus. Clinical whole exome sequencing (GeneDx) revealed a de novo variant in *WDR26* (c.1419+2dupT; splice site). No additional suspicious variants were reported.

Individual 12 (F47009, 51810, DGDW01P, Germany)
Individual 12 is the first child of healthy, non-consanguineous parents with an unremarkable family history. The pregnancy was complicated by pre-eclampsia. This girl was born at 38 weeks gestation with normal birth measurements [weight 2390 g (-1.9 SD), length: 47 cm (-1.5 SD) and OFC: 32 cm (-1.8 SD)]. At 10 months of age, the parents noted she was unable to crawl, and at 12 months of age, she had her first epileptic seizure. At that time, Down syndrome was excluded (karyotype: 46,XX). Her epilepsy has successfully been treated with valproate. Brain MRI did not reveal any anomalies. Her last examination was at age of 5.5 years demonstrated body measurements to be normal except for OCF, which showed microcephaly [height: 110 cm (-0.9 SD), weight: 15.8 kg (-1.8 SD), OFC: 47.5 cm (-2.9 SD)]. She is a very friendly and happy girl. She presented with upward slanting palpebral fissures, short nose with anteverted nostrils and a wide mouth with diastema. She was unable to speak a single word at 5.5 years and used some signs to express her wishes.
At the age of 22 months, the clinical diagnosis of Kleefstra syndrome was considered. A chromosome microarray and sequencing of the *EHMT1* gene revealed normal results. Subsequent exome sequencing identified two potential pathogenic variants: *WDR26* (novel *de novo* c.835C>T; p.(Arg279*)) and *TACC3* (novel *de novo* c.197C>T; p.(Thr66Met). The probability of LoF intolerance (pLi) for *TACC3* of 0.09 and the Z score for missense variants of -1.04. suggested that the *TACC3* variant was a less likely pathogenic candidate than the nonsense change in *WDR26*.

Individual 13 (IIJB01P, USA)
Individual 13 first presented for genetics evaluation at 4 years 7 months of age. He had previous diagnoses of gastroesophageal reflux, successfully treated as an infant, reactive airway disease, which has improved over time, and febrile seizures. He was

seen by orthopedics at 16 months for mild left hip dysplasia and motor delay. Soon after he began crawling and then pulling to a stand and cruising. Evaluation by a developmental pediatrician at 18 months was notable for no speech and subsequent audiology testing was normal. Neurology evaluation at 20 months noted limited walking (a few steps at a time), absent speech, and an otherwise normal neurologic exam. CPK and Fragile X testing were normal. Brain MRI at age 2-3 years was unremarkable. His dymorphology exam was notable for plagiocephaly with frontal bossing, hypertelorism with wavy palpebral fissures, low-set cupped and thickened ears, prominent nasal bridge, thin upper lip, and irregular right palmar creases. Diagnoses entertained included 22q11.2 deletion syndrome, Kabuki syndrome, and FG syndrome. He returned to genetics clinic for follow-up at 7 years 10 months of age. He continued to be nonverbal and was using an adaptive communication device. He has a history of about 20 febrile seizures, with many occurring in the previous year. Because of abnormal running, he was seen by orthopedics and diagnosed with moderate forefoot varus and accommodative shoes were prescribed. Exam was notable for hypertelorism, prominent ears, inverted nipples, and short fingers. No specific diagnoses were suspected. Chromosomal microarray was normal. Trio clinical exome sequencing identified a de novo frameshift variant in *WDR26* (c.574dupA); no other variants were reported.

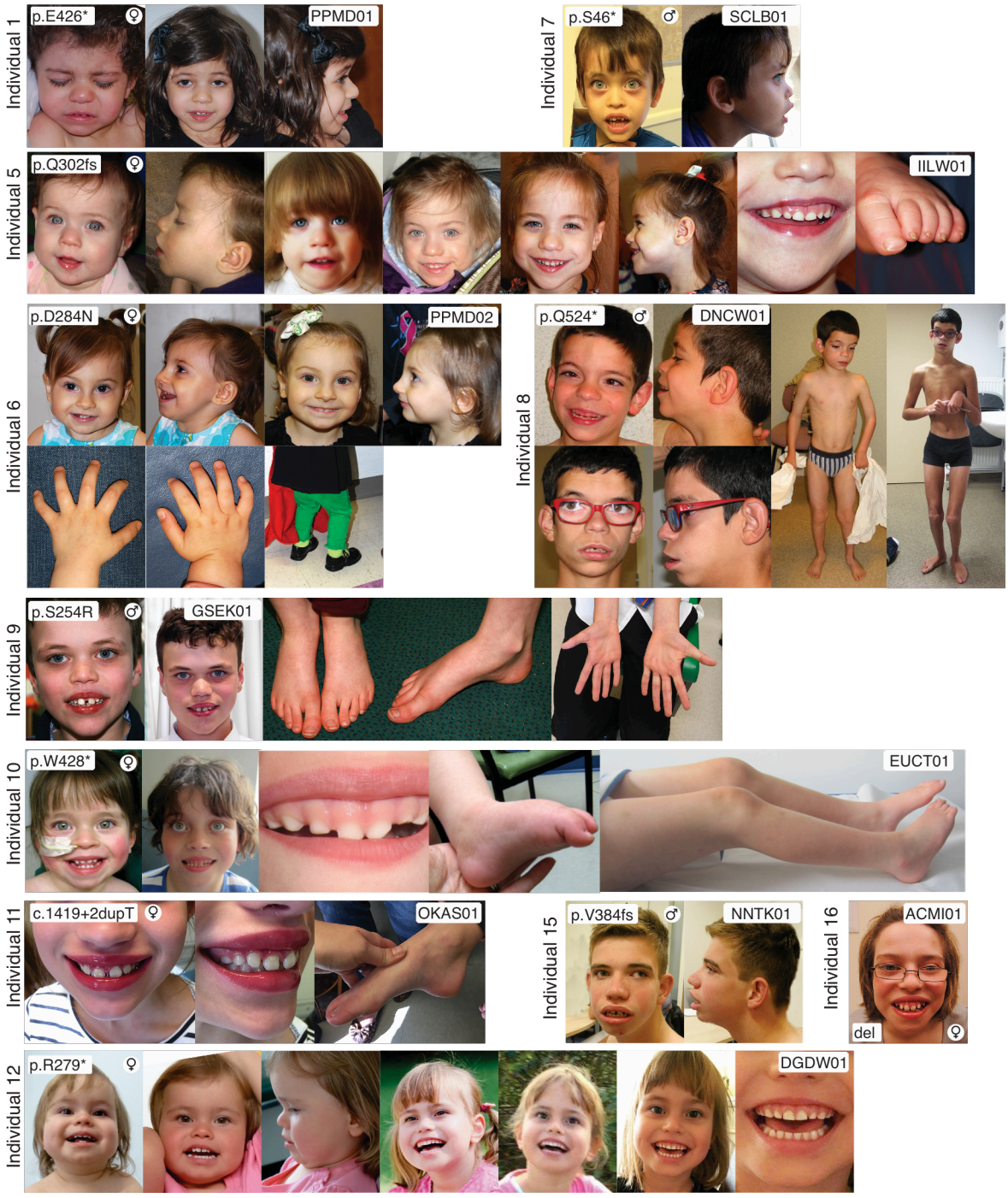

Figure S1. Detailed facial and clinical features of individuals with pathogenic *WDR26* variants. Each individual is noted with a number that corresponds to that used throughout the manuscript. Images are clustered for each individual. Included on the top left of each cluster is the variant identified and sex and an additional study identifier, also noted in Table S1 is noted in the top right. When available, frontal and facial profiles, varied ages, mouth, feet and stance are shown to display common findings.

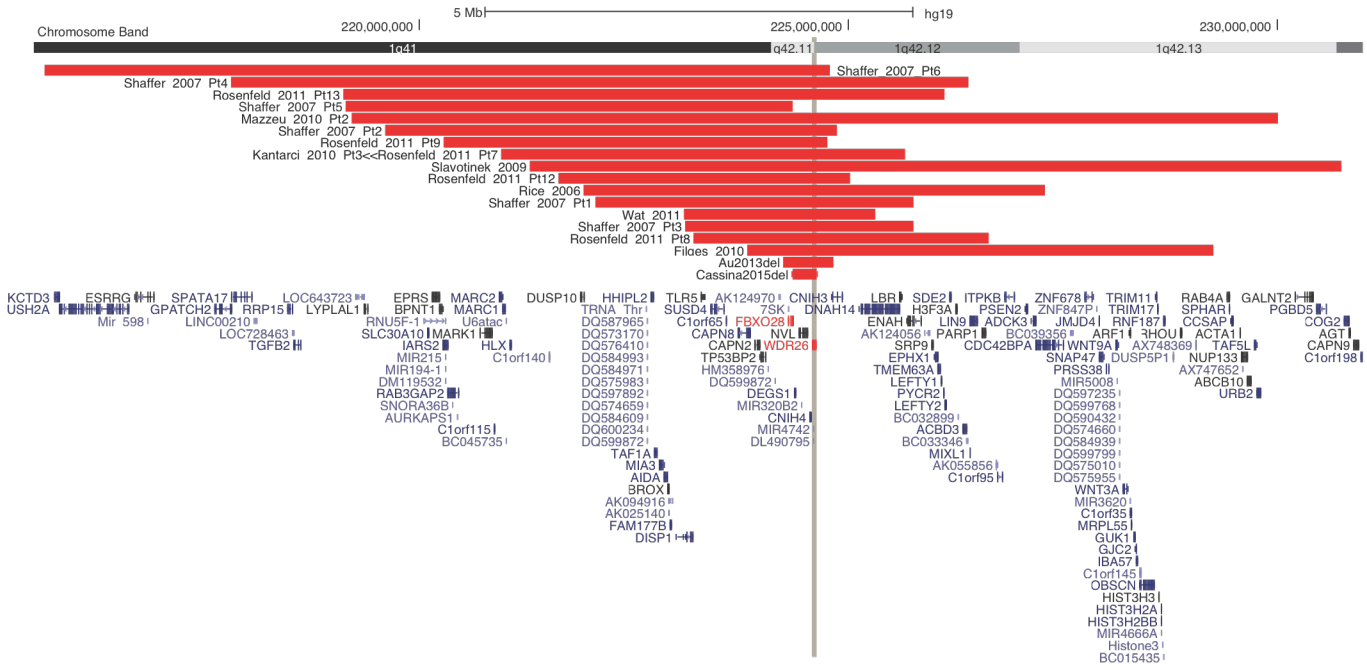

Figure S2. Chromosomal microdeletions involving the region 1q41q42.13. Demonstrated are microdeletions for which clinical and/or facial photographic information is available. Positions are based on hg19 coordinates (for detailed coordinates, see Table S1), with publication and subject identifiers noted. Genes in the region are noted beneath, with *FBX028* and *WDR26* in red to facilitate visualization. A grey bar spans the coordinates for *WDR26* across all deletions and genes to clarify locations of *WDR26* with respect to breakpoint ends. Of note, microdeletions for all reported subjects, with the exception of Patient 5 from Shaffer et al, 2007, include the *WDR26* gene, while this patient's breakpoint lies centromeric to *WDR26*.