Defining the Effect of the 16p11.2 Duplication on Cognition, Behavior, and Medical Comorbidities

Debra D'Angelo, MS; Sébastien Lebon, MD; Qixuan Chen, PhD; Sandra Martin-Brevet, MS; LeeAnne Green Snyder, PhD; Loyse Hippolyte, PhD; Ellen Hanson, PhD; Anne M. Maillard, PhD; W. Andrew Faucett, MS; Aurélien Macé, MS; Aurélie Pain, MS; Raphael Bernier, PhD; Samuel J. R. A. Chawner, MA; Albert David, MD; Joris Andrieux, MD, PhD; Elizabeth Aylward, MD; Genevieve Baujat, MD; Ines Caldeira, MD; Philippe Conus, MD; Carrina Ferrari, MS; Francesca Forzano, MD; Marion Gérard, MD; Robin P. Goin-Kochel, PhD; Ellen Grant, MD; Jill V. Hunter, MD; Bertrand Isidor, MD, PhD; Aurélie Jacquette, MD; Aia E. Jench, MD; Boris Keren, MD; Didier Lacombe, MD; Cédric Le Caignec, MD, PhD; Christa Lese Martin, PhD; Katrin Männik, PhD; Andres Metspalu, PhD; Cyril Mignot, MD; Pratik Mukherjee, MD; Michael J. Owen, PhD; Marzia Passeggeri, MD; Caroline Rooryck-Thambo, MD; Jill A. Rosenfeld, PhD; Sarah J. Spence, MD, PhD; Kyle J. Steinman, MD; Jennifer Tjemnagel, MS; Mieke Van Haelst, MD; Yiping Shen, PhD; Bogdan Draganski, MD; Elliott H. Sherr, MD, PhD; David H. Ledbetter, PhD; Marianne B. M. van den Bree, PhD; Jacques S. Beckmann, PhD; John E. Spiro, PhD; Alexandre Reymond, PhD; Sébastien Jacquemont, MD; Wendy K. Chung, MD, PhD; for the Cardiff University Experiences of Children With Copy Number Variants (ECHO) Study, the 16p11.2 European Consortium, and the Simons Variation in Individuals Project (VIP) Consortium

IMPORTANCE The 16p11.2 BP4-BPS duplication is the copy number variant most frequently associated with autism spectrum disorder (ASD), schizophrenia, and comorbidities such as decreased body mass index (BMI).

OBJECTIVES To characterize the effects of the 16p11.2 duplication on cognitive, behavioral, medical, and anthropometric traits and to understand the specificity of these effects by systematically comparing results in duplication carriers and reciprocal deletion carriers, who are also at risk for ASD.

DESIGN, SETTING, AND PARTICIPANTS This international cohort study of 1006 study participants compared 270 duplication carriers with their 102 intrafamilial control individuals, 390 reciprocal deletion carriers, and 244 deletion controls from European and North American cohorts. Data were collected from August 1, 2010, to May 31, 2015 and analyzed from January 1 to August 14, 2015. Linear mixed models were used to estimate the effect of the duplication and deletion on clinical traits by comparison with noncarrier relatives.

MAIN OUTCOMES AND MEASURES Findings on the Full-Scale IQ (FSIQ), Nonverbal IQ, and Verbal IQ; the presence of ASD or other DSM-IV diagnoses; BMI; head circumference; and medical data.

RESULTS Among the 1006 study participants, the duplication was associated with a mean FSIQ score that was lower by 26.3 points between proband carriers and noncarrier relatives and a lower mean FSIQ score (16.2-11.4 points) in nonproband carriers. The mean overall effect of the deletion was similar (–22.1 points; P < .001). However, broad variation in FSIQ was found, with a 19.4- and 2.0-fold increase in the proportion of FSIQ scores that were very low (<40) and higher than the mean (>100) compared with the deletion group (P < .001). Parental FSIQ predicted part of this variation (approximately 36.0% in hereditary probands). Although the frequency of ASD was similar in deletion and duplication proband carriers (16.0% and 20.0%, respectively), the FSIQ was significantly lower (by 26.3 points) in the duplication probands with ASD. There also were lower head circumference and BMI measurements among duplication carriers, which is consistent with the findings of previous studies.

CONCLUSIONS AND RELEVANCE The mean effect of the duplication on cognition is similar to that of the reciprocal deletion, but the variance in the duplication is significantly higher, with severe and mild subgroups not observed with the deletion. These results suggest that additional genetic and familial factors contribute to this variability. Additional studies will be necessary to characterize the predictors of cognitive deficits.
The 600-kilobase (kb) break points 4 and 5 (BP4-BP5) 16p11.2 deletion and duplications (chr16:29.6-30.2 megabase) are among the most frequent genetic causes of autism spectrum disorder (ASD), schizophrenia, and other neurodevelopmental disorders. These reciprocal copy number variants (CNVs) are associated with mirror phenotypes of obesity and being underweight and with increased and decreased global and regional brain volumes in deletion and duplication carriers, respectively. Previous studies have demonstrated that ASD is diagnosed in approximately 18% of deletion carriers and that this CNV affects global cognition by shifting the IQ approximately 2 SDs without altering the variance. To our knowledge, such studies have not been conducted for the reciprocal duplication. Akin to duplications of other genomic regions, case series have reported variable expressivity and suggested incomplete penetrance; however, incomplete penetrance was recently ruled out after recalling carriers identified in unselected populations. This phenotype variability and the limited available data underscore the need to systematically characterize the clinical impact of the duplication with standardized assessments in large numbers of carriers.

The goal of this study was to characterize and elucidate the effects of the 16p11.2 duplication on cognitive, behavioral, medical, and anthropometric traits and to understand the specificity of these effects by systematically comparing results in duplication carriers and reciprocal deletion carriers, who are also at risk for ASD. To this end, we established, to our knowledge, the largest cohort of duplication (n = 270) and deletion (n = 390) carriers to date from the 16p11.2 European and Simons Variation in Individuals Project (Simons VIP) consortia and the Cardiff University Experiences of Children With Copy Number Variants (ECHO) Study. We present here the natural history and phenotypic variation among the 16p11.2 duplication carriers and compare their results with those of their intrafamilial control individuals (n = 102) and of individuals with the reciprocal 16p11.2 deletion ascertained by similar methods.

Methods

Patients
This study was reviewed and approved by the ethical committee or institutional review board for the European consortium (http://www.cer-vd.ch). Written informed consent and, when appropriate, assent were obtained from the participants who underwent full clinical assessments.

Inclusion and Exclusion Criteria
This study describes only the proximal 600-kb recurrent 16p11.2 CNV delineated by BP4 and BP5 (29.6-30.2-Hg19). Carriers have the same BP4-BP5 duplication or deletion. Control participants were family members of the carriers who do not carry the 16p11.2 duplication or deletion. Individuals with an additional deleterious CNV were excluded. Deleterious CNVs were defined as (1) a known recurrent genomic disorder, (2) a CNV encompassing a published critical genomic region or disrupting a gene that is a known cause of neurodevelopmental disorders, or (3) rare (<1 of 1000) and large (>500 kb) CNVs. The percentages of additional deleterious CNVs were compared between duplication probands and deletion probands similarly ascertained on the basis of a neurodevelopmental disorder (eMethods in the Supplement). Ascertainment is detailed in eTable 1 and the eMethods in the Supplement. Data were collected from August 1, 2010, to May 31, 2015.

Cognitive Functioning, Psychiatric, and Behavioral Assessments
Phenotypic evaluations for the Simons VIP participants and the 16p11.2 European Consortium were performed as previously reported. The Wechsler Abbreviated Scales of Intelligence was used to assess IQ for the ECHO Study participants.

Statistical Analysis
Data were analyzed from January 1 to August 14, 2015. We examined differences in the Full Scale (FSIQ), Verbal (VIQ), and Nonverbal (NVIQ) IQs and z scores for body mass index (BMI) (calculated on height and weight) and head circumference (HC) between 16p11.2 duplication carriers and their noncarrier familial controls. The IQ values were derived from age and developmentally appropriate standardized measures (Differential Ability Scales, Mullen Scales for Early Learning—AGS Edition, and Wechsler Abbreviated Scales of Intelligence). Cognitive measures are standardized to a mean (SD) of 100 (15), with higher scores indicating more developed cognitive abilities. For participants performing out of normative range on instruments, we generated ratio IQ scores based on subtest raw score age equivalents (mental age/chronological age × 100) so that an accurate IQ estimate was established for each participant. The BMI z scores were estimated based on age and sex norms, and HC z scores were estimated based on age- and sex-normed orbitofrontal HC measurements obtained during laboratory visits.

Carriers were stratified into the following groups: probands, pediatric carrier relatives (<18 years of age), and adult carrier relatives (≥18 years of age). These groups were compared with noncarriers. We also compared differences in phenotypes between probands whose inheritance status (de novo and inherited) was documented and their noncarrier familial controls. The same analyses were performed with the deletion carriers and their noncarrier familial controls.

We used linear mixed models to compare differences in phenotypes between carrier or inheritance groups while accounting for correlated measures within families (familial clustering) to estimate the effect of the 16p11.2 duplication or deletion on the phenotype. The group differences were controlled for by study cohort (European vs United States), age, and sex. Additional contrasts were included for multilevel categorical variables to allow for pairwise comparison among all levels of the variable. To examine whether the group differences were driven by other diagnostic factors, additional linear mixed models were fitted by adding ASD, seizure diagnosis, and, when applicable, NVIQ to the existing models as covariates.

We used the Levene test to assess equality of variance and the Fisher exact test to assess the association between bi-
nary variables. To study the longitudinal trend of BMI and HC values among deletion and duplication groups, we grouped the data points into age windows. We used linear mixed models to compare the mean values of BMI and HC of carriers to the population means or familial controls (if available) at each time window. All statistical analyses were conducted using SAS (version 9.4; SAS Institute Inc) and R (R Core Team) software.

**Results**

Descriptive statistics for our 1006 study participants are shown in Table 1 and Table 2. We first compared duplication carriers with their familial controls for cognition, neurologic findings, psychiatric symptoms, BMI, and HC and then performed similar comparisons between deletion carriers and their familial controls.

**Global Cognitive Functioning**

The mean FSIQ across the 270 duplication carriers was 78.8. Forty-seven of 154 carriers (30.5%) met criteria for intellectual disability. When controlling for cohort, age, and sex, the FSIQ was significantly lower in duplication carriers compared with intrafamilial controls (18.0 points; *P* < .001; Table 3). The largest effect was observed in probands (decrease in mean FSIQ, 26.3 points) followed by pediatric and adult carrier relatives (decreases, approximately 16.2 and 11.4 points, respectively) relative to intrafamilial controls. When controlling for the same covariates, the effect of the reciprocal deletion was similar, with a mean decrease in carriers of 22.1 points (P < .001; eTable 2 in the Supplement) in FSIQ compared with intrafamilial controls.

The effect of cohort on FSIQ was the same in both CNV groups, with significantly lower FSIQ in the European vs the US cohort (by 13.3 points in the duplication group and 13.9 points in the deletion group; *P* < .001). The effects of both CNVs on FSIQ, VIQ, and NVIQ remained similar after additionally controlling for ASD and seizures (eTables 3-8 in the Supplement), which were associated with IQ in the duplication but not the deletion groups (see the Neurologic Findings and Psychiatric Symptoms subsections in this Results section).

**Variability of the Effect on Global Cognition**

The variance of FSIQ in duplication carriers was significantly higher than observed in deletion carriers (Levene test, *P* < .001). We found a 19.4-fold excess (Fisher exact test, *P* < .001) of very low FSIQ (≤40; 15 of 154 [9.7%]) in the duplication compared with the deletion carriers (1 of 200 [0.5%]) and a 2.0-fold enrichment (Fisher exact test, *P* = .01) of the duplication carriers greater than the population mean FSIQ compared with deletion carriers (>100; 30 of 154 [19.5%] vs 20 of 200 [10.0%]) who were ascertained by the same investigators using the same methods (Figure 1). The European and US duplication cohorts contributed (albeit not equally) to the lower- and higher-functioning participants (eFigures 1 and 2 in the Supplement). The large variance of FSIQ among duplication probands was not driven by cohort, the presence of ASD, seizure status, or HC (eFigure 2 in the Supplement).
Another factor underlying increased variation in IQ may have been additional undetected genetic variants. When we combined the European, Simons VIP, and Signature Genom-ics Laboratories datasets (described in Methods in the Supple-ment), the odds of an additional deleterious CNV were 2.5-fold higher in duplication compared with deletion carriers ascertained for neurodevelopmental disorders \((P = .006)\) (eMethods and eTable 9 in the Supplement). The mediansize and the mean number of genes included in additional CNVs are similar for 16p11.2 deletion and duplication carriers (eFigure 3 in the Supplement).

**Global Cognition of De Novo and Inherited Duplication Carriers**

The FSIQ, NVIQ, and VIQ were not significantly different in probands with de novo vs inherited duplications but were significantly greater in probands with de novo vs inherited deletions (eTables 10 and 11 in the Supplement). In families with inherited duplications, approximately 36.0% of the IQ variance in probands was accounted for by the IQ of the transmitting parent (eFigure 4 in the Supplement). Too few de novo carriers were available for this analysis \((n = 13)\). For deletion carriers, less of the variability was explained by parental IQ (11.0% for inherited and de novo cases; eFigure 4 in the Supplement).

**Neurologic Findings**

Epilepsy was reported in 35 of 180 of duplication probands (19.4%) and 2 of 90 of their carrier relatives (2.2%) (eTable 12 in the Supplement). We found a broad spectrum of severity ranging from benign focal epilepsy to severe epileptic syndromes, with focal epilepsies being the most frequent type (16 of 37 [43.2%]). In the reciprocal deletion group, the fre-

### Table 2. Mean IQ and Anthropometric Measures by 16p11.2 Status, Cohort, and Carrier Group

<table>
<thead>
<tr>
<th>Cohort by Carrier Group</th>
<th>FSIQ No. of Participants</th>
<th>Mean (SD)</th>
<th>NVIQ No. of Participants</th>
<th>Mean (SD)</th>
<th>VIQ No. of Participants</th>
<th>Mean (SD)</th>
<th>z Score BMI No. of Participants</th>
<th>Mean (SD)</th>
<th>HC No. of Participants</th>
<th>Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>16p11.2 Duplication</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>European</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proband carrier</td>
<td>30</td>
<td>63.9 (25.5)</td>
<td>27</td>
<td>65.1 (23.4)</td>
<td>24</td>
<td>69.0 (28.5)</td>
<td>90</td>
<td>-0.5 (1.7)</td>
<td>59</td>
<td>-1.2 (1.7)</td>
</tr>
<tr>
<td>Pediatric carrier relative</td>
<td>4</td>
<td>69.8 (17.0)</td>
<td>4</td>
<td>70.3 (10.7)</td>
<td>4</td>
<td>75.3 (24.5)</td>
<td>6</td>
<td>-1.5 (1.7)</td>
<td>5</td>
<td>-1.8 (1.3)</td>
</tr>
<tr>
<td>Adult carrier relative</td>
<td>14</td>
<td>71.8 (19.7)</td>
<td>13</td>
<td>70.5 (15.7)</td>
<td>2</td>
<td>80.5 (50.2)</td>
<td>24</td>
<td>-0.3 (1.3)</td>
<td>19</td>
<td>-0.9 (1.4)</td>
</tr>
<tr>
<td>Noncarrier</td>
<td>12</td>
<td>98.6 (14.6)</td>
<td>12</td>
<td>100.0 (15.7)</td>
<td>3</td>
<td>119.0 (3.0)</td>
<td>12</td>
<td>0.3 (1.5)</td>
<td>10</td>
<td>-0.3 (0.8)</td>
</tr>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proband carrier</td>
<td>51</td>
<td>72.0 (21.1)</td>
<td>50</td>
<td>73.2 (21.0)</td>
<td>48</td>
<td>75.3 (25.8)</td>
<td>76</td>
<td>-0.02 (1.3)</td>
<td>76</td>
<td>-0.7 (1.6)</td>
</tr>
<tr>
<td>Pediatric carrier relative</td>
<td>16</td>
<td>85.3 (18.5)</td>
<td>16</td>
<td>85.8 (16.0)</td>
<td>16</td>
<td>86.7 (22.8)</td>
<td>15</td>
<td>0.3 (0.9)</td>
<td>17</td>
<td>-0.6 (1.5)</td>
</tr>
<tr>
<td>Adult carrier relative</td>
<td>39</td>
<td>99.7 (14.7)</td>
<td>40</td>
<td>99.4 (16.3)</td>
<td>39</td>
<td>99.4 (13.1)</td>
<td>42</td>
<td>0.6 (1.1)</td>
<td>42</td>
<td>-0.8 (1.5)</td>
</tr>
<tr>
<td>Noncarrier</td>
<td>107</td>
<td>106.5 (16.4)</td>
<td>90</td>
<td>107.6 (17.3)</td>
<td>88</td>
<td>104.5 (15.6)</td>
<td>86</td>
<td>0.8 (1.2)</td>
<td>87</td>
<td>0.3 (1.2)</td>
</tr>
<tr>
<td><strong>16p11.2 Deletion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>European</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proband carrier</td>
<td>47</td>
<td>69.4 (15.1)</td>
<td>47</td>
<td>77.9 (13.7)</td>
<td>40</td>
<td>70.4 (15.2)</td>
<td>162</td>
<td>1.8 (2.4)</td>
<td>119</td>
<td>0.6 (1.5)</td>
</tr>
<tr>
<td>Pediatric carrier relative</td>
<td>15</td>
<td>69.8 (13.6)</td>
<td>15</td>
<td>77.9 (13.2)</td>
<td>15</td>
<td>69.7 (15.6)</td>
<td>19</td>
<td>1.4 (1.6)</td>
<td>14</td>
<td>0.03 (1.1)</td>
</tr>
<tr>
<td>Adult carrier relative</td>
<td>15</td>
<td>73.9 (17.2)</td>
<td>17</td>
<td>74.8 (14.2)</td>
<td>7</td>
<td>78.4 (15.1)</td>
<td>30</td>
<td>2.2 (1.8)</td>
<td>24</td>
<td>1.0 (1.4)</td>
</tr>
<tr>
<td>Noncarrier</td>
<td>31</td>
<td>94.7 (17.3)</td>
<td>31</td>
<td>96.9 (16.8)</td>
<td>19</td>
<td>91.2 (21.8)</td>
<td>32</td>
<td>0.5 (1.0)</td>
<td>30</td>
<td>-0.5 (1.2)</td>
</tr>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proband carrier</td>
<td>106</td>
<td>81.8 (16.1)</td>
<td>110</td>
<td>86.5 (16.8)</td>
<td>106</td>
<td>77.6 (19.1)</td>
<td>129</td>
<td>1.0 (1.4)</td>
<td>140</td>
<td>1.0 (1.5)</td>
</tr>
<tr>
<td>Pediatric carrier relative</td>
<td>7</td>
<td>82.9 (13.6)</td>
<td>7</td>
<td>87.3 (12.7)</td>
<td>7</td>
<td>80.6 (17.7)</td>
<td>11</td>
<td>1.1 (1.1)</td>
<td>10</td>
<td>1.6 (1.6)</td>
</tr>
<tr>
<td>Adult carrier relative</td>
<td>10</td>
<td>86.8 (15.9)</td>
<td>9</td>
<td>94.3 (8.5)</td>
<td>9</td>
<td>88.3 (18.7)</td>
<td>10</td>
<td>2.1 (1.1)</td>
<td>10</td>
<td>0.5 (0.8)</td>
</tr>
<tr>
<td>Noncarrier</td>
<td>211</td>
<td>109.5 (12.3)</td>
<td>211</td>
<td>110.6 (13.0)</td>
<td>211</td>
<td>106.6 (12.4)</td>
<td>203</td>
<td>1.0 (1.0)</td>
<td>209</td>
<td>0.4 (1.3)</td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index; FSIQ, Full-Scale IQ; HC, head circumference; NVIQ, Nonverbal IQ; VIQ, Verbal IQ.
The clinical spectrum was broad, with a predominance of genetic neurodevelopmental disorder, pediatric carrier relatives (mostly siblings of the probands), and adult carrier relatives (mostly transmitting parents).

### Psychiatric Symptoms

Diagnostic criteria for ASD were met in 36 of 180 duplication probands (20.0%) and 2 of 90 of their carrier relatives (2.2%). In the deletion group, the proportion of probands with a diagnosis of ASD was similar (51 of 377 [16.1%]; P = .27). However, among those with an ASD diagnosis, duplication probands were significantly more impaired in cognition than deletion probands by 26.3 points (2-sided unpaired t test, P < .001). Duplication probands with ASD also had significantly lower cognition than those without an ASD diagnosis (mean FSIQ, 52.8 vs 75.4; t test, P < .001; Figure 1E). Other DSM-IV-TR diagnoses were reported in 45 of 55 with ASD (81.8%), 157 of 266 probands (59.0%), and 31 of 69 of their carrier relatives without ASD (44.9%) (eTables 14 and 15 in the Supplement). We did not identify cases of schizophrenia beyond the 4 duplication carriers ascertained from a schizophrenia cohort.

### Body Mass Index

The mean BMI z score was approximately 0.6 points lower (P = .003) in duplication carriers compared with intrafamilial controls (Table 3 and Figure 2A); this decrease was consistent across all carrier groups, including probands, pediatric carrier relatives, and adult carrier relatives (P = .004, P = .09, and P = .01, respectively. The relative risk for obesity (BMI z score ≥2 SDs above the 98th percentile in children; BMI raw score [calculated as weight in kilograms divided by height in meters squared] ≥30 in adults) decreased 3-fold in pediatric and adult duplication carriers when compared with the control group (Fisher exact test, P < .001). In the reciprocal deletion carriers, BMI z score increased by 0.7 points in carriers compared with intrafamilial controls (eTable 2 in the Supplement). Body mass index was not associated with ASD, seizures, or NVIQ in duplications or deletions (eTables 16 and 17 in the Supplement). In the longitudinal analysis, BMI increased with age in deletion carriers, whereas it remained relatively stable from 0 to −1 SD in duplication carriers (Figure 2B).

### Head Circumference

The HC z score was a mean of 1.1 points lower in duplication carriers (P < .001; Table 3 and Figure 2C) and 0.5 points higher (P = .002) in deletion carriers compared with noncarriers (eTable 2 in the Supplement). Similar to BMI and in contrast to IQ, this effect on HC z score was consistent across proband and carrier relatives.

### Table 3. Effect of the Duplication on Global Intelligence and Anthropometric Measures

<table>
<thead>
<tr>
<th>Comparison</th>
<th>FSIQ (n = 253)</th>
<th>NVIQ (n = 251)</th>
<th>VIQ (n = 223)</th>
<th>BMI (n = 351)</th>
<th>HC (n = 314)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed effects parameters</td>
<td>Estimate</td>
<td>p Value</td>
<td>Estimate</td>
<td>p Value</td>
<td>Estimate</td>
</tr>
<tr>
<td>Intercept</td>
<td>97.5</td>
<td>&lt;.001</td>
<td>99.9</td>
<td>&lt;.001</td>
<td>98.3</td>
</tr>
<tr>
<td>Proband carrier vs noncarrier</td>
<td>-26.3</td>
<td>&lt;.001</td>
<td>-26.7</td>
<td>&lt;.001</td>
<td>-24.4</td>
</tr>
<tr>
<td>Pediatric carrier relative vs noncarrier</td>
<td>-16.2</td>
<td>&lt;.001</td>
<td>-16.6</td>
<td>&lt;.001</td>
<td>-15.6</td>
</tr>
<tr>
<td>Adult carrier relative vs noncarrier</td>
<td>-11.4</td>
<td>&lt;.001</td>
<td>-14.8</td>
<td>&lt;.001</td>
<td>-6.0</td>
</tr>
<tr>
<td>European vs US cohort</td>
<td>-13.3</td>
<td>&lt;.001</td>
<td>-14.0</td>
<td>&lt;.001</td>
<td>-8.4</td>
</tr>
<tr>
<td>Age, y</td>
<td>0.3</td>
<td>&lt;.001</td>
<td>0.3</td>
<td>&lt;.001</td>
<td>0.1</td>
</tr>
<tr>
<td>Female vs male</td>
<td>-1.5</td>
<td>.42</td>
<td>-4.1</td>
<td>.04</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Additional contrasts**

| Carrier* vs noncarrier | -18.0 | <.001 | -19.3 | <.001 | -15.3 | <.001 | -0.6 | .003 | -1.1 | <.001 |
| Proband carrier vs pediatric carrier relative | -10.1 | <.001 | -10.1 | <.001 | -8.8 | .08 | -0.1 | .98 | -0.1 | .73 |
| Proband carrier vs adult carrier relative | -14.9 | <.001 | -11.9 | <.001 | -18.4 | <.001 | -0.3 | .87 | 0.1 | .75 |
| Pediatric vs adult carrier relative | -4.8 | .33 | -1.8 | .71 | -9.6 | .11 | -0.03 | .94 | 0.02 | .96 |

**Abbreviations:** BMI, body mass index; FSIQ, Full-Scale IQ; HC, head circumference; NVIQ, Nonverbal IQ; VIQ, Verbal IQ.

* Carriers include proband carriers (individuals ascertained for a neurodevelopmental disorder), pediatric carrier relatives (mostly siblings of the probands), and adult carrier relatives (mostly transmitting parents).

* Linear mixed model analysis was used to estimate the effect of duplication on FSIQ, NVIQ, VIQ, BMI z score, and HC z score.
bands and relatives. Forty-eight of 215 duplication carriers (22.3%) were microcephalic (HC \textit{z} score, less than −2 SDs below the 2th percentile). Head circumference was significantly associated with NVIQ in duplications ($P = .03$) but not deletions ($P = .28$), and we found a marginal association between HC and ASD in deletions ($P = .07$) but no association in duplications ($P = .16$). Seizures were not associated with HC in duplications or deletions (eTables 18 and 19 in the Supplement). Head circumference and BMI \textit{z} scores were correlated within the deletion and duplication probands (for both groups, $r = 0.4; P < .001$). In the longitudinal analysis, the significant decrease in HC \textit{z} scores during the first 2 years of life mirrored the increasing HC \textit{z} scores during the same period observed in deletion carriers (Figure 2D). Malformations, medical problems, and sex differences are detailed in the eResults and eTables 20 to 23 in the Supplement.

**Discussion**

We present here a comprehensive phenotypic characterization of the 16p11.2 BP4-BP5 duplication and deletion ascertained in US and European cohorts to understand their specific effects on neurocognitive, behavioral, and anthropometric phenotypes. The large variance in FSIQ is an important feature of the duplication, with increased proportions of individuals at both extremes of the FSIQ distribution when compared with the deletion group. Unlike the deletion group, which
showed a consistent effect of 16p11.2 deletion on FSIQ across carrier groups and a normal distribution consistent with what is observed in the general population, the duplication was associated with a multimodal distribution in FSIQ and different effect sizes for probands and other carriers in the family. The mean IQ decrement in duplication probands (26.3 points) was likely influenced by the clinical ascertainment for neurodevelopmental disorders. In contrast, the 11.4-point mean decrease observed in adult carriers was most likely an underestimate of the duplication effect because most of these adults are transmitting parents ascertained for higher functional status. The mean effect of the duplication may therefore lie between these 2 estimates. Differences in IQ observed in the European and US cohorts did not influence these estimates. This finding was also in agreement with that of a recent adult population-based study from Iceland\textsuperscript{25} that reported a 15- to 19-point decrease in VIQ and NVIQ in 7 duplication carriers ($P = .006$ and $P < .001$, respectively). We suspect that the subpopulation of low-functioning duplication carriers with FSIQ of 40 or less harbors additional factors that are not tolerated and possibly lethal before birth in deletion carriers, who almost never present such severe cognitive impairment.

Participants with second pathogenic CNVs, other identified monogenic disorders, prematurity, fetal alcohol syndrome, and neonatal hypoxia were intentionally excluded from the main analyses, but other undetected factors may have influenced the severity of the clinical presentation in the probands. The 2- to 3-fold increase of additional deleterious CNVs in duplication compared with deletion probands ascertained for neurodevelopmental disorders suggests that the duplication requires additional factors to reach the threshold for clinical evaluation compared with the deletion. Some of these
unknown genetic factors may be inherited from parents as suggested by the correlation between FSIQ in probands and their parents (r = 0.4, similar to previously published studies estimating the heritability of IQ in the general population26,27). The remaining unexplained variation was substantial, making the use of parental IQ alone as a predictor insufficient (eFigure 4 in the Supplement). The significant decrease in IQ in probands with an inherited vs a de novo deletion confirmed our hypothesis that families with an inherited deletion may be enriched in additional genetic or environmental factors that affect cognition. We did not observe this phenomenon for inherited duplications.

Differences in the European vs US cohorts may be the consequence of access to clinical chromosome microarrays that differ by health care system. Recruitment methods also differed in both cohorts. Probands from the European cohort were directly referred from genetic units to the research center, whereas the Simons VIP participants required active participation of the proband’s family. Nonetheless, these differences between cohorts did not influence the effect of the duplication on IQ.

The frequency of ASD was similar in deletion and duplication probands and was consistent with previous case-control association studies28-30 that have demonstrated that both reciprocal CNVs equally predispose to ASD. However, our study suggests that the duplication is associated with a form of low-functioning ASD, whereas cognition in deletion carriers with ASD is mostly within the normal range. This finding also applies in epilepsy, equally frequent in duplication and deletion probands but only associated with lower FSIQ in the duplication group. This finding suggests that these neuropsychiatric diagnoses may occur in the presence of additional factors with a negative effect on IQ. Similar to ASD cohorts, an excess of male participants and lower IQ in female participants were observed in the duplication and deletion carriers ascertained for neurodevelopmental disorders.

The low frequency of schizophrenia in the duplication cohort is discordant with the association reported in prior studies.4 This discordance is likely in part owing to the youth of our participants (mean ages, 18.2 years in the US and 26.7 years in the European cohorts) and the fact that adults were ascertained as parents. Following up our probands is required to estimate the risk for schizophrenia accurately.

Although the penetrance of obesity is higher in the deletion group compared with being underweight in the duplication group, the effect sizes of both variants appear to be similar when compared with intrafamilial controls. The effect of the duplication mirrors that of the deletion with the exception of the age-related effect.3 As expected, geographic location influences BMI, but the effect of the duplication is similar in both cohorts.

The 1-point decrease in mean HC z score in duplication carriers occurs during the first two years of life and mirrors the early increased growth observed in the deletion carriers (Figure 2D). Head circumference, which is highly correlated with brain volume,7,8 is associated with NVIQ in the duplication carriers (albeit with a small effect size) and a trend was observed for ASD in deletion carriers. The main limitation of this study is the ascertainment bias in the probands who came to clinical attention and underwent clinical testing with a chromosome microarray. We attempted to minimize this bias by performing cascade genetic testing within families to identify additional duplication carriers and include all duplications carriers within the study.

Conclusions

The 16p11.2 duplication has a consistent effect on some traits, such as HC and BMI. The duplication may interact with additional factors that lead to different severities of neurobehavioral phenotypes, including a subgroup of low-functioning duplication carriers with ASD, which is absent in the deletion group. The estimated effect size of the duplication on IQ suggests that this CNV contributes to approximately half of the cognitive deficit in carriers with mild to moderate intellectual disability. Additional factors may contribute to the neurodevelopmental outcome in some individuals. Future studies will aim to quantify the contribution of additional genetic and environmental factors to the phenotype.
Drafting of the manuscript: D'Angelo, Lebon, Chen, Martin-Brevet, Snyder, Hippolyte, Grant, Janch, Martin, Metspalu, Passeggeri, Rooyck, Jacquemont, Chung.

Critical revision of the manuscript for important intellectual content: D'Angelo, Chen, Martin-Brevet, Snyder, Hanson, Maillard, Faucett, Macé, Pain, Bernier, Chawner, Albert, Andrieux, Aylward, Baujat, Caldeira, Conus, Ferrari, Forzano, Gérard, Goin-Kochel, Hunter, Isidor, Jacquette, Keren, Lacombe, Le Caignec, Martin, Métcalfe, Mignot, Mukherjee, Owen, Rosenberg, Spence, Steinman, Tjernagel, Van Haelst, Shen, Draganski, Serr, Ledbetter, van den Bree, Beckmann, Sprio, Reymond, Jacquemont, Chung.

Statistical analysis: D'Angelo, Lebon, Chen, Martin-Brevet, Snyder, Macé, Passeggeri.

Obtained funding: Hanso, Goin-Kochel, Martin, Metspalu, Owen, van den Bree, Reymond, Jacquemont, Chung.

Administrative, technical, or material support: Martin-Brevet, Hanson, Maillard, Faucett, Pain, Bernier, Chawner, Andrieux, Forzano, Goin-Kochel, Keren, Le Caignec, Mignot, Mukherjee, Owen, Rooyck, Tjernagel, Van Haelst, Draganski, Serr, van den Bree, Sprio, Reymond, Chung.

Study supervision: Snyder, Hanson, Faucett, Aylward, Conus, Goin-Kochel, Martin, Metspalu, Steinman, Tjernagel, Shen, Draganski, Serr, Ledbetter, Beckmann, Sprio, Reymond, Jacquemont, Chung.

Conflict of Interest Disclosures: None reported.

Funding/Support: This study was supported by the Center of Excellence in Genomics, by grant SPIGARENG (University of Tartu); by grant IU20-60 from the Estonian Research Council; by a fellowship from the Swiss Scientific Exchange NMS Program (Dr Männik); by a Bursary Professorship fellowship of the Swiss National Science Foundation (SNSF) (Dr Jacquemont); by grant SAFR124424 from the Simons Foundation (Dr Reymond); by grant 31030A160203 from the SNSF (Dr Reymond); by Sinergia grant CRSII13-133043 from the SNSF (Dr Reymond); and by a Medical Research Council (MRC) doctoral fellowship grant at the MRC Centre for Neuropsychiatric Genetics and Genomics, Cardiff University (Mr Chawner). Dr Draganski is supported by project grants 2302030, 315769 and SPUM 33CM301430321 from the Swiss National Science Foundation (NCCR Synapsis), Foundation Parkinson Switzerland, Foundation Synapsis and the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement 604102 (Human Brain Projects). LREN receives financial support from the Roger de Spoelberch and Partridge Foundations. The Simons VIP program is supported by the Simons Foundation Autism Research Initiative (SFARI).

Role of the Funder/Sponsor: The funding sources had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Group Information: Members of the European 16p11.2 Consortium include the following: Nine V. A. M. Knoers, MD, PhD, doctoral training grant of Medical Genetics, University Medical Centre Utrecht, Utrecht, the Netherlands; Danielle Martinet, PhD, Service of Medical Genetics, Centre Hospitalier Universitaire Vaudois (CHUV), Lausanne, Switzerland; Marco Belfiore, PhD, Service of Medical Genetics, CHUV, Jean-Christophe Cuvellier, MD, Service de Neuropédiatrie, Hôpital Roger Salengro, Centre Hospitalier Régional Universitaire (CHR) de Lille, Lille, France; Bert de Vries, MD, PhD, Department of Human Genetics, Radboud University Nijmegen Medical Centre, Nijmegen, the Netherlands; Marie-Ange Delrue, MD, Department of Medical Genetics, Centre Hospitalier Universitaire (CHU) de Bordeaux, GHT Pellegrin, Bordeaux, France; Martine Duc-Penfely, MD, Service de Généétique, Hôpital Maison Blanche (HMB), EA3801-CHU Reims, Reims, France; Robert Lebeau, MD, Greenwood Genetic Center, Greenwood, South Carolina; Bruno Leheup, MD, PhD, Service de Médecine Infantile III et Génétique Clinique, CHU-Nancy of the University of Lorraine, Université Henri Poincaré, Vandœuvre-lès-Nancy, France; Suzanne Lewis, MD, Department of Medical Genetics, University of British Columbia, Vancouver, British Columbia, Canada; Maria Antonietta Mencarelli, MD, PhD, Medical Genetics, University of Siena, and Genetica Medica, Azienda Ospedaliero Universitaria Senese, Siena, Italy; Jean-Claude Minet, MD, Department of Pediatrics, Hôpital du Jura, Délémont, Switzerland; Catherine Vincent-Delorme, MD, Institut de Génétique Médicale, Hôpital Jeanne de Flandre, Lille, Alexandre Moerman, MD, Institut de Génétique Médicale, Hôpital Jeanne de Flandre, Lille, Mafalda Muccio, MD, PhD, Medical Genetics, University of Siena, Siena; Katrin Ounap, MD, Department of Genetics, United Laboratories, Tartu University Hospital, Tartu, Estonia; Evića Rajcan-Separovic, PhD, Department of Pathology (Cytogenetics), University of British Columbia, Vancouver; Alessandra Renieri, MD, Medical Genetics, University of Siena, and Genetica Medica, Azienda Ospedaliero Universitaria Senese, Siena; Damien Sanlaville, MD, PhD, Service de Cytogénétique Constitutionnelle, Hospices Civils de Lyon, CHU de Lyon and Centre de Recherche en Neuroscience de Lyon, UCBL1, U1028 Institut National de la Santé et de la Recherche Medicale (INSERM), Unités Mixtes de Recherche (UMR) 5292 Centre de Recherche en Neurosciences, Lyon, France; Brigitte H Faas, PhD, Department of Human Genetics, Radboud University Nijmegen Medical Centre, Nijmegen; David A Koczen, MD, PhD, Department of Human Genetics, Radboud University Nijmegen Medical Centre; JIll A. Rosenfeld, MS, Signature Genomics Laboratories, PerkinElmer Inc, Spokane, Washington; Isabel Filges, MD, Department of Medical Genetics, BC Children's and Women's Hospital, and Child and Family Research Institute, University of British Columbia; Division of Medical Genetics, University of British Columbia; Biomedicine, University Hospitals Basel, Basel, Switzerland; Eveline Achatz, MD, Institute of Human Genetics, Medical University of Graz, Graz, Austria; Katharina M. Roetzer, MD, Institute of Human Genetics, Medical University of Graz, Graz; Dominique Bonneau, MD, PhD, Department of Biochemistry and Genetics, Angers University Hospital, Angers, France; Aignès Guichet, MD, Department of Biochemistry and Genetics, Angers University Hospital; Leila Lazaro, MD, CH Côte-Basque, Service de Pédiatrie, Bayonne, France; Ghislaine Plessis, MD, Service de Génétique Clinique, CHU Caen, France; Peter C Froel, MD, Institute of Human Genetics, Medical


