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Beyond the Global Brain Differences: Intraindividual Variability Differences in 1q21.1 Distal and 15q11.2 BP1-BP2 Deletion Carriers

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ABSTRACT

BACKGROUND: Carriers of the 1q21.1 distal and 15q11.2 BP1-BP2 copy number variants exhibit regional and global brain differences compared with noncarriers. However, interpreting regional differences is challenging if a global difference drives the regional brain differences. Intraindividual variability measures can be used to test for regional differences beyond global differences in brain structure.

METHODS: Magnetic resonance imaging data were used to obtain regional brain values for 1q21.1 distal deletion (n = 30) and duplication (n = 27) and 15q11.2 BP1-BP2 deletion (n = 170) and duplication (n = 243) carriers and matched noncarriers (n = 2350). Regional intra-deviation scores, i.e., the standardized difference between an individual's regional difference and global difference, were used to test for regional differences that diverge from the global difference.

RESULTS: For the 1q21.1 distal deletion carriers, cortical surface area for regions in the medial visual cortex, posterior cingulate, and temporal pole differed less and regions in the prefrontal and superior temporal cortex differed more than the global difference in cortical surface area. For the 15q11.2 BP1-BP2 deletion carriers, cortical thickness in regions in the medial visual cortex, auditory cortex, and temporal pole differed less and the prefrontal and somatosensory cortex differed more than the global difference in cortical thickness.

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CONCLUSIONS: We find evidence for regional effects beyond differences in global brain measures in 1q21.1 distal and 15q11.2 BP1-BP2 copy number variants. The results provide new insight into brain profiling of the 1q21.1 distal and 15q11.2 BP1-BP2 copy number variants, with the potential to increase understanding of the mechanisms involved in altered neurodevelopment.

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Carriers of certain rare recurrent copy number variants (CNVs), i.e., deletions or duplications of a segment of the genome, have a higher risk of developing psychiatric and neurodevelopmental disorders, including schizophrenia and autism spectrum disorder (1–5). Several rare recurrent CNVs have moderate to large effects on structural brain measures derived from magnetic resonance imaging (MRI) (6,7). The effects of CNVs on brain structure have been suggested to occur primarily during early neurodevelopment (8), and some rare recurrent CNVs have been associated with altered cellular function, composition, and size derived from cortical organoids that model fetal and early neurodevelopment (9–12). The 1q21.1 distal and 15q11.2 BP1-BP2 deletions are two of the most common recurrent CNVs (1,13,14). They yield a higher risk of psychiatric and neurodevelopmental disorders (1–5) and show moderate to large effects on brain structure (15,16). Thus, studying 1q21.1 distal and 15q11.2 BP1-BP2 deletion carriers offers a promising genetics-first approach to study deviations in neurodevelopment and brain structure, which may underlie the increased risk of developing psychiatric and neurodevelopmental disorders (5,8).

To date, neuroimaging studies on CNVs have focused on conventional mean comparisons between carriers and noncarriers, which have been informative for brain profiling of CNV carriers. For instance, several CNVs have shown global effects on the brain, as demonstrated by group differences in mean cortical thickness, total cortical surface area, and total subcortical volume, in addition to widespread regional differences (6,7). However, brain profiling may be challenging if an overall global difference in the brain drives many of the regional mean differences or if regional differences are driven by distinct subgroups in each comparison, rendering interregional brain profiles difficult to interpret. To overcome this challenge, detecting brain regions that diverge from the global difference could benefit from intraindividual variability measures, in which regional values represent the relative position within an individualized brain profile. Identification of brain regions that diverge from the overall global difference of the CNV may provide valuable insights into the regional penetrance, brain organization, and functional consequences in CNV carriers. Indeed, as has been demonstrated in other fields, such as cognitive science and neuropsychology (17–22), novel scientific and clinical insights can be achieved by looking beyond mean group differences through investigating intraindividual variability.

Both 1q21.1 distal and 15q11.2 BP1-BP2 deletion carriers exhibit global differences in brain structure, with the former displaying a lower total cortical surface area (15) and the latter showing a higher mean cortical thickness and lower total cortical surface area (16). Additionally, these deletions exhibit regional differences across the cortex (15,16). However, the regional differences vary across the brain as indicated by variation in effect sizes across brain regions. This could indicate that the carriers of the 1q21.1 distal and 15q11.2 BP1-BP2 deletions exhibit higher variability in brain structure, along with systematic interregional differences in brain structure as measured by MRI-derived features.

In both 1q21.1 distal and 15q11.2 BP1-BP2 CNV carriers, the largest regional differences are typically found in frontal regions, associated with higher cognitive processing. In contrast, the posterior brain regions, associated with primary sensory processing, typically do not show significant differences (15,16). Insight into variation in brain structure may be useful for understanding differences in brain function, as cortical morphology overlaps with the functional hierarchical gradient of the brain (23). This functional hierarchical gradient reflects a sensorimotor (i.e., involved in unimodal and functional specific processes) to association (i.e., involved in higher-order cognitive processes) axis in the human brain (23–25), which has been supported by anatomical, functional, and evolutionary data (24). Thus, a more fine-grained brain profile of the structural differences in 1q21.1 distal and 15q11.2 BP1-BP2 CNV carriers may aid understanding of their phenotypic profile.

Brain structural differences in 1q21.1 distal and 15q11.2 BP1-BP2 CNV carriers indicate global mean differences (i.e., cortical thickness and cortical surface area) as well as regional group differences in primarily frontal brain regions. The regional group differences indicate that some brain regions are more affected than others. Here, we define more affected brain regions as regions that differ more than the global mean difference and less affected brain regions as regions that differ less than the global mean difference. To measure this, we used an intraindividual variability measure to detect brain regions that diverge from the global difference, where the regional values represent its position within an individualized brain profile. We expected that anterior regions within the association cortices would be more affected, whereas posterior regions within the primary sensorimotor cortices would be less affected in carriers of the 1q21.1 distal and 15q11.2 BP1-BP2 CNVs.

METHODS AND MATERIALS

Sample

Individuals carrying a 1q21.1 distal or 15q11.2 CNV and a matched noncarrier group were obtained from the Enhancing NeuroImaging Genetics through Meta Analysis (ENIGMA) CNV

Working Group core dataset and the UK Biobank across 61 scanner sites. Each CNV carrier was matched with 5 noncarriers based on age, sex, scanner site, and intracranial volume using the MatchIt package in R (26). This resulted in 4 subsets (sample characteristics are presented in Tables 1 and 2; see also Note 1 in Supplement 1).

MRI-Derived Features, CNVs, and Quality Control

Neuroimaging data were obtained from the UK Biobank, as described elsewhere (27), and from the ENIGMA-CNV core dataset. The ENIGMA-CNV neuroimaging measures were collected from several sites (see Appendix 1 in Supplement 2 for details) and analyzed using the standardized ENIGMA protocol (https://enigma.ini.usc.edu/protocols/imaging-protocols/). Details of the quality control of MRI are provided in Note 2 in Supplement 1. Briefly, the MRI data from the ENIGMA-CNV Working Group were subjected to the ENIGMA cortical quality control procedures (https://enigma.ini.usc.edu/protocols/imaging-protocols/), where the 68 cortical and 14 subcortical regions were extracted using the Desikan-Killiany atlas. For the UK Biobank sample, we used the Euler number as a proxy for image quality (28) and removed all participants with Euler numbers below minus 4 standard deviations from downstream analyses (n = 437). To account for site effects in the samples, we ran each of the 4 subsets through ComBat, an instrument for data harmonization (29). CNV calling in ENIGMA-CNV was based on previous publications (15,16). For the UK Biobank sample, we identified CNVs based on the returned dataset from Crawford *et al.* (30). All participants with a CNV as defined in previous publications (15,16,30) were removed from downstream analyses except for the individuals flagged with the 1q21.1 distal or the 15q11.2 BP1-BP2 CNV.

Derivation of Dependent Variables

We adjusted for the effect of age, age^2, sex, and intracranial volume on every brain regional value using linear regression across the carriers and the noncarriers. The residualized brain regional values were used to calculate the mean and standard deviation for the noncarriers only. We estimated 1) z scores per region [similar calculations as in (31)] and created 2) global index and 3) intraindividual standard deviation [similar calculations as in (21)] as well as 4) regional intra-deviation (RID) score.

z Scores. Specifically, z scores for CNV carriers and noncarriers were calculated based on the mean and standard deviation from the noncarriers as shown in equation 1:

$$Z_{if} = \frac{(X_{if} - M_{if})}{SD_{if}} \tag{1}$$

where Z_{if} is the standardized value for brain region i using feature f (i.e., cortical thickness, surface area, or subcortical volume), X_{if} is the regional value for brain region i for feature f, and M_{if} and SD_{if} represent the mean and standard deviation, respectively, for brain region i using feature f across the noncarriers. Thus, for every individual, we obtained a vector of standardized z scores across 68 cortical regions for cortical thickness and cortical surface area and 14 subcortical regions.

Global Index. We created an individualized global index for cortical thickness, cortical surface area, and subcortical volume, respectively, by calculating the mean z score across the cortical and subcortical regions as shown in equation 2:

$$GI_f = \frac{1}{n_f} \sum_{i=1}^{n_f} Z_{if} \tag{2}$$

where GI_f is the global index for feature f, n is the total number of brain regions for feature f, and Z_{if} is the standardized value for the brain region I for feature f derived from equation 1.

Intraindividual Standard Deviation. We also calculated the intraindividual standard deviation across the z scores for cortical thickness, cortical surface area, and subcortical volume to obtain measures of within-individual variability, as shown in equation 3:

$$iSD_f = \sqrt{\frac{\sum_{i=1}^{n_f} (Z_{if} - GI_f)^2}{n_f - 1}} \tag{3}$$

where iSD_f is the intraindividual standard deviation for feature f, n_f is total number of brain regions for feature f, Z_{if} is the standardized value for brain region i for feature f, and GI_f is the global index for feature f (i.e., mean z score across brain regions for an individual) as derived from equation 2. A low intraindividual standard deviation indicates that an individual's z scores across brain regions are relatively consistent and do not vary much across brain regions, while

Table 1. Sample Characteristics for 1q21.1 Distal CNVs and Noncarrier Comparison Groups

	1q21.1 Distal Deletion, n = 30	1q21.1 Distal Deletion Comparison Group, n = 150	1q21.1 Distal Duplication, n = 27	1q21.1 Distal Duplication Comparison Group, n = 135
Age, Years, Mean	41.6	44.6	56.4	53.7
Age, Years, Range	7.7–68.7	9.2–76.2	18.7–73.1	9.5–77.2
Females, n (%)	14 (46.7%)	73 (48.7%)	15 (55.6%)	77 (57.0%)
Intracranial Volume, mm^3 × 10^6, Mean (SD)	1.25 (0.23)	1.26 (0.25)	1.59 (0.16)	1.56 (0.30)

CNV, copy number variant.

Table 2. Sample Characteristics for 15q11.2 BP1-BP2 CNVs and Noncarrier Comparison Groups

	15q11.2 BP1-BP2 Deletion, n = 170	15q11.2 BP1-BP2 Deletion Comparison Group, n = 850	15q11.2 BP1-BP2 Duplication, n = 243	15q11.2 BP1-BP2 Duplication Comparison Group, n = 1215
Age, Years, Mean	55.9	55.9	55.8	55.9
Age, Years, Range	7.1–77.7	6.8–90.0	7.83–88.5	3.75–89.8
Females, n (%)	90 (52.9%)	428 (50.4%)	127 (52.3%)	608 (50.0%)
Intracranial Volume, $mm^3 \times 10^6$, Mean (SD)	1.48 (0.20)	1.50 (0.20)	1.46 (0.19)	1.46 (0.20)

CNV, copy number variant.

a high intraindividual standard deviation indicates that the z scores across brain regions are relatively inconsistent, indexing a more variable brain.

Regional Intra-deviation Score. Finally, to identify regions that diverge more than expected from an individual's global index and intraindividual standard deviation, we created an RID score calculated using equation 4 for every brain region across feature f:

$$RID_{if} = \frac{(Z_{if} - GI_f)}{iSD_f} \quad (4)$$

where RID_{if} is the RID score for brain region i using feature f, Z_{if} is the standardized value for brain region i for feature f, and GI_f is the global index for feature f as shown in equation 2. The iSD_f reflects the intraindividual standard deviation for the z score across brain regions in feature f as formulated in equation 3. Here, we define regions that are less affected as those that do not follow the global tendency in the data, whereas the regions that exceed the global tendency of the data are considered to be more affected. To establish brain-cognition relationships between the brain measures and cognition, we tested for associations between RID and z scores and cognitive ability (Note 3 and Figure S1 in Supplement 1; Table S1).

Statistical Analyses

All statistical analyses were conducted in Rstudio (R version 4.0.0; https://www.R-project.org/), and brain visualizations were created using the ENIGMA toolbox (32). For the per-CNV analyses, we tested for group differences by including carrier status (i.e., either carrier or noncarrier) in a linear regression model. The deletion and duplication carriers were tested separately with their corresponding matched noncarrier group used as the reference. The estimated standardized beta values were extracted from the models and are presented in the results as a measure of effect size. The p values underwent a false discovery rate (FDR) (33) adjustment to account for multiple comparisons for each of the 4 CNV groups. Corrected p values $<$ .05 were considered statistically significant. Three main analyses were performed: First, in line with the conventional mass-univariate analysis approach, we performed group comparisons on the z scores across all the regions of interest (ROIs) for cortical thickness, cortical surface area, and subcortical volume (FDR corrected for 150 comparisons). Second, we compared the global index and intraindividual standard deviation and mean corrected intraindividual standard deviation values between carriers and noncarriers (FDR corrected for 12 comparisons). The mean corrected intraindividual standard deviation represents the intraindividual standard deviation after regressing out the global index, as the mean values tend to be correlated with the standard deviation. Third, for the RID scores, group comparisons were computed between carriers and noncarriers for all ROIs for cortical thickness, cortical surface area, and subcortical volume (FDR corrected for 150 comparisons). Due to missing values in some brain regions, the analyses were restricted to individuals with complete observations for the feature that was analyzed (i.e., cortical thickness, cortical surface area, and subcortical volume). Sensitivity analyses were conducted for the significant RID score differences by adjusting for affection status (i.e., known psychiatric or neurological diagnoses). In addition, we examined the interaction term between carrier status and affection status and between carrier status and cognitive ability. Finally, we compared the brain profile of significant differences in RID scores with the significant differences in z scores adjusted for the global index.

RESULTS

Global Measures

The group differences in the global index and the intraindividual standard deviation measures are presented in Table 3 with reference values for the noncarrier groups in Table S2. The 1q21.1 distal deletion carriers had a lower global index for surface area, whereas the 15q11.2 BP1-BP2 deletion carriers had a lower global index for surface area and a higher global index for cortical thickness. In addition, the 15q11.2 BP1-BP2 duplication carriers had a lower global index for cortical thickness. Furthermore, there was a higher intraindividual standard deviation for cortical surface for both the 1q21.1 distal duplication carriers (both for the mean corrected measure and for the uncorrected measure) and the 15q11.2 BP1-BP2 deletion carriers (only for the mean corrected measure) as well as a higher intraindividual standard deviation for cortical thickness in the 15q11.2 BP1-BP2 deletion carriers (both for the mean corrected measure and for the uncorrected measure). With one exception, correlations between the intraindividual standard deviation measures across CNV groups did not show any significant differences (Note 4 and Figure S2 in Supplement 1).

1q21.1 Distal CNV

1q21.1. Distal Deletion. The 1q21.1. distal deletion carriers showed widespread lower cortical surface area with significant differences in 63 ROIs using z scores (Figure 1A, B,

Table 3. Group Differences in Global Index and Intraindividual Standard Deviation

	1q21.1 Distal Deletion	1q21.1 Distal Duplication	15q11.2 BP1-BP2 Deletion	15q11.2 BP1-BP2 Duplication
Global Index				
Cortical surface area	−1.29 (0.18)[d]	0.40 (0.22)	−0.22 (0.09)[b]	−0.09 (0.07)
Cortical thickness	0.39 (0.21)	−0.04 (0.22)	0.35 (0.09)[d]	−0.24 (0.07)[b]
Subcortical volume	−0.15 (0.20)	−0.48 (0.22)[a]	−0.17 (0.09)[a]	0.02 (0.07)
Intraindividual Standard Deviation, Mean Uncorrected				
Cortical surface area	−0.20 (0.21)	0.73 (0.22)[c]	0.15 (0.09)	−0.02 (0.07)
Cortical thickness	0.37 (0.21)	0.44 (0.22)[a]	0.20 (0.09)[b]	0.00 (0.07)
Subcortical volume	−0.08 (0.20)	0.22 (0.22)	0.04 (0.09)	0.02 (0.07)
Intraindividual Standard Deviation, Mean Corrected				
Cortical surface area	0.24 (0.21)	0.62 (0.22)[b]	0.23 (0.09)[b]	0.06 (0.07)
Cortical thickness	0.37 (0.21)	0.46 (0.22)[a]	0.19 (0.08)[b]	0.00 (0.07)
Subcortical volume	−0.06 (0.20)	0.30 (0.22)	0.08 (0.09)	0.02 (0.07)

Values represent the standardized beta coefficient between carriers and noncarriers, with noncarriers as the reference. Standard error is presented in parentheses.
p_{FDR}, false discovery rate–corrected p.
[a]$p < .05$
[b]$p_{FDR} < .05$
[c]$p_{FDR} < .01$
[d]$p_{FDR} < .001$.

top; Table S3) and exhibited a higher RID score for cortical surface area in regions within the occipital, superior parietal, temporal pole, and posterior cingulate cortex as well as lower RID scores in regions within the superior temporal and frontal regions (Figure 1A–C, bottom; Table S4). Further, 1q21.1 distal deletion carriers showed higher cortical thickness compared with noncarriers in 19 ROIs using *z* scores (Figure 2A, B, top; Table S3), in addition to lower RID scores for regions within the occipital lobe and paracentral lobule and higher RID scores for regions within the superior temporal and inferior frontal cortex (Figure 2A–C, bottom; Table S4). The 1q21.1 distal deletion carriers also exhibited lower subcortical volume in left thalamus and right nucleus accumbens (Table S3) and lower RID score for the left thalamus (Table S4). All significant RID score differences survived adjustment for affection status. The interaction term between carrier status and affection status was not associated with the significant RID scores (Note 5 in Supplement 1; Table S5). A subset of the significant RID scores were implicated in the brain-cognition RID map (Figure S1 in Supplement 1). However, we did not observe any significant interactions between carrier status and cognitive ability on any of the significant RID scores (Note 6 in Supplement 1; Table S6). The results yielded more significant group differences in RID scores (i.e., 24) compared with *z* scores adjusted for the global index between 15q11.2 BP1-BP2 deletion carriers and noncarriers (i.e., 13) (Supplementary Note 7 and Figure S3 in Supplement 1; Table S7).

1q21.1 Distal Duplication. The 1q21.1 distal duplication carriers showed higher cortical surface area in the right pars opercularis and right superior frontal gyrus and lower volume in the right and left hippocampus compared with noncarriers (Table S8). Using RID scores, no significant differences in the ROIs were found (Table S9).

15q11.2 BP1-BP2 CNV

15q11.2 BP1-BP2 Deletion. The 15q11.2 BP1-BP2 deletion carriers showed lower cortical surface area in 10 ROIs using *z* scores (Figure 3A and B, top; Table S10) and higher RID scores for the left frontal pole and right pars opercularis surface area, but lower RID scores for the left and right pars orbitalis surface area compared with noncarriers (Figure 3A–C, bottom; Table S11). For cortical thickness, the 15q11.2 BP1-BP2 deletion carriers showed higher cortical thickness in 30 regions using *z* scores (Figure 4A, B, top; Table S10). The RID scores for cortical thickness were lower in regions within occipital and temporal regions and higher in motor and frontal regions compared with noncarriers (Figure 4A–C, bottom; Table S11). The 15q11.2 BP1-BP2 deletion carriers also showed lower *z* scores for left caudate, right pallidum, and right nucleus accumbens (Table S10). All significant RID scores remained significant after adjustment for affection status. No significant interactions between carrier status and affection status (Table S12; Note 5 in Supplement 1) or between carrier status and cognitive ability for the 15q11.2 BP1-BP2 deletion carriers were observed (Table S13; Note 6 in Supplement 1). The results yielded more significant group differences in RID scores (i.e., 14) compared with *z* scores adjusted for global index (i.e., 12) between 15q11.2 BP1-BP2 deletion carriers and noncarriers (Note 7 and Figure S4 in Supplement 1; Table S14).

15q11.2 BP1-BP2 Duplication. The 15q11.2 BP1-BP2 duplication carriers showed lower cortical thickness in 11 ROIs and higher right superior frontal cortical surface area using *z* scores (Table S15), but showed no significant differences in the ROIs using RID scores (Table S16).

DISCUSSION

To our knowledge, the current study is the first to identify intraindividual variability differences in brain structure in CNV carriers. Using the intraindividual standard deviation measure, we observed higher variability in the regional effects for cortical surface area in both 1q21.1 distal duplication and 15q11.2 BP1-BP2 deletion carriers and higher variability in the regional effects for cortical thickness for the 15q11.2 BP1-BP2 deletion

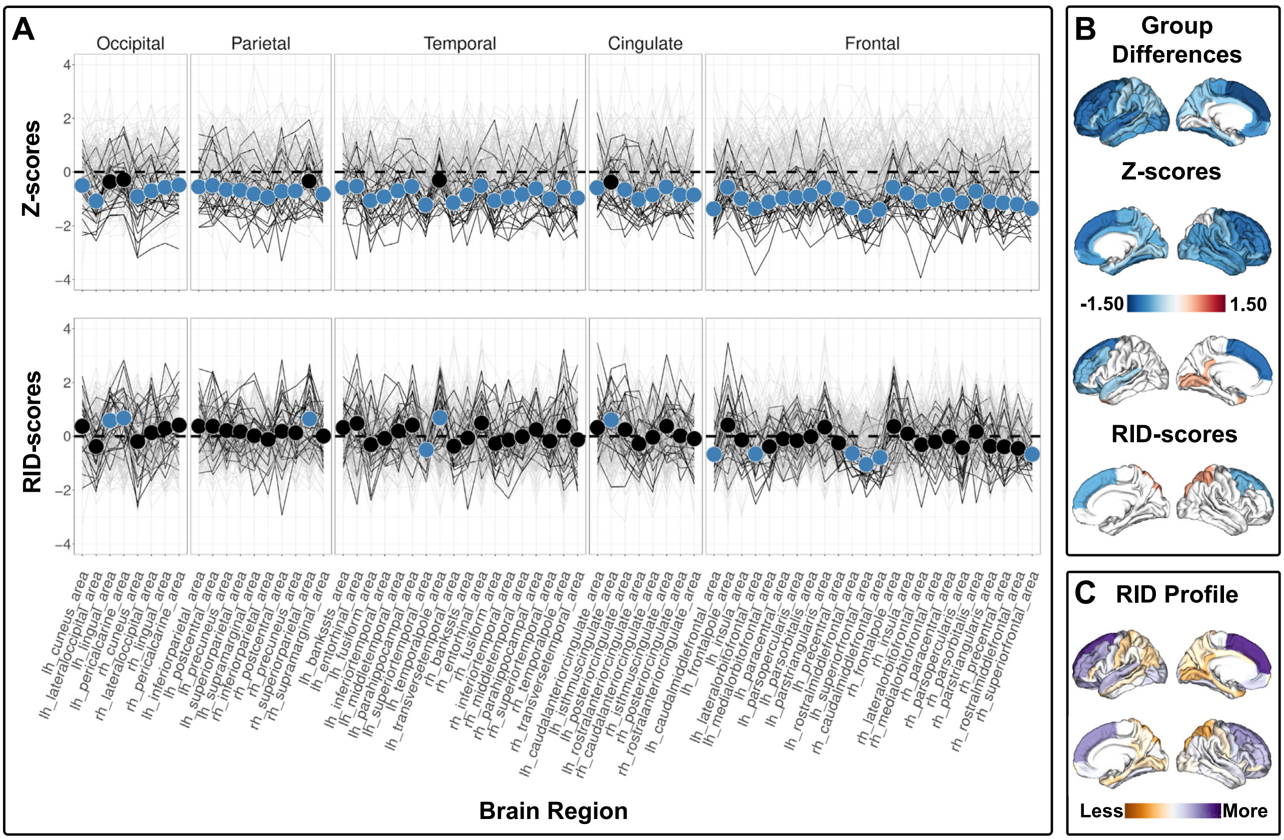

Figure 1. Cortical surface area comparison between 1q21.1 distal deletion carriers and noncarriers. **(A)** Top panel shows *z* scores, i.e., group differences in regional cortical surface area. Bottom panel shows regional intra-deviation (RID) scores, i.e., group differences in regional cortical surface area that are scaled to the individual's own global index. Noncarriers are represented by gray lines, and 1q21.1 distal deletion carriers are represented by black lines. Blue dots indicate significant differences. The insular cortex is included under the frontal cortex for visualization purposes. **(B)** Top panel shows the significant differences in *z* scores, and bottom panel shows the significant differences in RID scores. Blue-red diverging maps represent the effect size. **(C)** Spatial distribution of all the mean differences in RID scores. All values are shown regardless of significance. Yellow-purple diverging maps represent the direction of the mean differences. Increased yellow intensity represents values that are less deviant than the overall global mean difference in cortical surface area, and increased purple intensity represents values that are more deviant than the overall global mean difference in cortical surface area. The *z* scores and RID scores are based on raw values adjusted for age, age^2, sex, and intracranial volume on site harmonized data.

carriers compared with noncarriers. Using RID scores, we found that a subset of brain regions diverged significantly from noncarriers for both the 1q21.1 distal and the 15q11.2 BP1-BP2 deletion carriers. We also found a higher number of significant regional differences using RID scores compared with the conventional global covariation approach. The current results hold promise for identifying specific CNV-associated brain profiles by targeting regional differences using an individualized approach, which are overlooked in studies applying conventional brain MRI measures.

In line with previous results (15), the 1q21.1 distal deletion carriers showed lower global cortical surface area compared with noncarriers. The observed differences in *z* scores indicate widespread lower cortical surface area, whereas the RID scores indicate that the cortical surface area in posterior and primary sensory regions (i.e., lingual, pericalcarine, superior parietal, isthmus of the cingulate gyrus) is less affected, and frontal and association cortices (i.e., caudal middle frontal, lateral orbitofrontal, rostral middle frontal, superior frontal cortex) are more affected. Thus, the observed regional *z* score group differences along lateral and medial parietal to lateral inferior temporal and motor cortex appear to be largely reflective of the global effect. A subset of the significant RID scores (i.e., the superior temporal gyri and left supramarginal gyrus cortical thickness and left lateral orbitofrontal and left lateral superior temporal gyrus cortical surface area) were associated with cognitive ability in noncarriers. However, the effect sizes are low, and the current sample size of CNV carriers is too small to reliably detect such brain-cognition associations.

The 15q11.2 BP1-BP2 deletion showed a higher global cortical thickness compared with noncarriers, primarily concentrated in the frontal cortex, recapitulating previously reported group differences in cortical thickness (16). We complement these findings by showing group differences in RID scores, which indicates that the cortical thickness in sensory cortices (i.e., cuneus and pericalcarine area) is less affected, and the association cortices (i.e., rostral middle frontal and superior frontal cortex) are more affected by the deletion. The association cortices that show cortical thickness

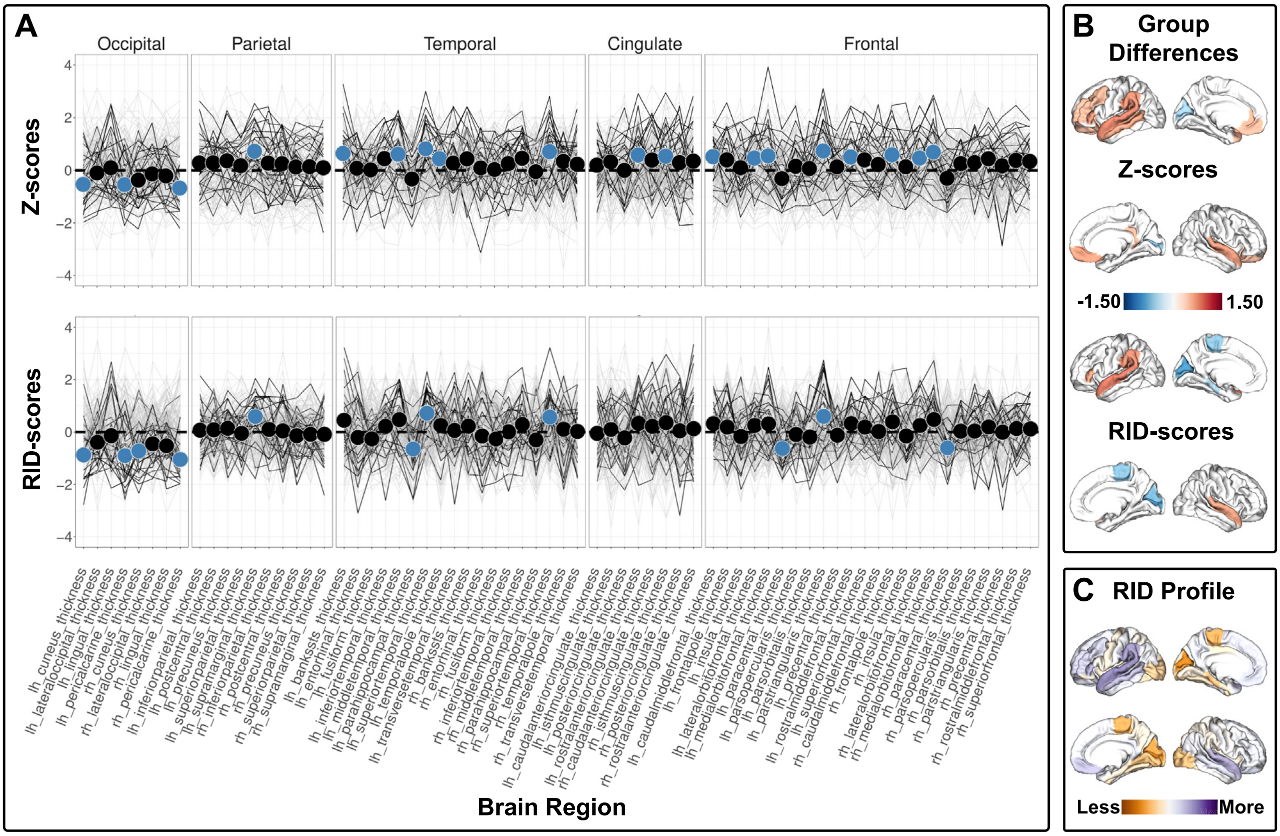

Figure 2. Cortical thickness comparison between 1q21.1 distal deletion carriers and noncarriers. **(A)** Top panel shows *z* scores, i.e., group differences in regional cortical thickness. Bottom panel shows regional intra-deviation (RID) scores, i.e., group differences in regional cortical thickness that are scaled to the individual's own global index. Noncarriers are represented by gray lines, and 1q21.1 distal deletion carriers are represented by black lines. Blue dots indicate significant differences. The insular cortex is included under the frontal cortex for visualization purposes. **(B)** Top panel shows the significant differences in *z* scores, and bottom panel shows the significant differences in RID scores. Blue-red diverging maps represent the effect size. **(C)** Spatial distribution of all the mean differences in RID scores. All values are shown regardless of significance. Yellow-purple diverging maps represent the direction of the mean differences. Increased yellow intensity represents values that are less deviant than the overall global mean difference in cortical thickness, and increased purple intensity represents values that are more deviant than the overall global mean difference in cortical thickness. The *z* scores and RID scores are based on raw values adjusted for age, age^2, sex, and intracranial volume on site harmonized data.

differences using RID scores are regions that underlie complex cognitive functions (23–25) and may subserve the lower cognitive performance in 15q11.2 BP1-BP2 deletion carriers compared with control individuals (14,34).

Notably, some findings deviated from the interpretation of a less affected sensorimotor cortex and a more affected association cortex. Both the 1q21.1 distal and the 15q11.2 BP1-BP2 deletion carriers showed evidence for a relatively less affected cortical surface area and cortical thickness, respectively, in the left temporal pole. We also found that the cortical thickness of the postcentral gyri, a primary somatosensory region, is more affected in the 15q11.2 BP1-BP2 deletion carriers. To speculate, this may be associated with the motor delay observed in clinically affected 15q11.2 BP1-BP2 deletion carriers (35). For cortical surface area in the 15q11.2 BP1-BP2 deletion carriers, we found inconsistent effects for frontal regions: although we observed a relatively more different bilateral pars orbitalis, we also found evidence for a less different left frontal pole and right pars opercularis. Furthermore, we did not find significant differences in RID scores in the 15q11.2 BP1-BP2 duplication carriers or in the 1q21.1 distal duplication carriers. The results complement previous findings of lower effect sizes in brain measures for duplication versus deletion carriers (6,7) and thus may support that carrying the deletion distorts the anatomical relationships in the brain more than carrying the duplication.

Global and frontal regional group differences in cortical thickness are prominent brain features of several neurodevelopmental disorders, including autism spectrum disorder (36) and schizophrenia (37). Thus, group differences in brain structure may be confounded by individuals with neurodevelopmental or psychiatric disorders. Here, all the significant RID score differences in 1q21.1 distal and 15q11.2 BP1-BP2 deletions survived adjustment for affection status, and there were no interaction effects between carrier status and affection status on the significant RID scores.

The current results implicate novel mechanisms in neurodevelopment. Compelling candidates for the changes in the 1q21.1 distal CNV are the human specific *NOTCH2NL* genes, which have been linked to the evolutionary expansion of the

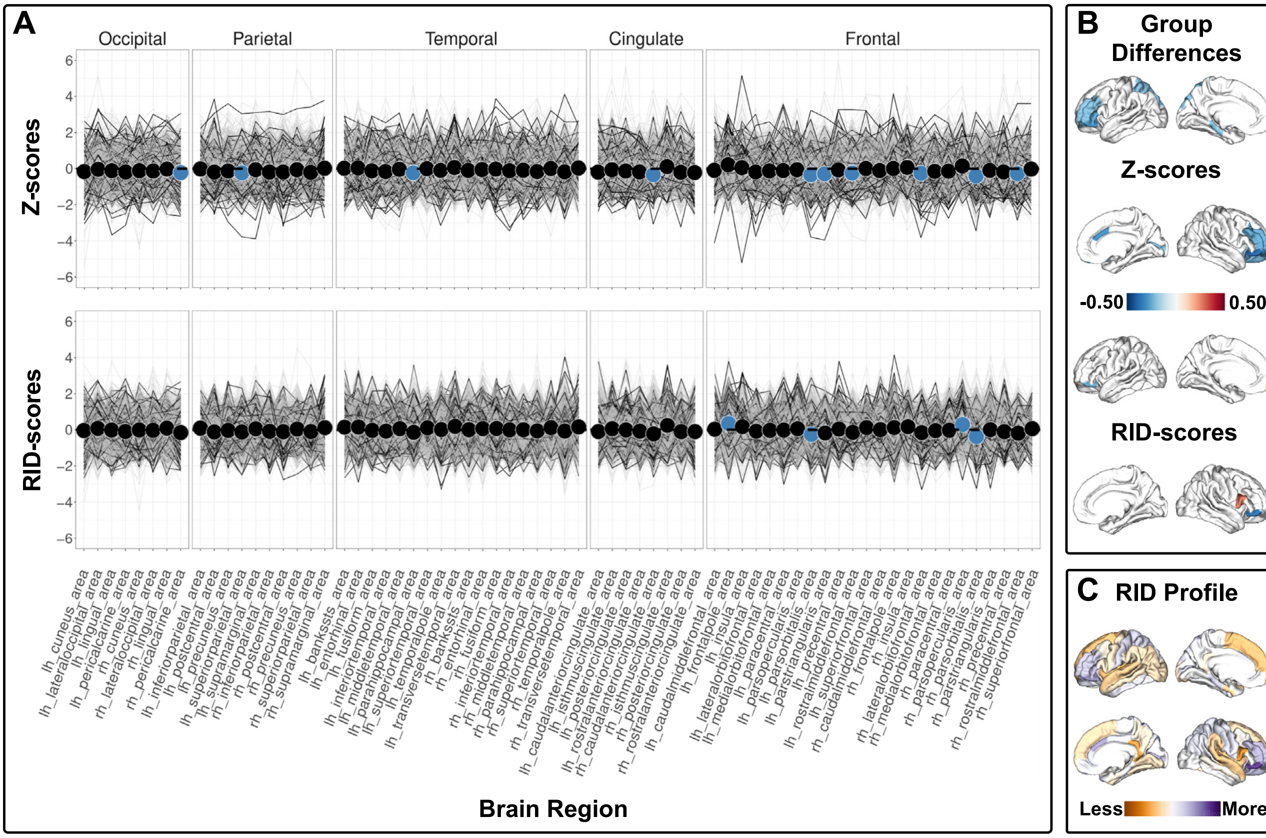

Figure 3. Cortical surface area comparison between 15q11.2 BP1-BP2 deletion carriers and noncarriers. **(A)** Top panel shows *z* scores, i.e., group differences in regional cortical surface area. Bottom panel shows regional intra-deviation (RID) scores, i.e., group differences in regional cortical surface area that are scaled to the individual's own global index. Noncarriers are represented by gray lines, and 15q11.2 BP1-BP2 deletion carriers are represented by black lines. Blue dots indicate significant differences. The insular cortex is included under the frontal cortex for visualization purposes. **(B)** Top panel shows the significant differences in *z* scores, and bottom panel shows the significant differences in RID scores. Blue-red diverging maps represent the effect size. **(C)** Spatial distribution of all the mean differences in RID scores. All values are shown regardless of significance. Yellow-purple diverging maps represent the direction of the mean differences. Increased yellow intensity represents values that are less deviant than the overall global mean difference in cortical surface area, and increased purple intensity represents values that are more deviant than the overall global mean difference in cortical surface area. The *z* scores and RID scores are based on raw values adjusted for age, age^2, sex, and intracranial volume on site harmonized data.

human neocortex (38,39). NOTCH signaling is important for outer radial glial cell self-renewal, which is thought to contribute to cortical expansion (40). Deletion of the *NOTCH2NL* genes in human cortical organoids yields smaller organoids compared with control organoids (38), and *NOTCH2NL* increases the number of cycling basal progenitors in the mouse embryonic neocortex (41). Thus, *NOTCH2NL* could yield a potential mechanistic link between the assumed lower gene expression levels in 1q21.1 distal deletion carriers and the lower cortical surface area, which is possibly important for the expansion of frontal regions.

Among the 4 genes in the 15q11.2 BP1-BP2 loci (42), *CYFIP1* has gained considerable interest due to its association with schizophrenia (43,44) and autism (45–47). Cyfip1 exhibits high expression levels in the developing mouse brain (47). *CYFIP1* has also been linked to variation in cortical surface area (48) as well as various cellular phenotypes, including myelination (49), neurite length and branch number, cell size (50), dendritic spine formation (51), and regulation of radial glial cells (52). Notably, *Cyfip1* haploinsufficiency reduces myelination thickness in rats (49). Cortical thickness, as estimated with MRI, has been suggested to be influenced by myelination (53). Thus, the higher cortical thickness observed in 15q11.2 BP1-BP2 deletion carriers may be due to altered myelination in the brain, possibly with somatosensory cortex being particularly sensitive to these alterations. *Cyfip1* deficiency has also been associated with functional connectivity deficits in motor cortices as well as aberrant motor coordination in mice (54). Finally, it should be noted that the 1q21.1 distal and the 15q11.2 BP1-BP2 loci span several genes, and genes within CNVs are likely to be involved in multifaceted genetic interactions (55). More research is needed to identify the causative biological mechanisms of the brain structural phenotypes.

This study has strengths and limitations. We used an intraindividual variability approach to examine brain metrics that are related to an individual's own interregional brain profile. By examining metrics that consider the variation within individuals, it is possible to map the heterogeneity and deviations in CNV carriers compared with noncarriers. However,

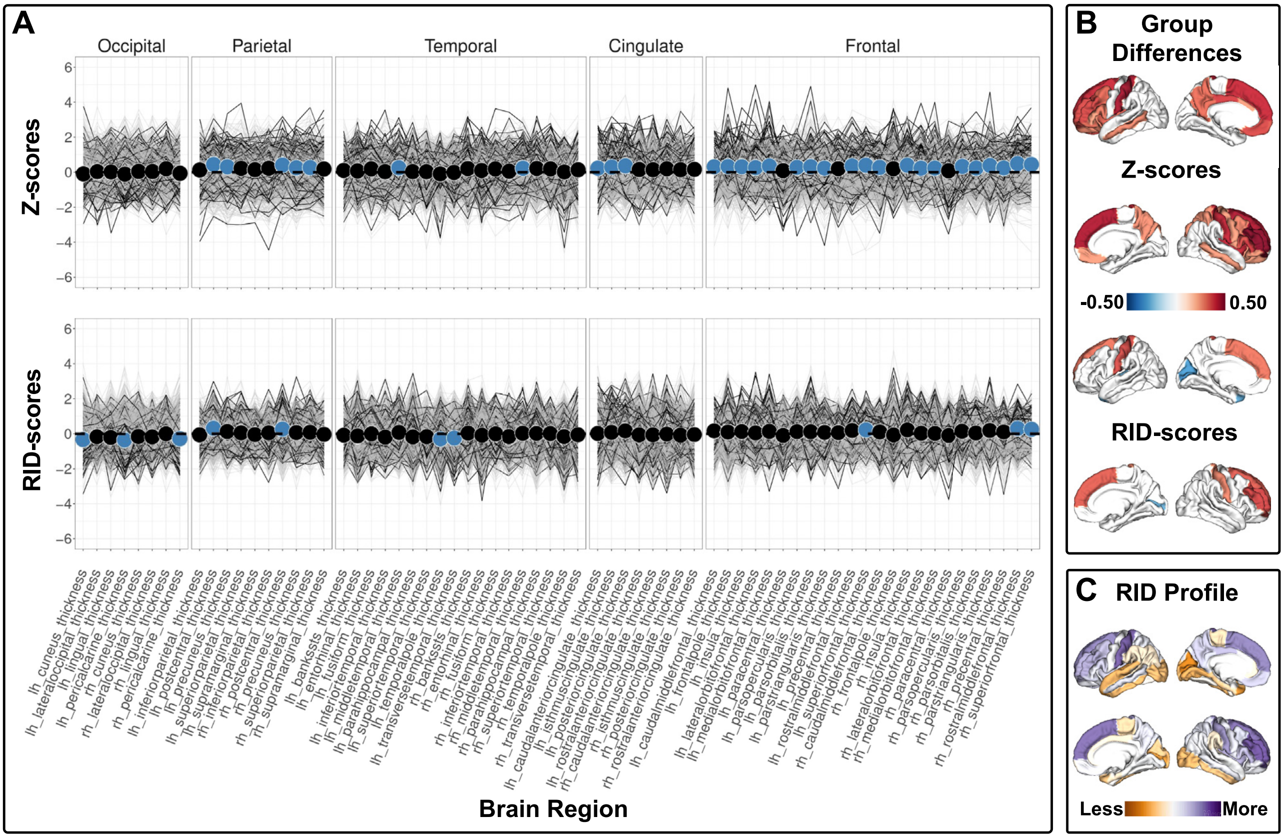

Figure 4. Cortical thickness comparison between 15q11.2 BP1-BP2 deletion carriers and noncarriers. **(A)** Top panel shows *z* scores, i.e., group differences in regional cortical thickness. Bottom panel shows regional intra-deviation (RID) scores, i.e., group differences in regional cortical thickness that are scaled to the individual's own global index. Noncarriers are represented by gray lines, and 15q11.2 BP1-BP2 deletion carriers are represented by black lines. Blue dots indicate significant differences. The insular cortex is included under the frontal cortex for visualization purposes. **(B)** Top panel shows the significant differences in *z* scores, and bottom panel shows the significant differences in RID scores. Blue-red diverging maps represent the effect size. **(C)** Spatial distribution of all the mean differences in RID scores. All values are shown regardless of significance. Yellow-purple diverging maps represent the direction of the mean differences. Increased yellow intensity represents values that are less deviant than the overall global mean difference in cortical thickness, and increased purple intensity represents values that are more deviant than the overall global mean difference in cortical thickness. The *z* scores and RID scores are based on raw values adjusted for age, age^2, sex, and intracranial volume on site harmonized data.

variability measures should be interpreted with caution, as some effects on the brain may be so extreme that further deviations are unlikely to be observed. That is, CNVs may yield large effects on brain structure, but only to a certain extent due to biological constraints. Thus, we urge caution when interpreting intraindividual standard deviation in brain measures, as ceiling and floor effects may bias the variability metrics. Still, we identified structures that are significantly less different or more different relative to the mean difference, indicating sufficient variability in the individualized brain metrics. About one half (1q21.1 distal) and two thirds (15q11.2 BP1-BP2) of the carriers are derived from the UK Biobank, which has a healthy volunteer bias (56), possibly yielding underestimations of brain structural differences. However, this is somewhat counterbalanced by the ENIGMA-CNV dataset that likely increases the heterogeneity in the study sample (although some datasets are likely to have similar bias toward healthy individuals as the UK Biobank). Indeed, the variability observed in brain structure within individuals underscores the heterogeneity between and within individuals in the sample. Future studies with larger sample sizes are needed to examine the phenotypic heterogeneity observed in CNV carriers.

The results of the current study aid understanding of 1q21.1 distal and 15q11.2 BP1-BP2 CNV brain profiles by identifying regional differences using intraindividual variability metrics, which has the potential to give better insight into the neuronal mechanisms in neurodevelopment and risk for psychiatric diseases. We find evidence for regional differences beyond the global differences in brain structure, where the spatial effects partly support the hypothesis of less affected sensorimotor cortex and more affected association cortex in both 1q21.1 distal and 15q11.2 BP1-BP2 deletion carriers.

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