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Prenatal exposure to chlorpyrifos (CPF), an organophosphate insecticide, is associated with neurobehavioral deficits in humans and animal models. We investigated associations between CPF exposure and brain morphology using magnetic resonance imaging in 40 children, 5.9–11.2 y, selected from a nonclinical, representative community-based cohort. Twenty high-exposure children (upper tertile of CPF concentrations in umbilical cord blood) were compared with 20 low-exposure children on cortical surface features; all participants had minimal prenatal exposure to environmental tobacco smoke and polycyclic aromatic hydrocarbons. High CPF exposure was associated with enlargement of superior temporal, posterior middle temporal, and inferior postcentral gyri bilaterally, and enlarged superior frontal gyrus, gyrus rectus, cuneus, and precuneus along the mesial wall of the right hemisphere. Group differences were derived from exposure effects on underlying white matter. A significant exposure × IQ interaction was derived from CPF disruption of normal IQ associations with surface measures in low-exposure children. In preliminary analyses, high-exposure children did not show expected sex differences in the right inferior parietal lobule and superior marginal gyrus, and displayed reversal of sex differences in the right mesial superior frontal gyrus, consistent with disruption by CPF of normal sex differences in cognitive and emotion-related behaviors. These studies, using different biomarkers of exposure (urinary metabolites, umbilical cord blood), show that prenatal organophosphate exposure produces a consistent pattern of early cognitive and behavioral deficits across both agricultural and urban populations.

Author contributions: V.A.R. designed research; M.K.H., R.B., X.H., and J.L. performed research; D.B.B. contributed new reagents/analytic tools; R.B., X.H., and J.L. analyzed data; and V.A.R., R.B., T.A.S., and B.S.P. wrote the paper.

Conflict of interest statement: T.A.S. has provided expert testimony on the health effects of chlorpyrifos on behalf of government entities, corporations, and/or individuals.

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Chlorpyrifos (CPF) is a widely used, broad-spectrum organophosphate insecticide first registered in 1965 for agricultural uses and pest control. Before regulatory action by the Environmental Protection Agency that phased out residential use in 2001 (1), CPF applications were particularly heavy in urban areas, where exposed populations included pregnant women (2, 3). CPF remains heavily used in agriculture, with continuing exposures of workers and residents of agricultural communities, as well as the general population through consumption of CPF-treated agricultural products. The major concern for human health is the propensity of organophosphate insecticides to elicit neurodevelopmental toxicity. Animal studies show that developmental exposures to CPF have adverse effects on brain development and produce neurobehavioral abnormalities at exposures well below the threshold for systemic toxicity caused by cholinesterase inhibition, the biochemical measure most commonly used to assess exposure and safety (4). A major component of the neurodevelopmental toxicity of CPF is likely to be unrelated to its ability to inhibit cholinesterase, instead involving disruption of the cellular machinery controlling neuronal replication and differentiation, apoptosis, axon formation, synaptogenesis, and neural circuit formation (4, 5).

The effects of low-level organophosphate exposures on brain development in animal models triggered a series of studies in children to examine whether purportedly “safe” exposure levels had consequences similar to those in animals. Organophosphate insecticides in humans are detectable in amniotic fluid (6) and readily cross the placenta (7). Prenatal exposures to CPF and other organophosphate pesticides have been linked to smaller head size (8), lower birth weight (9), deviant neonatal reflexes (10, 11), attention problems (12, 13), and neurodevelopmental anomalies resembling pervasive development disorder (13, 14) in preschool-aged children. Three recent studies undertaken by different research groups all concluded that prenatal organophosphate exposure is associated with a significant reduction in childhood IQ (15–17). These studies, using different biomarkers of exposure (urinary metabolites, umbilical cord blood), show that prenatal organophosphate exposure produces a consistent pattern of early cognitive and behavioral deficits across both agricultural and urban populations.

Despite this converging evidence for the neurodevelopmental toxicity of organophosphate insecticides, their specific effects on brain structure that disrupt behavior and cognition in humans are unknown. The few animal studies that have examined morphological consequences of early life organophosphate exposure indicate subtle changes in cortical thickness and neuronal and glial cell proportions in the septal nucleus, striatum, somatosensory cortex, and hippocampus—brain regions that subserve mood, behavior, and cognition (18, 19). These studies have shown CPF effects on glial cell numbers, changes in number and types of neurons in all four regions, as well as delayed alterations in hippocampal cell number accompanied by perikaryal swelling and excessive astrocytic processes, likely representing early stages of astroglialosis, the glial scarring that occurs in response to cellular injury—all at a dose too low for signs of systemic toxicity (19). Consistent with these glial-based effects of early postnatal exposure, prenatal exposure to CPF has been shown to increase the levels of glial cell markers in rodents (20). Notably, early life CPF exposure interferes with normal sexual differentiation of the brain, reducing or reversing the normal sex differences in cognitive and emotion-related behaviors (21, 22) and correlating with sex-specific effects on the neurotransmitter systems that support those behaviors.
In the current study, we compared morphological measures of the cerebral surface, as well as measures of the thickness of the cortical mantle, across two groups of children exposed prenatally to high or low levels of CPF. We assessed whether those regional abnormalities related to CPF exposure were associated with reductions in measures of intellectual functioning. We hypothesized that children exposed prenatally to high levels of CPF compared with those with low levels of exposure would have altered morphological characteristics in brain regions (frontal, parietal, and lateral temporal) that subserve higher-cognitive functions. We also assessed in preliminary analyses whether prenatal CPF exposure disrupted normal sex differences in brain structure in our sample of school-aged children.

Results

Sample Description. The sample was selected from a larger cohort of 369 children with complete prenatal CPF, polycyclic aromatic hydrocarbons (PAH), and environmental tobacco smoke (ETS) exposure data, and 7-y cognitive testing (WISC-IV). Of these children, 70 had CPF exposure levels in the upper tertile of the distribution (>4.39 pg/g), 28 of whom also met the criteria of (i) no/very low prenatal ETS exposure, classified by maternal report and validated by cotinine levels <15 ng/mL in umbilical cord blood (23); and (ii) low prenatal PAH exposure levels, measured by third-trimester personal monitoring, and defined as below the median (2.26 ng/m²). Of these 28 eligible high-exposure children, 20 completed the MRI with usable imaging data. For the low-exposure group, 99 had CPF below the upper tertile, PAH below the median, and no/very low ETS exposure. Of these, 38 were randomly selected and 20 completed the MRI with usable imaging data. Written informed consent was obtained from all parents and signed assent from all children. The Institutional Review Boards for the New York State Psychiatric Institute and Columbia University approved the study.

Table 1 compares high- and low-exposure groups, and the full sample with the larger cohort (all children with exposure data and 7-y testing) on selected characteristics. There were no significant differences between the study sample (n = 40) and the larger cohort (n = 329, excluding the study sample), or any significant differences between high- and low-exposure groups on any characteristic. CPF concentration was not significantly associated with lead in the study sample (Spearman’s rho = 0.15, P = 0.46) or the larger cohort (Spearman’s rho = 0.07; P = 0.30). The sample was largely full-term because of third-trimester air monitoring.

Effects on Morphology of the Cerebral Surface. Main effects of exposure. Overall brain size did not differ significantly across exposure groups, either unadjusted (high vs. low exposure 1,257.2 ± 103.5 vs. 1,247.9 ± 77.6 cm²; t = 0.64, df = 37, P = 0.52) or adjusted for age, sex, and height (high vs. low exposure 1,265.1 ± 17.7 vs. 1,242.1 ± 16.8, F = 0.84, df = 1, 35, P = 0.37). Nevertheless, the high-CPF group had significant enlargement bilaterally of the superior temporal, posterior middle temporal, and inferior postcentral gyri bilaterally; the supramarginal gyrus and inferior parietal lobule of the right hemisphere; and superior frontal gyrus, gyrus rectus, cuneus, and precuneus along the mesial wall of the right hemisphere, with or without correction for overall brain size (Fig. 1 and Figs. S1 and S2). Additional analyses of white matter surface demonstrated that this enlargement at the cerebral surface derived primarily from enlarged underlying white matter (Fig. S3). In addition, we detected inward deformations in the dorsal and mesial surfaces of the left superior frontal gyrus (Fig. 1). Within the high-CPF group, we found a significant positive dose–response relationship between exposure level and enlargement of the mesial surface of the superior frontal gyrus bilaterally.

**Table 1. Socio demographic characteristics of the study sample by prenatal CPF exposure group, compared with the larger cohort from which the sample was selected**

<table>
<thead>
<tr>
<th>Characteristic*</th>
<th>High exposure</th>
<th>Low exposure</th>
<th>P†</th>
<th>Full sample</th>
<th>Larger cohort</th>
<th>P‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (%) Mean ± SD</td>
<td>N (%) Mean ± SD</td>
<td>N (%) Mean ± SD</td>
<td>N (%) Mean ± SD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Income</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;$20,000</td>
<td>11 (55.0)</td>
<td>12 (60.0)</td>
<td>N.S.</td>
<td>23 (57.5)</td>
<td>170 (51.7)</td>
<td>N.S.</td>
</tr>
<tr>
<td>≥$20,000</td>
<td>9 (45.0)</td>
<td>8 (40.0)</td>
<td>N.S.</td>
<td>17 (42.5)</td>
<td>159 (48.3)</td>
<td>N.S.</td>
</tr>
<tr>
<td><strong>Maternal education, y</strong></td>
<td>12.9 ± 2.5</td>
<td>13.4 ± 2.9</td>
<td>N.S.</td>
<td>12.4 ± 1.9</td>
<td>12.3 ± 2.6</td>
<td>N.S.</td>
</tr>
<tr>
<td><strong>Maternal IQ</strong></td>
<td>87.5 ± 12.6</td>
<td>89.8 ± 10.0</td>
<td>N.S.</td>
<td>85.2 ± 14.7</td>
<td>85.0 ± 12.9</td>
<td>N.S.</td>
</tr>
<tr>
<td><strong>Maternal race/ethnicity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominican</td>
<td>11 (27.5)</td>
<td>14 (35.0)</td>
<td>N.S.</td>
<td>25 (62.5)</td>
<td>202 (61.4)</td>
<td>N.S.</td>
</tr>
<tr>
<td>African American</td>
<td>9 (22.5)</td>
<td>6 (15.0)</td>
<td>N.S.</td>
<td>15 (37.5)</td>
<td>127 (38.6)</td>
<td>N.S.</td>
</tr>
<tr>
<td><strong>Child sex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6 (30.0)</td>
<td>9 (45.0)</td>
<td>N.S.</td>
<td>15 (37.5)</td>
<td>155 (47.1)</td>
<td>N.S.</td>
</tr>
<tr>
<td>Female</td>
<td>14 (70.0)</td>
<td>11 (55.0)</td>
<td>N.S.</td>
<td>25 (62.5)</td>
<td>174 (52.9)</td>
<td>N.S.</td>
</tr>
<tr>
<td><strong>Gestational age, wk</strong></td>
<td>39.3 ± 1.4</td>
<td>39.3 ± 2.5</td>
<td>N.S.</td>
<td>39.3 ± 2.0</td>
<td>39.3 ± 1.4</td>
<td>N.S.</td>
</tr>
<tr>
<td><strong>Birth weight, g</strong></td>
<td>3,199.5 ± 625.0</td>
<td>3,362.9 ± 509.6</td>
<td>N.S.</td>
<td>3,281.2 ± 568.9</td>
<td>3,400 ± 479.9</td>
<td>N.S.</td>
</tr>
<tr>
<td><strong>Child age at MRI, y</strong></td>
<td>8.5 ± 1.2</td>
<td>7.8 ± 0.9</td>
<td>N.S.</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Prenatal lead, μg/dL</strong></td>
<td>1.4 ± 1.2</td>
<td>0.8 ± 0.5</td>
<td>N.S.</td>
<td>1.1 ± 0.9</td>
<td>1.2 ± 0.9</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

N.S., not significant.

*Comparison of high CPF exposed (≥4.39 pg/g) with low CPF exposed (<4.39 pg/g); P < 0.05.

†Comparison of study sample with cohort of all eligible children having prenatal exposure data for CPF, PAH, ETS, and 7-y cognitive assessments, minus study sample; P < 0.05.

‡Years of education completed at child age 7.

Based on Brown et al. (53).
not the high-CPF group (Fig. 2). We also found a significant interaction in the right fusiform gyrus, where IQ correlated inversely with surface measures in the low-CPF group but positively in the high group (Fig. 2).

**Main Effects of Exposure on Surface Measures**

**Correlation with CPF Levels**

*High Exposure Group*

**Disruptive Effects of CPF Exposure on Cognition**

*Interaction of CPF Exposure with FSIQ*

**Sex × exposure interaction.** We found significant sex × exposure interactions within the right inferior parietal lobule, right superior marginal gyrus, and right mesial superior frontal gyrus (Fig. 3), reflecting disruption of normal, female-larger-than-male sex differences.
differences in the right parietal lobe and a reversal of normal, male-larger-than-female differences in the right mesial superior frontal gyrus (Fig. 3). Within the right dorsal parietal lobe of the high-CPF group, we also found a significant sex × exposure interaction, in which CPF levels correlated positively with surface measures in girls but inversely in boys (Fig. 3).

**Cortical thickness.** We detected scattered reductions in cortical thickness in dorsal parietal and frontal cortices in the high- vs. low-exposure group (Fig. S4). Within the high group, we saw an inverse dose–response relationship of cortical thickness with CPF, in which thinner cortices were associated bilaterally with higher exposures in the frontal pole, dorsal parietal, and orbitofrontal cortices (Fig. S5).

**Discussion**

Our findings indicate that prenatal CPF exposure, at levels observed with routine (nonoccupational) use and below the threshold for any signs of acute exposure, has a measurable effect on brain structure in a sample of 40 children 5.9–11.2 y of age. We found significant abnormalities in morphological measures of the cerebral surface associated with higher prenatal CPF exposure, after adjusting for possible confounders. Regional enlargements of the cerebral surface predominated and were located in the superior temporal, posterior middle temporal, and inferior postcentral gyri bilaterally, and in the superior frontal gyrus, gyrus rectus, cuneus, and precuneus along the mesial wall of the right hemisphere (Fig. 1). The enlargements derived primarily from enlargements of underlying white matter. The cognitive and behavioral processes that these cortical regions subserve include attention and receptive language in the posterior temporal regions (24); social cognition in the mesial superior frontal gyrus, cuneus, and precuneus (25), and superior temporal gyrus (26); and reward, emotion, and inhibitory control in the gyrus rectus and related orbitofrontal regions (27). Inward deformations were detected in the dorsal and mesial surfaces of the left superior frontal gyrus, a region supporting executive functioning. A positive dose–response relationship between CPF concentrations and surface measures was detected in the mesial portion of the superior frontal gyrus bilaterally.

These findings are consistent with the effects of early developmental exposure to CPF in animal models. CPF exposure is cytotoxic to both glia and neurons (18–20, 28), and the signs of neural damage include excessive astrocytic processes and perikaryal swelling, progressing to more extensive astrogliosis and glial scarring in response to the earlier cellular injury (19, 29). The white matter origins of the abnormalities in local cortical volumes seen here may thus represent similar glial scarring as an effect of prenatal exposure in humans. Likewise, the direct neurotoxic effects of early CPF exposure in animals include altered neuronal cell replication, apoptosis, and cortical lamination (18, 19, 30), providing a highly plausible cellular basis for the dose-related cortical thinning that we detected bilaterally in dorsal parietal, frontal, and orbitofrontal cortices of the high-exposure group. The exposures at which these mechanisms become manifest in animal models are comparable to exposure levels in our own population.

In addition, we found evidence for a detrimental effect of exposure on general cognition that was likely mediated by the effects of CPF on surface measures of the superior temporal and inferior frontal cortices. We found a significant IQ × exposure interaction effect on surface measures in the superior temporal gyrus and inferior portions of the precentral, postcentral, and inferior frontal gyri (Fig. 2). This interaction derived from significant positive correlations of surface measures with IQ in the low-CPF group that were disrupted in the high group. Scatterplots of this interaction suggest that these regions were significantly enlarged in the high-CPF group (Fig. 2), particularly for those with lower IQ
scores, consistent with findings for the main effects of CPF on surface measures (Fig. 1) and with prior reports that prenatal CPF exposure is associated with child cognitive impairment (15–17). The high-CPF group also displayed disruption of normal sexual dimorphisms in brain structure—features that were preserved in the low-CPF group, including enlargement of the right inferior parietal lobule, supramarginal gyrus, and bilateral superior and middle temporal gyri in females (31, 32), and enlargement of the left mesial surface of the superior frontal gyrus in males (33). These expected sex differences were reversed in the high-CPF group. Our morphological findings are consistent with those from animal models showing that early CPF exposure obtunds or reverses normal sex differences in learning, memory, and emotional behaviors (21, 22, 34). In the cohort from which this sample was drawn, prenatal CPF exposure was shown to have an inverse dose–response effect on cognition (working memory scores and, to a lesser extent, full-scale IQ) among 264 7- to 10-year-old children (17). Because the dorsolateral prefrontal cortex subserves cognitive processes, including working memory, we suspect that the impaired cognitive scores associated with prenatal CPF exposure in the larger cohort likely derived from either reduced surface morpho-

methods

Participants and Procedures. Participants were recruited from a prospective cohort study conducted by the Columbia Center for Children’s Environmental Health (38) to evaluate the effects of prenatal exposures to air pollutants on neurodevelopment in children from low-income urban communities. Non-smoking African American or Dominican women, aged 18–35, and registered at New York Presbyterian Medical Center or Harlem Hospital prenatal clinics by the 20th week of pregnancy, were approached for consent. Eligible women were low risk (free of diabetes, hypertension, known HIV, and documented drug abuse), and resident in the area for at least 1 y.

Exposure Assessment. Umbilical cord blood (30–60 mL) was collected at delivery and portions sent to the Centers for Disease Control for analysis of plasma levels of CPF, cotinine, and metals, as described elsewhere (39). Methods for the laboratory assay for CPF (quality control, limits of detection) are previously published (36). The high-CPF group included upper tertile exposures (≥4.39 pg/g), whereas exposures below this level (300 pg/g) were classified by maternal report validated by cord-blood cotinine levels (≤15 ng/mL) (23). We measured PAH exposure by third-trimester maternal monitoring, excluding poor-quality samples; low exposure was defined as below the median (2.26 ng/mL) (40). Cord-blood lead concentrations (μg/dL) were available in subsets of the sample (n = 28) and the larger cohort (n = 202).

MRI Acquisition. High-resolution, T1-weighted anatomical images were acquired using a GE Signa 3 Tesla whole-body scanner with an eight-channel head receiver coil and a fast spoiled-gradient recall sequence (SI Methods).

Image Processing. All processing was conducted on Sun Ultra 10 workstations using ANALYZE 8.0 Biomedical Imaging Resource (Mayo Foundation, Rochester, MN) and in-house software, blind to participant characteristics and hemisphere (images were randomly flipped in the transverse plane before preprocessing). Morphometric analyses were performed with the MRI dataset resliced to correct for residual head rotation, tilt, or flexion/extension.

Preprocessing. Large-scale variations in image intensity were corrected by an algorithm developed at the Montreal Neurological Institute (41). Extracerebral tissues were removed by an automated tool (42) that uses an anisotropic filter to smooth image intensity, and a Marr–Hildreth edge detector (43) to identify 3D edges, before selecting as the brain the largest connected component with a closed boundary. Connecting dura was removed similarly on each hemisphere, and checked and checked in orthogonal views. The brainstem was transacted at the pontomedullary junction.

Cortical gray matter segmentation. Gray-scale values of “pure” representations of cortical gray and white matter were sampled bilaterally at four standard brain locations (frontal, temporal, occipital, and parietal) using 8 × 8 = 64 pixel array, large enough for statistical stability but small enough to avoid partial volume effects, including other tissue types. SI Methods detail the computation of threshold values for classification of cortical gray and white matter (44).

Morphological maps of the cerebral surface. Detailed procedures used to analyze surface morphologies, and their related validation studies, appear elsewhere (45, 46) and in SI Methods.

Cortical thickness. From the coregistered brain of each child we subtracted its cortical mantle, and used a 3D morphological operator to distance transform this brain without the cortex from the coregistered brain of the same child that contained the cortex (47, 48). Operation details appear in SI Methods.

Choice of template brain. We first identified a brain, representative of the sample by child age, weight, and height. Brains for the remaining participants were coregistered to this preliminary template. We determined point correspondence on cortical surfaces, and computed distances of corresponding points on the cerebral surface of other participants from the template surface. The brain for which all points across the surface are closest to the average of computed distances (by least squares) was selected as the final template. Brains underwent a second coregistration to this representative template. We used a single representative template rather than an averaged brain because it has well-defined tissue interfaces (e.g., CSF/gray matter or gray/white matter interfaces). Averaging images for a template blurs these
boundaries and increases registration errors important for distinguishing subtle effects across populations.

Sulcal overlay. To aid visual identification of findings on the brain surface, we overlaid our template maps the sulcal boundaries and 3D labels of cortical gyri identified on the International Consortium for Brain Mapping high-resolution, single-participant template (49), using a high-dimensional, nonrigid warping algorithm.

**Cognitive Assessment.** To assess IQ at 7 y (±1 mo), we used the Wechsler Scales of Intelligence for Children (WISC-IV) (50), which is sensitive to low-dose neurotoxic exposures. Scores on the WISC-IV are derived from five subtests of lead toxicity in 6- to 7.5-y-old children (51). The instrument measures overall IQ and four areas of cognitive functioning (verbal comprehension, perceptual reasoning, processing speed, and working memory) that are associated with, but distinct from, overall IQ, and is sensitive to cognitive deficits related to learning and working memory that have been linked to CPF exposure in rodent studies (22).

**Statistical Analysis.** Each imaging measure (Euclidean distance or cortical thickness) was subjected to statistical modeling at each voxel of the cortical sulcal overlay. We used general linear modeling to compare measures across CPF groups, covarying for age and sex. P values were corrected for multiple comparisons using a false discovery rate < 0.05 (52), then color-coded and plotted for each voxel at the cerebral surface. We assessed correlations of surface distances and cortical thickness with measures of CPF exposure and full-scale IQ at each voxel across the brain surface.

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