A GLOBAL NEURODEVELOPMENTAL PANDEMIC?
PRENATAL CHEMICAL EXPOSURES AND THE DEVELOPING BRAIN

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A global pandemic of neurodevelopmental toxicity

• “Subclinical decrements in brain function are even more common than these neurodevelopmental disorders (Autism & ADHD)”

• “Strong evidence exists that industrial chemicals widely disseminated in the environment are important contributors to what we have called the global, silent pandemic of neurodevelopmental toxicity”

Source: Grandjean and Landrigan (Lancet Neurology, 2014)
Overview

• Introduction
  • Neurodevelopmental Disorders and Trends
  • Vulnerability of Developing and Young Brain
  • Epigenetic role in acquiring a disorder
  • Toxic Environmental Agents
  • Literature Survey Selection Criteria

• Findings from Literature Survey

• Concluding Remarks

• Discussion
Neurodevelopmental Disorders

Attention Deficit Hyperactivity Disorder (ADHD)
- 3 types: hyperactive, inattentive, combined (most common)
- difficulty sustaining attention, impulsivity, hyperactivity, impaired executive function (i.e. planning, working memory, ability to “shift gears”)

Autistic Spectrum Disorder (ASD)
- Social reciprocity and relationships, perceiving others’ emotions, verbal and nonverbal communication and abstract language
- Inflexible behavior (upset by change)
- Issues in other areas, e.g., obsessive compulsivity, anxiety, sensory processing, digestive and immune system, sleep

Subclinical decrements of brain function
- Behaviors resemble ASD or ADHD, but do not meet criteria for a diagnosis
- may include: Lower memory, lower IQ (even a few points), lower motor or visual perceptual skill ability, sensory processing issues, mood dysregulation, learning disability
Prevalence of Neurodevelopmental Disorders over Time

• **ASD**: Current 1 in 68 (2010) vs. 1 in 152 (2002)

• **ADHD diagnoses**: Current 11.0% in 2011 (9.5% in 2007, 7.8% in 2003)

• **Learning disability**: In 2010, nearly 10% of children age 12-17 yrs were affected

Source: CDC
The Significance of Small Effects: IQ Points

Example: population of 260 million
The Significance of Small Effects: 5 point decrease in Mean IQ

“As a community, we have not effectively communicated this point to risk assessors and other decision makers…a risk assessment that focuses solely on individual risk and fails to consider the problem in a public health context is potentially misleading”- Bellinger, PhD

Example: population of 260 million
Toxic Environmental Agents

• Over 80,000 synthetic chemicals used in the US
  • Most untested with little regulatory oversight in assuring safety
  • Roughly 1,000 of these chemicals are “High Production Volume“ (HPV)

• Over 200 chemicals reported to be neurotoxic to human adults (NTP)
  • About half of these are HPV
  • Additional 1,000 chemicals have been reported to be neurotoxic to animals in lab studies
Vulnerability of the Developing and Young Brain

• “The Central Nervous System (brain and spinal cord) is the most vulnerable of all the body systems to developmental injury.” (Rodier, 2004)

• Environmental chemicals can cause permanent brain injury at low levels of exposure that would have little or no adverse effect in an adult. The placenta does not block passage of these toxicants. (Grandjean and Landrigan, 2014)
CNS and Brain Formation

- **Neural cell proliferation** and complex **differentiation**
- Migration of neural cells into different regions of the brain
- Formation of connector cables called **axons** and **dendrites**
- Formation of **synapses** (electrochemical messages between cells)
- Normal cell death or **pruning** of excess neurons & synapses
- **Myelination**, fatty insulator sheaths formed on neurons & synapses
What causes Neurodevelopmental Disorders?

Multiple factors interact in complex ways during fetal development.

- **Internal factors**
  - Heredity:
    - Genetic traits & susceptibility

- **External factors**
  - Exposure to toxins (triggering epigenetic mechanisms)
  - Nutrition
  - Social environment
Epigenetic Mechanisms of Toxic Chemicals

Source: Singh and Li (2012)
“Patient exposure to toxic environmental chemicals and other stressors is ubiquitous, and preconception and prenatal exposure can have a profound and lasting effect.”

“…calling for timely action to identify and reduce exposure while addressing the consequences of such exposure.”
Economic Implications

- **Special education** 13.3% (1 in 8) of Oregon children received special education services in 2013-14 (ODOE)
  - costs an additional $9,370/yr per student (NEA)
  - ~ $800 million/yr on Special Ed and early intervention (ODOE, 2005)

- **Medical costs** are typically higher for children with ASD or ADHD

- **Emotional costs** to impaired individuals and their families are incalculable
Neurotoxic Environmental Agents Covered

- Lead (Pb)
- Methylmercury (CH₃Hg)
- Polychlorinated biphenyls (PCBs)
- Brominated flame retardants (PBDEs)
- Pesticides (Organophosphate Insecticides)
- Other Endocrine Disruptors (phthalates, BPA)
- Perfluorinated chemicals (e.g., in Teflon, Scotchguard)

Air Toxics, including:
- Motor vehicle exhaust (inc. Diesel Particulate Matter, DPM)
- Polycyclic aromatic hydrocarbons (PAHs)
Criteria for Literature Presented

- Prenatal Human Exposures
- Longitudinal Study with Prospective Cohorts
  - Exception: Air and Soil pollution studies
- Biomonitoring Conducted
- Validated neurodevelopmental Tests/Instruments, Imaging, or spatiotemporal modeling techniques
- Statistically significant findings (p<0.05)
- Biological plausability of exposure & neurodevelopmental effect
- Peer-reviewed studies
- Preferably corroborated
Lead (Pb)
Methyl Mercury (CH$_3$Hg)
and
PCB Studies
Aviation fuel (avgas) used by piston-engine aircraft is leaded
Effects of Lead on Cognitive and Behavioral Traits (well-established, from previous studies)

**ADHD**
- ↑ hyperactivity
- ↑ impulsivity
- ↑ distractibility
- ↑ diff. w instructions
- ↑ conduct problems
- ↓ executive function
- ↓ attention/vigilance
- ↓ social skills

**LD**
- ↓ reading, math
- ↓ spelling
- ↓ pattern recognition
- ↓ word recognition

**OTHER**
- ↓ fine motor
- ↓ visual motor
- ↑ aggressive
- ↑ antisocial
- ↑ off-task
# Neurodevelopmental Effects of Prenatal Lead (Pb) Exposure

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>SUBJECTS</th>
<th>EXPOSURE PATHWAY</th>
<th>OUTCOMES AT FOLLOW-UP (F/U)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td><strong>N</strong></td>
<td><strong>F/U</strong></td>
<td><strong>Ingestion of game animals (hunted w/ lead shot)</strong></td>
</tr>
<tr>
<td>Boucher et al. (2014, EHP)</td>
<td>Canadian Arctic</td>
<td>94</td>
<td>6 mo &amp; 11 mo</td>
</tr>
<tr>
<td>Boucher et al. (2012, EHP)</td>
<td>Inuit population</td>
<td>279</td>
<td>11.3 yrs old (mean)</td>
</tr>
<tr>
<td>Jedrychowski et al. (2009, Early Hum Dev)</td>
<td>Krakow, Poland</td>
<td>457</td>
<td>3 yrs old</td>
</tr>
<tr>
<td>McDermott et al. (2014, Dev Med &amp; Child Neuro) (Retrospective study)</td>
<td>South Carolina</td>
<td>10,051 pregnant Medicaid recips</td>
<td>Until 9 yrs old</td>
</tr>
</tbody>
</table>

F/U:= follow up

* this one study also looked at post-natal exposure for comparison

** low cord blood lead levels: med value = 1.21 µg/dL; only 1% had levels above 3 µg/dL
Methylmercury

The coal-fired Gavin Power Plant in Cheshire, Ohio
Faroes Islands in N. Atlantic, midway between Iceland & Denmark

Seychelles Islands in Indian Ocean, off east-central coast of Africa
The Mercury Cycle

The mercury cycle

(WASTEWATER TREATMENT) (URBAN) (INDUSTRIAL) (MINING) (AGRICULTURAL) (PRECIPITATION) (RUNOFF)

ALGAE

Hg → CH₃Hg

INVERTEBRATES

(Illustration by Connie J. Dean, U.S. Geological Survey)
# Neurodevelopmental Effects of Prenatal Methylmercury Exposure

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>SUBJECTS</th>
<th>EXPOSURE PATHWAY</th>
<th>OUTCOMES AT FOLLOW-UP (F/U)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boucher et al. (2014)</strong></td>
<td><strong>Canadian Arctic</strong></td>
<td><strong>Seafood ingestion</strong></td>
<td><strong>Traits associated with ADHD</strong></td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>N</td>
<td>F/U</td>
</tr>
<tr>
<td></td>
<td>Canadian Arctic</td>
<td>94</td>
<td>6 mo 11 mo</td>
</tr>
<tr>
<td><strong>Boucher et al. (2012)</strong></td>
<td><strong>Inuit population</strong></td>
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</tr>
<tr>
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<td>Location</td>
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<td>F/U</td>
</tr>
<tr>
<td></td>
<td>Inuit population</td>
<td>279</td>
<td>11.3 yrs old (mean)</td>
</tr>
<tr>
<td><strong>Ng et al. (2013)</strong></td>
<td><strong>Taiwan</strong></td>
<td><strong>Seafood ingestion</strong></td>
<td><strong>Decline in all areas of development in genetically predisposed individuals</strong></td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>N</td>
<td>F/U</td>
</tr>
<tr>
<td></td>
<td>Taiwan</td>
<td>168</td>
<td>2 yrs old</td>
</tr>
<tr>
<td><strong>Orenstein et al. (2014)</strong></td>
<td><strong>New Bedford Harbor area, MA</strong></td>
<td><strong>Contaminated harbor (Superfund site)</strong></td>
<td><strong>Decreased visual and verbal memory and impaired learning associated with Hg in maternal hair</strong></td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>N</td>
<td>F/U</td>
</tr>
<tr>
<td></td>
<td>New Bedford Harbor area, MA</td>
<td>393</td>
<td>8 yrs old</td>
</tr>
<tr>
<td><strong>McDermott et al. (2014)</strong></td>
<td><strong>South Carolina</strong></td>
<td><strong>Contaminated soil during pregnancy</strong></td>
<td><strong>Increased incidence of mild intellectual disability (p = .007)</strong>*</td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>N</td>
<td>F/U</td>
</tr>
<tr>
<td></td>
<td>South Carolina</td>
<td>10,051</td>
<td>≤ 9 yrs old</td>
</tr>
<tr>
<td></td>
<td>pregnant Medicaid recip</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Blanchard et al. (2011)</strong></td>
<td><strong>Bexar Co. TX &amp; Santa Clara Co. CA</strong></td>
<td><strong>Inhalation of ambient air near coal plants</strong></td>
<td><strong>Higher Autism rates among children living in areas having higher concentration of ambient air mercury per square mile (levels &gt; 3 SD above mean level of Hg distribution)</strong> **</td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>N</td>
<td>F/U</td>
</tr>
<tr>
<td></td>
<td>Bexar Co. TX &amp; Santa Clara Co. CA</td>
<td>3-5 yrs old</td>
<td></td>
</tr>
<tr>
<td><strong>Windham et al. (2006)</strong></td>
<td><strong>SF Bay area</strong></td>
<td><strong>Inhalation of ambient air in urban setting</strong></td>
<td><strong>Association between autism and estimated metal concentrations in air (p &lt; 0.05)</strong> **</td>
</tr>
<tr>
<td></td>
<td>Location</td>
<td>N</td>
<td>F/U</td>
</tr>
<tr>
<td></td>
<td>SF Bay area</td>
<td>284 children w/ASD; 657 controls</td>
<td>&lt;9 yrs old</td>
</tr>
</tbody>
</table>

* Retrospective; Spatial/Temporal Model  ** Spatiotemporal Modeling using US EPA ambient air monitoring data
Elevated PCB levels detected in resident fish near the Bonneville Dam
Portland Harbor Superfund Site -- high PCB levels in resident fish (on Willamette River from Broadway Bridge to Columbia R. slough)

Image courtesy of Mother Nature Network
# Neurodevelopmental Effects of Prenatal Exposure to PCBs

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>SUBJECTS</th>
<th>EXPOSURE PATHWAY</th>
<th>OUTCOMES AT FOLLOW-UP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boucher et al. (2009)</strong>&lt;br&gt;(review of 9 studies)</td>
<td>US, Canada, and Europe&lt;br&gt;Varies, from 135 to 900&lt;br&gt;Varies by study</td>
<td>Ingestion of seafood and unknown sources</td>
<td><strong>Traits assoc. with ADHD, and decreased cognition</strong>—visual recognition memory and verbal ability</td>
</tr>
<tr>
<td><strong>Sagiv et al. (2012)</strong></td>
<td>New Bedford Harbor area, MA&lt;br&gt;578 + 584&lt;br&gt;8 yrs old</td>
<td>Living on contaminated harbor (Superfund site)</td>
<td><strong>Traits assoc. with ADHD, but only in boys</strong></td>
</tr>
<tr>
<td><strong>Boucher et al. (2014)</strong></td>
<td>Canadian Arctic (Inuit population)&lt;br&gt;94&lt;br&gt;6 mo. &amp; 11 mo.</td>
<td>Seafood consumption</td>
<td><strong>Decreased cognition</strong> (visual recognition memory) in infants</td>
</tr>
<tr>
<td><strong>Boucher et al. (2012)</strong></td>
<td>Canadian Arctic (Inuit population)&lt;br&gt;279&lt;br&gt;mean age 11.3 yrs</td>
<td>Seafood consumption</td>
<td><strong>No associations</strong> with ADHD traits</td>
</tr>
<tr>
<td><strong>Orenstein et al. (2014)</strong></td>
<td>New Bedford Harbor area, MA&lt;br&gt;393&lt;br&gt;8 yrs old</td>
<td>Living on contaminated harbor (Superfund site)</td>
<td><strong>No associations</strong> with decreased cognitive function (Authors state exposure levels quite low)</td>
</tr>
</tbody>
</table>
Polybrominated Chemicals (PBDEs)
Phthalates
Bisphenol-A (BPA)
Pesticides
Fluorochemicals (PFOA/S)
Polybrominated Diphenyl Ether (PBDE) Exposure

- California’s Technical Bulletin 117 (TB117)*
  - Furniture foam withstand open flame for 12 seconds
  - Penta-BDE used from 1975-2004 (98% of use in N America)
  - ≥3 pieces of stuffed furniture in the home associated with ~27% increase in women’s blood PBDE levels (Castorina et al., 2011)

- Baby Products: Car seats, changing table pads, sleep positioners, mattresses, nursing pillows, and other products (Stapleton et al., 2011)

*as of Jan 1, 2014, TB117-2013 is in effect and flame retardants are not needed, but can still be used
Biological Pathways of Neurotoxicity associated with PBDE Exposure

- Structurally similar to PCBs & PBBs, Dioxins and Furans

<table>
<thead>
<tr>
<th>PCBs (X = Cl) and PBBs (X = Br)</th>
<th>PBDEs</th>
<th>Dioxins (X = Cl or Br)</th>
<th>Furans (X = Cl or Br)</th>
</tr>
</thead>
</table>

- Animal studies
  - certain PBDEs can mimic thyroid hormones
  - PBDEs can disrupt the equilibrium of the thyroid hormone system → impair neurological functioning (Darnerud et al. 2001)

- Human Studies: 10-fold increase in PBDE chemicals in pregnant women → decrease TSH (~11-19 %; Chevrier et al., 2010)

Source: GreenSciencePolicyInstitute.org
# Neurotoxicity of Prenatal PBDE Exposure

<table>
<thead>
<tr>
<th>Source &amp; Congener</th>
<th>Standard Assessment</th>
<th>Assessment Age (N)</th>
<th>Outcome (p&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbstman et al. (2010)</td>
<td>BSID-II</td>
<td>1-3 yrs (~110/BDE)</td>
<td>2 yrs: ↓ MDI</td>
</tr>
<tr>
<td>BDE-47,-99,-100,-153</td>
<td>WPPSI-R</td>
<td>4 &amp; 6 yrs (~100 /yr)</td>
<td>4 yrs: ↓ Full –scale IQ, Verbal IQ &amp; Performance IQ 6 yrs: ↓ Full IQ, ↓ Performance IQ *</td>
</tr>
<tr>
<td>Eskanazi et al. (2013)</td>
<td>CBCL, K-CPT, &amp; WPPSI-III</td>
<td>5 yrs (~240)</td>
<td>↑ ADHD traits (on K-CPT)</td>
</tr>
<tr>
<td>ΣPBDE (47,99, 100, &amp; 153)</td>
<td>CADS, BASC-II, &amp; WISC-IV</td>
<td>7 yrs (~260 )</td>
<td>↑ ADHD traits (by CADS) ↓ Verbal Comprehension IQ</td>
</tr>
<tr>
<td>Chen et al. (2014)</td>
<td>BSID-II</td>
<td>1-3 yrs (&gt;220/yr)</td>
<td>No significant associations</td>
</tr>
<tr>
<td>BDE-47 &amp; ΣPBDE</td>
<td>BASC-2</td>
<td>2-5 yrs old (&gt;165/yr)</td>
<td>2&amp;3 years: Externalizing Behavior 3&amp;5 years: hyperactivity 3 years: Behavioral Symptoms</td>
</tr>
<tr>
<td></td>
<td>WPPSI-III</td>
<td>5 yrs old (190)</td>
<td>↓ Full Scale IQ</td>
</tr>
</tbody>
</table>

*when language & interview/assessment location included in multivariate linear regression model

**BASC-2:** Behavior Assessment System for Children, 2nd Edition; **BSID-II:** Bayley Scales of Infant Development-II; **CADS:** Conners' ADHD/DSM-IV Scales; **CBCL:** Child Behavior Checklist; **K-CPT:** Conner’s Kiddie Continuous Performance Test; **WISC:** Wechsler Preschool and Primary Scale of Intelligence; **WPPSI:** Wechsler Preschool and Primary Scale of Intelligence (R= Revised; III= 3rd Ed.)

**Figure** adapted from Castorina et al. (2011)
Phthalate Exposure

Ingestion
• Direct: Infant formula and cow’s milk, groundwater & drinking water (e.g., DEHP), medications & nutritional supplements (DBP & DEP)
• Indirect: Toys * & Plastic Containers

Dermal Absorption
• Clothing (e.g., waterproof clothing or faux leather gloves w/ DEHP)
• Cosmetics & personal care products (e.g., lotions)
• Denture material (soft lining plasticizers)

Inhalation
• Personal care products (e.g., fragrance)
• Indoor air and house dust
• Baked modeling clay

Intraveneous
• medical devices (e.g., made with PVC softened with DEHP)

*As of 2008- DEHP, DBP, BBP banned in US; DINP, DIDP, DnOP provisionally banned (Section 108 of the Consumer Product Safety Improvement Act of 2008 & 2011 Amendments)
Biological Pathways of Neurotoxicity associated with Prenatal Phthalate Exposure

In laboratory rat studies, phthalate exposures modify:

- **Thyroid function or reduce Thyroid hormone levels**
  - Thyroid function plays key role in fetal & postnatal brain development

- **Testosterone production in male rats**
  - Testosterone plays key role in male brain development

- **Fatty acid transfer across placenta (possibly)**
  - Reduces the lipid content of fetal brain

- **Aromatase activity directly (possibly)**
  - Estradiol is synthesized from cholesterol, catalyzed by aromatase
  - In males & females, estradiol is necessary for brain development
# Neurotoxicity of Prenatal Phthalate Exposure

<table>
<thead>
<tr>
<th>Source &amp; No. metabolites</th>
<th>Standard Assessment</th>
<th>Assessment Age (N)</th>
<th>Outcome (p&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kim et al. (2011) 3 metabolites</td>
<td>BSID-III for MDI and PDI</td>
<td>6 Mths (460)</td>
<td><strong>Boys</strong>: prenatal phthalate $\rightarrow$ ↓ MDI and PDI</td>
</tr>
<tr>
<td>Tellez-Rojo et al. (2013) 9 metabolites</td>
<td>BSID-III for MDI and PDI</td>
<td>2-3 yrs (135)</td>
<td><strong>Girls</strong>: 5 phthalate metabolites $\rightarrow$ ↓ MDI</td>
</tr>
<tr>
<td>Whyatt et al. (2012) 4 metabolites</td>
<td>BSID-III for MDI and PDI</td>
<td>3 yrs (319)</td>
<td><strong>Boys &amp; Girls</strong>: MnBP &amp; MiBP $\rightarrow$ ↓ PDI</td>
</tr>
<tr>
<td>Kobrosly et al. (2014) 7 metabolites</td>
<td>CBCL</td>
<td>6-10 yrs (153)</td>
<td><strong>Boys</strong>: inattentiveness, rule-breaking, aggression, conduct problems, or oppositional behavior</td>
</tr>
<tr>
<td>Lien et al. (2014) 7 metabolites</td>
<td>CBCL</td>
<td>8-9 yrs (122)</td>
<td><strong>Boys &amp; girls</strong>: all DEHP metabolites $\rightarrow$ delinquent &amp; aggressive behavior, internalizing &amp;/or externalizing problems</td>
</tr>
<tr>
<td>Factor-Litvak et al. (2014) 6 metabolites</td>
<td>Weschler, 4th Ed (WISC IV)</td>
<td>7 yrs (328)</td>
<td><strong>Boys &amp; girls</strong>: MnBP &amp; MiBP $\rightarrow$ ↓ full scale IQ</td>
</tr>
</tbody>
</table>

BSID-III:= Bayley Scales of Infant Development-III; CBCL := Child Behavior Checklist; MDI:= Mental Development Index; PDI := Psychomotor Development Index; N:= number of mother-child pairs
Bisphenol A (BPA) Exposure

93% of all urine samples collected by the CDC in the 2003-04 National Health and Nutrition Examination Survey (NHANES III) found detectable levels of BPA in people ≥ 6 yrs old

Dietary Ingestion (primary route)
• Canned food & food storage containers, polycarbonate tableware, water bottles
  • temperature, rather than age, of container may influence leaching
• Breast milk

Dermal Absorption (limited extent)
• paper currencies and cash register receipts
Biological Pathways of Neurotoxicity associated with Prenatal BPA Exposure

In laboratory mice and rat studies, BPA:

- Acts as a thyroid hormone (TH) antagonist
  - TH deficits in-utero → “permanent alterations of cerebral cortical architecture consistent with those observed in brains of patients with autism” (Miodovnik et al., 2011)

- Binds to estrogen receptor → estrogen signaling pathways
  - Estrogen & Testosterone regulate & interact w/ neurotransmitters
  - Effects the structure and function of brain

- Alters brain structure → changes in behavior
  - ↑agression, memory impairment & hyperactivity in male mice
  - Disrupts cognition, social behaviors & brain function
# Neurotoxicity of Prenatal BPA (p-PBA) Exposure

<table>
<thead>
<tr>
<th>Source</th>
<th>Standard Assessment</th>
<th>Age (N)</th>
<th>Outcome (p&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braun et al. (2009)</td>
<td>BASC-2</td>
<td>2 yrs old (249)</td>
<td><strong>Girls</strong>: ↑ Aggression (16 wk p-BPA stronger association than 26-week)</td>
</tr>
<tr>
<td>Braun et al. (2011)</td>
<td>BASC-2, BRIEF-P</td>
<td>3 yrs old (244)</td>
<td><strong>Girls</strong>: mean p-BPA → hyperactivity, anxiety &amp; depression (BASC-2) &amp; emotional control &amp; inhibit scales of BRIEF-P</td>
</tr>
</tbody>
</table>
| Perera et al. (2012) | CBCL                | 3-5 yrs old (198) | **Boys**: ↑ emotionally reactive & aggression  
**Girls**: ↑ anxiety/depression & aggression |
| Harley et al. (2013) | BASC-2, CADS, CPT   | 7 yrs (~290)    | **Boys**: internalizing problems, anxiety, & depression (BASC-2)  
No significant association (Boys or Girls) w/CPT scores |

**N:** number of mother-child pairs

**BASC-2:** Behavior Assessment System for Children 2; **BRIEF-P:** Behavior Rating Inventory of Executive Function- Preschool; **CADS:** Conners’ ADHD/DSM-IV Scales; **CBCL:** Child Behavior Checklist; **CPT:** Connors’ Continuous Performance Test for ADHD;
Organophosphate (OP) Insecticides

- In 2007, roughly 33 million pounds of OP insecticide applied (~ 36% of all insecticides, Grube et al., 2011)
- In the US, over 30 OP pesticides registered in 2010

Graph adapted from EPA (2011)
Chlorpyrifos (CPF)

- Major OP insecticide
- In use since 1965 for agricultural & pest control
  - EPA phased out residential use in 2001, but still heavily used in agricultural

<table>
<thead>
<tr>
<th>2007 Rank</th>
<th>Active OP Ingredient</th>
<th>Millions of Pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chlorpyrifos</td>
<td>8-11</td>
</tr>
<tr>
<td>2</td>
<td>Malathion</td>
<td>5-9</td>
</tr>
<tr>
<td>3</td>
<td>Acephate</td>
<td>4-6</td>
</tr>
<tr>
<td>4</td>
<td>Naled</td>
<td>1-2</td>
</tr>
<tr>
<td>5</td>
<td>Dicrotophos</td>
<td>1-2</td>
</tr>
</tbody>
</table>

Source: EPA (2011)
OP Insecticide Exposure & Metabolism

• Diet is primary route of exposure

• Secondary routes: soil track-in & indirect ingestion (hand-to-mouth activity) by children

• Rapid metabolism of OPs
  • excreted in urine w/in 3-6 days of exposure

• Majority of OP pesticides breaks down into 6 DAP metabolites
  • cannot be traced back to original parent compound
OP Insecticide Toxicity

- Inhibits cholinesterase enzymes in nervous system
- Increases level of glial cell markers in rodents
- Vulnerable subpopulations
  - fetus and children with lower levels of detoxifying enzymes (paraoxonase or CPF-oxonase) (Holland et al., 2006)
  - certain genetic polymorphisms can affect CPF metabolism (Berkowitz et al., 2004)
## Neurotoxicity of Prenatal OP Exposure

<table>
<thead>
<tr>
<th>Source &amp; Pesticide</th>
<th>Assessment</th>
<th>Assessment Age (N)</th>
<th>Outcome (p&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eskanazi et al. (2007)</td>
<td>BSID-II</td>
<td>6&amp;12 mths (395)</td>
<td>No significant associations&lt;br&gt;↑OP → ↓MDI &amp; increased risk of PDD traits&lt;br&gt;<strong>CPF &amp; Malathion NOT associated w/any outcome</strong></td>
</tr>
<tr>
<td>CPF &amp; Malathion</td>
<td>BSID-II &amp; CBCL</td>
<td>24 mths (372)</td>
<td></td>
</tr>
<tr>
<td>Marks et al. (2010)</td>
<td>NEPSY-II &amp; CBCL</td>
<td>3.5 yrs (~320)</td>
<td>↑OP → ↑ADHD traits in boys (CBCL)</td>
</tr>
<tr>
<td></td>
<td>CBCL, K-CPT, &amp; Hillside</td>
<td>5 yrs (~320)</td>
<td>↑OP → ↑ADHD traits (CBCL)</td>
</tr>
<tr>
<td>Bouchard et al. (2011)</td>
<td>WISC-IV</td>
<td>7 yrs (329)</td>
<td>↑ OP → ↓Full Scale IQ (&amp; all four subscales of WISC-IV)</td>
</tr>
<tr>
<td>Lovasi et al. (2011)</td>
<td>BSID-II</td>
<td>3 yrs (265)</td>
<td>↑CPF → ↓MDI</td>
</tr>
<tr>
<td>Rauh et al. (2011)</td>
<td>CBCL &amp; WISC-IV</td>
<td>7 yrs (265)</td>
<td>↑CPF → ↓Full Scale IQ &amp; Working Memory Index</td>
</tr>
<tr>
<td>Rauh et al. (2012)</td>
<td>MRI brain scans</td>
<td>6-11 yrs (40)</td>
<td>↑CPF → Enlargements of brain regions, correlating with decreased IQ</td>
</tr>
</tbody>
</table>

•OPs measured by 6 DAP metabolites  
CPF:= chlorpyrifos  
N:= number of mother-child pairs

BSID-II := Bayley Scale of Infant Intelligence-Revised; CBCL:= Child Behavior Checklist; Hillside:= Hillside Behavior Rating Scale for ADHD scale; K-CPT:= Conners’ Kiddie Continuous Performance Test; MDI := Mental Development Index Score; MRI:= magnetic resonance imaging; NEPSY-II:= Visual attention subtest; PDD := Pervasive Developmental Disorder; WISC-IV:= Wechsler Intelligence Scale for Children, 4th Ed.
Glyphosate

Estimated Agricultural Use for Glyphosate, 2012

Over 250 million pounds used in 2012
Source: USGS, 2012
Perfluoroctanoic acid (PFOA) & Perfluorooctane Sulfonate (PFOS) Exposure

### Ingestion (primary route of exposure)
- **Direct:** Fish, Drinking Water, Breast Milk
- **Indirect:** Food packaging (e.g., microwave popcorn), non-stick cookware (e.g., Teflon), Dust

### Dermal Contact
- Personal care products (e.g., makeup, lotions, dental floss)
- Clothing (e.g., waterproof material)
- Furniture (e.g., upholstery)

---

2010/15 PFOA Stewardship Program: 8 major companies, inc. BASF, 3M/Dyneon & Dupont, will phase out PFOA emissions & product content by 2015
Neurodevelopmental Toxicity associated with Prenatal PFOA/S Exposure is *very limited*

<table>
<thead>
<tr>
<th>Reference &amp; Chemical</th>
<th>Standard Assessment</th>
<th>Assessment Age (N)</th>
<th>Outcome (p&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fei &amp; Olsen (2011)</td>
<td>SDQ &amp; DCDQ</td>
<td>7 yrs (787 &amp; 537)</td>
<td>No adverse association w PFOA/S levels and hyperactivity (SDQ) and motor difficulties (DCDQ)</td>
</tr>
<tr>
<td>Stein et al. (2013)</td>
<td>CCPT-II, WASI, WIAT-II, NEPSY-II</td>
<td>6-12 yrs (320)</td>
<td>No adverse association b/w PFOA &amp; IQ, cognitive development, attention &amp; impulsivity &amp; other neuropsychological effects. Those w/greatest PFOA exposure level were “most dissimilar to ADHD profile”.</td>
</tr>
<tr>
<td>Ode et al. (2014)*</td>
<td>ADHD (using DSM criteria)</td>
<td>n/a** (206)</td>
<td>No adverse association b/w fetal exposure to PFOA/S and ADHD</td>
</tr>
<tr>
<td>Hoyer et al. (2015)</td>
<td>SDQ &amp; DCDQ</td>
<td>5-9 yrs (1,106)</td>
<td>PFOA associated with ↑ hyperactivity score (SDQ) No adverse association b/w PFOA/S levels and motor difficulties (DCDQ)</td>
</tr>
</tbody>
</table>

*matched case-control study; ** year of delivery from 1978-2000; N:= number of mother-child pairs

**SDQ := Strengths and Difficulties Questionnaire (ADHD) ; DCDQ:= Developmental Coordination Disorder Questionnaire (motor coordination); CCPT-II:= Connor’s Continuous Performance Test-II (computer administrated to test for sustained attention and impulsivity); NEPSY-II:= neuropsychologically-based instrument designed to test specific brain behavior and ID markers or atypical cognitive development; WASI := Weschler Abbreviated Scale of Intelligence (full-, verbal -, and Performance- IQ); WIAT-II:= Weschler Inidividual Acheivement Test-II**
Air Pollution Studies
Smog is under control. Air Toxics are not.
Criteria for Pollutants (monitored):

- Ozone ($O_3$)
- Nitrogen oxides ($NO_x$)
- Carbon monoxide (CO)
- Particulate matter (PM 2.5 and 10)
- Sulfur oxides ($SO_x$)
- Lead (also an air toxic)

Air Toxics:

- Volatile Organic Compounds
- Polycyclic Aromatic Hydrocarbons (PAHS)
- Metals
- Dioxins and many others

Greenhouse gases:

- Carbon dioxide ($CO_2$)
- Methane ($CH_4$)
- Nitrous Oxide ($N_2O$)
Sources of Air Pollution

- Mobile Sources
- Industrial Sources
- Regional Sources

Chemistry & Meteorology

VOC, NOx, PM

Biogenic Sources

Health and Ecosystem Effects
Criteria Pollutants: **Particulate Matter**

Considered the most lethal form of air pollution.
Entering the System

Some pollutants penetrate through the lungs

Pollutants trapped in nasal mucous tend to leave the body.

Toxicants attached to particulate pollution more easily enter the body.
Polycyclic Aromatic Hydrocarbons (PAHs)

- Large family of organic chemicals
  - examples: benzo(a)pyrene, dioxins, naphthalene

- Many very carcinogenic, estrogen receptors, and/or genotoxic

- Often enter the body on or in particulate
Exposure to diesel particulate

1996 Modeled Exposure Concentrations for Diesel Particulate Matter

Oregon Average: 0.96 micrograms/cubic meter
Multnomah County Average: 2.06 micrograms/cubic meter

Source: EPA, 1996 National Air Toxics Assessment Exposure and Risk Data

MCHD- Environmental Health
Diesel: A Toxic Soup of Its Own

“...A child riding a school bus is being exposed to as much as 46 times the cancer risk considered “significant” by EPA and under federal law.”

Acetaldehyde ● ethyl benzene ● phenol ● arsenic formaldehyde ● phosphorus ● benzene ● hexane
PAHs ● biphenyl ● lead ● selenium ● 1,3-butadiene manganese ● styrene ● cadmium ● methanol ● toluene ● chromium ● naphthalene ● xylen ● cresol ● nickel
Proposed Mechanisms of Neurodevelopmental Effects of Air Toxins

- Inflammatory agents in brain cells
  - produce reactive oxygen species (ROS) that disrupt normal brain structure, architecture and function

- Inflammatory cytokines and mitochondrial damage

- Enzymes which scavenge ROS (protects cells) are more effective in girls

- Epigenetic agents of change during development
  - Disrupting normal gene function and timing of brain neuron connections

- Immune dysregulation

Source: Costa et al. (2014)
Columbia Center for Children's Environmental Health (CCEHS) Studies

- Gold Standard: Perera et al. at Columbia University in New York
  - linking an environmental factor with a biomarker measurement and a specific measurable neurodevelopmental outcome

- Peterson et al (2015): Prenatal PAH exposure to ↓ white matter (on left) by MRI, ↓ cognition, ↑ ADHD traits
Neurodevelopmental Effects of Prenatal PAHs (90% Diesel Exhaust) Exposure

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>N</th>
<th>Assessment</th>
<th>Outcomes (p&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cord Blood PAH-DNA Adducts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perera et al. (2014)</td>
<td>NYC</td>
<td>740</td>
<td>CBCL, Connors</td>
<td>Inattentive, ADHD</td>
</tr>
<tr>
<td>Jedrychowski et al. (2014)</td>
<td>Poland</td>
<td>170</td>
<td>Full-scale WISC, verbal IQ</td>
<td>↓ verbal IQ</td>
</tr>
<tr>
<td><strong>Spatiotemporal Models</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Lin et al. (2014)</td>
<td>Taiwan</td>
<td>533</td>
<td>BSID</td>
<td>↓ gross motor development</td>
</tr>
<tr>
<td>Kim et al. (2014)</td>
<td>S Korea</td>
<td>520</td>
<td>BSID</td>
<td>↓ psychomotor &amp; cognitive development</td>
</tr>
<tr>
<td>Newman et al. (2013)</td>
<td>Cincinnati</td>
<td>576</td>
<td>BAS</td>
<td>↑ Hyperactivity</td>
</tr>
<tr>
<td>Volk et al. (2013)</td>
<td>Calif.</td>
<td>279</td>
<td>ASD Diagnostic Instruments</td>
<td>↑ risk of ASD</td>
</tr>
<tr>
<td>Siddique et al. (2011)</td>
<td>New Delhi</td>
<td>969</td>
<td>DSM-IV</td>
<td>↑ ADHD (boys only)</td>
</tr>
</tbody>
</table>

HC := Head Circumference; BSID := Bayley Scale of Infant Development; BAS := Behavioral Assessment System
### Air Pollution Effects in Recent Novel Studies

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>N</th>
<th>Assessment</th>
<th>Outcome (p&lt;0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raz et al. (2015)</td>
<td>USA</td>
<td>100,000</td>
<td>Retrospective Interview</td>
<td>↑ Risk ASD with PM2.5 all three trimesters but mostly third trimester (ST modeling). Corroborates previous publications.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>245</td>
<td></td>
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<td></td>
<td></td>
<td>ASD</td>
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<tr>
<td>Calderon-Garciduenas et al. (2011)</td>
<td>Mexico City</td>
<td>20</td>
<td>MRI, WISC, serum inflammatory marker</td>
<td>↓ Brain volume in Parietal &amp; Temporal cortical matter, with ↑ white matter hyperintensities,; ↓ Vocabulary and Digit spans; ↑ inflammatory marker</td>
</tr>
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<td></td>
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<tr>
<td>Amoly et al. (2014)</td>
<td>Barcelona</td>
<td>2011</td>
<td>CBCL</td>
<td>Complex ST modeling: Living AND playing near Green (parks) and Blue (ocean) spaces, &gt;300 meters from major pollution sources , children have ↓ ADHD symptoms. Children living closer have ↑ risk of ADHD symptoms</td>
</tr>
</tbody>
</table>

ST := spatiotemporal
Concluding Remarks
### “Recommendations to Limit Toxic Chemical Exposures” Handout

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Pb</th>
<th>MeMg</th>
<th>PCBs</th>
<th>BPA</th>
<th>PBDEs</th>
<th>Phthalates</th>
<th>Pesticides</th>
<th>PFOA/S</th>
<th>Outdoor AP</th>
<th>Indoor AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remove shoes when entering your home</td>
<td>X</td>
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<td></td>
<td>X</td>
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<tr>
<td>Wear gloves when gardening and wash hands after contact with soil</td>
<td>X</td>
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<tr>
<td>If your home was built before 1978, garden in raised beds</td>
<td>X</td>
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<tr>
<td>Avoid certain fish, check your local fish advisory for current levels*</td>
<td></td>
<td>X</td>
<td>X</td>
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<td>Avoid frozen and prepared foods labeled “microwavable in package”</td>
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<td>X</td>
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<tr>
<td>And others...</td>
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</tbody>
</table>
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• Thank you for attending our session!
Discussion