Evidence of Health Effects of Blood Lead Levels < 10 µg/dL in Children

Reported by a

Work Group of the Advisory Committee on Childhood Lead Poisoning Prevention

Centers for Disease Control and Prevention
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Introduction

Because recent studies showed an inverse association between children's health and blood lead levels (BLLs) in the range < 10 micrograms per deciliter (µg/dL), the Advisory Committee on Childhood Lead Poisoning Prevention established a work group (WG) to review available evidence that blood lead levels below those currently defined as elevated by CDC could adversely impact children's health. The WG attempted to answer two questions:

1) Does available evidence support a negative association between measured blood lead levels in the range < 10 µg/dL and children's health?

2) Are the observed associations likely to represent causal effects of lead on health?

The WG reviewed evidence from published studies relating blood lead levels measured in children to cognitive function and other health measures. Among studies, both cross-sectional and longitudinal that have examined the relation of blood lead level to cognitive function as measured by IQ or the McCarthy Scales of Children's Ability (MSCA) General Cognitive Index (GCI), the majority showed an inverse relation of blood lead level to measured cognitive function that is attenuated but not eliminated with adjustment for potential confounders. There was no evidence that the estimated slope of the inverse blood lead-cognitive function relation tended to decrease with decreasing population blood lead levels, which one would expect if a threshold existed. In addition, in two prospective studies, (Canfield et al., 2003 and Bellinger et al., 2003), the estimated slope among children whose measured blood lead levels did not exceed 10 µg/dL, was greater than the slope estimated for the cohort as a whole. In these two studies, no threshold for the association is evident in the range of routinely measured blood lead levels. On the basis of this review, the WG concluded that the inverse association between children's blood lead levels and children's cognitive function that has been observed in populations of children with higher blood lead levels is also present in populations of children with measured blood lead levels less than 10 µg/dL.

The WG identified and considered several issues that bear on drawing causal inference from the observed associations among children with blood lead levels < 10 µg/dL. After considering these issues in the light of available evidence, the WG concludes that these associations are likely to be at least partly due to a causal adverse health impact of lead occurring at blood lead levels < 10 µg/dL. However, the WG also concluded that the possibility of residual confounding and other factors leaves considerable uncertainty as to the absolute size of the effect and shape of the dose response relationship at blood lead levels < 10 µg/dL.

Additional but limited evidence is available concerning associations of blood lead levels < 10 μg/dL with impairment of health domains other than cognitive function, including other neurologic functions, growth, sexual maturation, and dental caries. Because of the limitations of this evidence, which is mostly from cross-sectional studies such as the Third National Health and Nutrition Examination Survey (NHANES III), the WG did not draw conclusions concerning whether or not these associations represent causal effects at blood lead levels < 10 μg/dL.

Evidence of Health Effects Related to Blood Lead Levels < 10 µg/dL in Children

Reported by

A Work Group of the CDC Advisory Committee on Childhood Lead Poisoning Prevention on Health Effects of Blood Lead Levels < 10 µg/dL in Children

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Abbreviations and Acronyms

AAS	atomic absorption spectrometry
ACCLPP	Advisory Committee on Childhood Lead Poisoning Prevention
ALAD	amino levulinic acid dehydratase
ASV	anodic stripping voltammetry
ATSDR	Agency for Toxic Substances and Disease Registry
BLL	blood lead level
EBLL	elevated blood lead level
EP	erythrocyte protoporphyrin
EPA	Environmental Protection Agency
ETAAS	electrothermal atomization techniques based on the graphite Furnace
ETS	environmental tobacco smoke
FEP	free erythrocyte protoporphyrin
GCI	General Cognitive Index

GFAAS	graphite furnace atomic absorption spectrophotometry
HOME	Home Observation for Measurement Environment
ICP-MS	inductively coupled plasma mass spectrometry
ID-MS	isotope dilution mass spectrometry
MCV	mean corpuscular volume
MDI	Mental Developmental Index of the Bayley Scales of Infant Development for children
MSCA	McCarthy Scales of Children's Ability
NCCLS	National Committee for Clinical Laboratory Standards
NCEH	National Center for Environmental Health
NHANES	National Health and Nutrition Examination Survey
NMDA	N-methyl-D-aspartate
PCAACN	Practice Committee of the American Academy of Clinical Neuropsychology
PKC	protein kinase C, a calcium dependent enzyme
SES	socioeconomic status

U-RBP	urinary retinal binding protein
WG	work group
WISC-R	Wechsler Intelligence Scale for Children – Revised
WISC-III	Wechsler Intelligence Scale for Children – Third Edition
WRAT	Wide Ranging Achievement test arithmetic and reading scores
ZPP	zinc protoporphyrin

Appendix A
Literature Review and Classification

The literature review began with the Agency for Toxic Substances and Disease Registry's Toxicological Profile for Lead (ATSDR Tox Profile), published July 1999. The Health Effects chapter was thoroughly read and all articles relating to low blood-lead levels in children were chosen, whether they found significant results or not. New literature searches were then performed by Battelle's Technical Information Center. The year 1995 was chosen as the cutoff date for the new searches because it was felt that before this time, there was little focus on blood-lead levels less than 10 and that most relevant articles before 1995 were cited in the ATSDR Tox Profile. Searches were performed on a variety of databases using DIALOG and a set of keywords.

The following is an example of the DIALOG, including databases and keywords:

```
SYSTEM:OS  - DIALOG OneSearch
File   6:NTIS  1964-2003/May W3 (c) 2003 NTIS, Intl Cpyrght All Rights Res
File 103:Energy SciTec  1974-2003/May B1 (c) 2003 Contains copyrighted material
File 266:FEDRIP  2003/Mar Comp & dist by NTIS, Intl Copyright All Rights Res
File 161:Occ.Saf.& Hth.  1973-1998/Q3 (c) Format only 1998 The Dialog Corp.
File 156:ToxFile  1965-2003/May W2 (c) format only 2003 The Dialog Corporation
File 155:MEDLINE(R)  1966-2003/May W2 (c) format only 2003 The Dialog Corp.
File 162:Global Health  1983-2003/Apr (c) 2003 CAB International
File  71:ELSEVIER BIOBASE  1994-2003/May W3 (c) 2003  Elsevier Science B.V.
File  40:Enviroline(R)  1975-2003/May
File  73:EMBASE  1974-2003/May W1 (c) 2003 Elsevier Science B.V.
File  34:SciSearch(R) Cited Ref Sci  1990-2003/May W2 (c) 2003 Inst for Sci Info
File   5:Biosis Previews(R)  1969-2003/May W2 (c) 2003 BIOSIS

Set     Items   Description
S1     512735   NATAL? OR PRENATAL? OR PERINATAL? OR POSTNATAL?
S2    1244432   INFANT? ? OR INFANCY
S3    2607491   CHILD? ? OR CHILDREN? ?
S4     253558   LEAD/TI,DE,ID
S5     184354   PB
S6      68959   RN=7439-92-1
S7    5798237   BLOOD
S8      14048   (S1:S3) AND (S4:S6) AND S7
S9    2153692   GROWTH/TI,DE,ID
S10     31450   STATURE
S11    634981   NUTRITION
S12    169948   HEARING
S13    200409   (RENAL OR KIDNEY)(3N)FUNCTION?
S14    669012   BLOOD()PRESSURE
S15        13   HEMESYNTHESIS
S16     61334   HEMATOPOIESIS
S17     20269   (VITAMIN()D)(3N)METABOLI?
S18      1441   S8 AND (S9:S17)
S19       438   S18 AND PY=1990:1996
S20       422   S19/ENG OR (S19 AND LA=ENGLISH)
S21       353   S20/HUMAN
S22       190   RD (unique items)
S23       190   Sort S22/ALL/PY,D
S24     19583   NEUROBEHAVIO?
S25    272980   NEUROLOGICAL?
S26    166224   NEUROLOGIC
S27    148942   NEUROTOXIC?
S28     15459   NEURODEVELOPMENT?
S29      7061   COGNITIVE()DEVELOPMENT
S30   2878983   BEHAVIOR? OR BEHAVIOUR?
S31         3   IMPULSITIVITY
```

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S32      54987   HYPERACTIVITY
S33      10725   ADHD
S34      31451   IQ OR (INTELLIGENCE()QUOTIENT? ?)
S35       3350   WISC
Ref   Items  Index-term
E1   715223 *DC=A8.186.       (Central nervous system)
E2   645734  DC=A8.186.211.   (Brain)
E3    23250  DC=A8.186.211.132.       (Brain stem)
S36     715223   DC='A8.186.':DC='A8.186.211.132.'
S37       2936   (S8 AND (S24:S36)) NOT S18
S38        964   S37 AND PY=1990:1996
S39        941   S38/ENG OR (S38 AND LA=ENGLISH)
S40        808   S39/HUMAN
S41        415   RD (unique items)
```

This literature search was first run for the years 1995 to 2002. In the spring of 2003, the search was rerun for the years 2002-2003 to determine the relevance of recently published articles. Also in the spring of 2003, the search was rerun for the years 1990 to 1996 for relevant articles that were not cited in the ATSDR Tox Profile. Titles and abstracts from each literature search were reviewed, and relevant ones were ordered for further review. Additional articles were identified while reviewing the selected articles and were added to the list of references, as were a number of articles recommended by workgroup members.

The table below provides a summary of all the articles obtained from the various sources. This table shows when the search was performed, the years covered in the search, the number of articles found in the literature search, the number of articles ordered after the titles and abstracts had been reviewed, and the number of articles that were relevant for abstraction.

Summary of Literature Review Results

Date of Search	Years Covered	Number of Unique References Found	Number of reviewed for relevance	Number of Articles Abstracted into the Database
9/02	1995-2002	327	79	12
4/03	2002-2003	119	14	4[a]
5/03	1990-1996	605	25	4
ATSDR Tox Profile	Prior to 1996	-	107	24
Referrals[b]	various	10	12	7
		Total:	**235**	**51**
Relevant articles cited in tables 2-5-				**44**

[a] A 5th article, Stone et al., 2003, was obtained from this search and is not abstracted into the database but its relevance is discussed elsewhere in the report.

[b] Referrals include articles that were recommended by workgroup members, as well as those articles cited as references in studies identified in the ATSDR Tox Profile or literature searches.

Appendix B

Critique of NHANES III data by Stone et al. (2003)

Stone et al. (2003) reanalyzed the data used by Lanphear et al.. While the results they present are largely consistent with the findings of Lanphear et al., they provided a critique of the validity of the NHANES III data for evaluating lead-related impacts on neuropsychological development in children. Because their critique cuts across on neuropyschological measurements performed in the survey, the main points of their paper are summarized here.

- Stone et al. note that the weighted mean values for the 4 measures used by Lanphear et al. are below the predicted mean based on standardization data for these tests collected in the early 1970s for the WISC-R) and early 1980s for the WRAT. Stone et al. argue that the mean values should be higher than predicted by the standardization means due to secular improvements in cognitive test scores. One possible reason cited for the discrepancy is that NHANES tests were not administered by a psychologist. It is unclear, however, if the population sample used in the standardization data were equally representative of the U.S. population at that time or if changes in the population composition since then would lead to an increase or decrease in overall mean test performance. More importantly, it is unclear how a bias in mean score, even if real, and the use of non-psychologists for testing could produce associations between blood lead levels and test scores, given that examiners could not have known the participants blood lead levels. If non-psychologists produced less precise test results than psychologists would have, the expected impact on regression coefficients would be a bias toward the null.
- The age-adjusted scores used in NHANES are correlated with age, and they should not be. Stone et al. show that age is negatively correlated with arithmetic, block design, and digit span and positively correlated with reading. However, since blood lead levels decrease with age across the age range studied, the negative correlations would tend to produce a trend towards higher scores with increasing blood lead for those tests, the opposite of the findings of Stone et al.
- Imputation of missing covariate values was performed for a substantial proportion of observations in the analyses performed by Lanphear et al.. While imputation could increase covariate mismeasurement and residual confounding, analyses presented by Stone et al. show essentially similar findings when analyses are restricted to observations with full rank data.
- Relevant covariates, including whether a child has repeated a grade, whether interviews were in Spanish, and several other factors, were not included in analyses. However, two problems are evident in alternative "two stage" analysis provided by Stone et al.. First, it uses predicted rather than residual blood lead level as an independent variable in a model relating blood lead to test scores. This amounts to testing the relation to test scores of a linear combination of covariates, many included in the model with test score as the outcome. In addition at least one variable – having to repeat a grade – is included as a covariate, possibly result serious over control as discussed earlier. Lead associated cognitive and

behavioral effects have, not surprisingly, been associated with an increased risk of failure to complete high school. Thus, controlling for failure to complete a grade could amount to controlling for an effect of, rather than a confounder of the lead effect.

Taken as a whole, the Stone et al. critique of the NHANES III data, do not provide a convincing argument that the findings reported by Lanphear et al. are due to problems with the sample or testing methods. More importantly, Lanphear et al. must be considered in the context of other findings, including the more persuasive cohort studies, which are largely consistent with the associations he reports.

Background

Charge to the Work Group

In March 2002, the Advisory Committee on Childhood Lead Poisoning Prevention agreed to establish a work group (WG) to review evidence of possible health effects of lead at blood lead levels less than 10 micrograms per deciliter (µg/dL), currently the threshold for defining an elevated blood lead level according to CDC guidelines (CDC, 1991).

> "In October 1991, the Centers for Disease Control and Prevention issued Preventing Lead Poisoning in Young Children. This document heralded a change in the definition of the level for intervention for children with elevated blood lead levels (EBLLs) from a lead level of 25 µg/dL to 10 µg/dL. The report explained that this change was due to new data that indicated significant adverse effects of lead exposure in children at levels once thought to be unassociated with adverse effects. The 1991 document identified a goal to reduce children's blood lead levels below 10 µg/dL. Interventions for individual children were recommended at levels of 15 µg/dL and above.
>
> Research findings published and disseminated since October 1991 suggest that adverse effects from lead exposure and toxicity occur at blood lead levels below 10 µg/dL. Some studies suggest that some effects may be greater at blood lead levels (BLLs) below 10 µg/dL than at higher BLLs. Such research findings raise concerns about the inability to control lead exposure with conventional methods and lend credence to the importance of primary prevention measures to prevent lead exposure to children.
>
> The work group will be convened by the Advisory Committee on Childhood Lead Poisoning Prevention to review the existing evidence for adverse effects of lead exposure and toxicity on children at very low blood lead levels and to focus on effects at levels of 10 µg/dL and below. Rigorous criteria will be established for the literature review. The work group will then create, in conjunction with the committee, a summary of the evidence for publication."

Scientific and Public Health Context for the WG Review

Prior reviews that compiled the extensive evidence from in *vitro*, animal, and human studies establishing lead as a multi-organ toxicant, including studies showing health effects at blood lead levels near 10 µg/dL (ATSDR, 1999; WHO, 1995; EPA, 1986). Among the published studies, a large body of literature establishes, beyond a doubt, that lead is a developmental toxicant and that harmful effects of lead on children's development can occur without clinical signs, symptoms, or abnormal routine laboratory tests. In addition, a growing number of studies suggest that blood lead levels prevalent in the general population are associated with adverse health effects in adults and in the offspring of pregnant women. Finally, in more recent years, bone lead levels, measured by x-ray fluorescence, have been used in epidemiologic studies as a measure of cumulative lead exposure. Although these are not

considered in this review, a number of studies showing inverse relations of bone lead level to health general population samples (e.g., Cheng et al., 2001) adds further evidence that cumulative lead exposure may be harmful to health at typical background exposure levels for the population in the United States.

That available epidemiologic evidence does not demonstrate a threshold below which no effect of lead is possible is not a new idea. A review prepared for a 1986 workshop on lead exposure and child development stated, "There is little evidence for a threshold or no-effect level below which the lead/IQ association is not found. IQ deficits have been reported in studies where the mean lead level is 13 μg/dl (Yule, et al., 1981) and similar deficits in the Danish study where the primary measure was tooth lead, but blood lead levels are lower at around 7 μg/dl." (Smith 1989) A review, metaregression, and reanalysis of existing data (Schwartz, 1994) reached essentially the same conclusion. Available data did not suggest a threshold below which no association between blood lead levels and intelligence in young children was evident. Recent studies (Canfield, et al. 2003; Lanphear, et al., 2000; Moss, et al., 1999; Wu, et al., 2003) provided more direct evidence of an association between blood lead levels and adverse health effects in the domains of cognitive function, neurologic function, growth, dental caries, and onset of puberty at levels well below 10 μg/dL. Thus, a reexamination of this issue is in order.

As the evidence from experimental animal studies and human epidemiologic studies has grown, the blood lead level (BLL) considered elevated for the purpose of interpreting clinical test results in a child has been successively lowered by CDC (Table 1). These same guidelines also have provided criteria for identifying children who have more severe manifestations of lead toxicity and/or a higher risk of lead-related sequellae. For example, CDC's 1975 and 1978 guidelines defined clinical "lead poisoning" on the basis of BLLs, symptoms, and/or levels of erythrocyte protoporphyrin (EP) or other indicators of lead-related biochemical derangements. CDC's 1985 guidelines used the terms "lead toxicity" and "lead poisoning" interchangeably to refer to BLL ≥ 25 μg/dL with EP ≥ 35 μg/dL. But the guidelines acknowledged that "lead poisoning" is generally understood for clinical purposes to refer to episodic, acute, symptomatic illness from lead toxicity. CDC's 1985 guidance also cautioned that blood lead thresholds that guided follow-up and treatment for individual children "should not be interpreted as implying that a safe level of blood lead has been established." The 1991 guidelines more directly acknowledged the difficulty in assigning terms to specific ranges of blood lead levels given the different settings in which blood lead levels are interpreted and given that manifestations of lead toxicity occur along a continuum: "It is not possible to select a single number to define lead poisoning for the various purposes of all of these groups [e.g. clinicians, public health officials, and policy makers]" (CDC, 1991). These guidelines also noted, "Some [epidemiologic] studies have suggested harmful effects at even lower levels [than a BLL of 10 μg/dL]."

In addition to these changes in criteria used to evaluate blood lead test results for the Individual child, recent analyses by the Department of Housing and Urban Development (HUD, 1999) and the U.S. Environmental Protection Agency (EPA 2000) to support the development of regulations governing lead exposure have assumed that the relation of increasing blood lead to decrements in children's IQ extends to blood lead levels < 10 µg/dL.

As blood lead levels considered elevated have fallen, measures to reduce or remove lead from a number of sources, including gasoline, soldered food and beverage containers, paint, drinking water, and industrial emissions have resulted in a dramatic decline in BLLs in the United States since the mid-1970s (Pirkle et al. 1994). The Second National Health and Nutrition Examination Survey (NHANES II) conducted from 1976 to 1980 showed that, among U.S. children ages 6 months through 2 years, 84% of white children and more than 99% of black children had blood lead levels ≥ 10 µg/dL, and the median blood lead level was 14 and 19 µg/dL respectively (Mahaffey, et al., 1982). A decline in blood lead levels during the course of that survey was noted, paralleling the falling consumption of lead in gasoline (Annest, et al., 1983). A continued decline in blood lead levels was evident in subsequent NHANES surveys (Pirkle et al.1994; NCEH 2003) and in clinical blood lead test data compiled by state and local health agencies (Hayes et al. 1994; CDC 2000). Nationally, it is estimated that by 1999-2000, the prevalence of BLL ≥10 µg/dL among children 1 to 5 years of age had fallen to 2.2% and the median level to 2.2 µg/dL (NCEH 2003).

These reductions in lead exposure are not cause for complacency, however. As noted above, scientific advances have shed light on harmful effects of lead at levels of exposure once thought safe. In addition, even at the lower exposure levels that prevail today, typical body burdens of lead may be more than two orders of magnitude higher than those estimated to have been present in pre-industrial humans (Smith et al. 1992). Therefore, the potential exists for discovery of additional harmful effects of lead from currently prevailing exposures. Finally, though falling blood lead levels have benefited all demographic groups (Pirkle et al. 1994), stark demographic and geographic disparities continue to reflect the historic pattern: the risk of elevated BLL in communities where poverty and older (Pre-1950) housing are prevalent is several fold higher than the national average (Lanphear et al., 1998).

Review Methods

Scope and approach

Given the charge to the work group and the scientific and public health context summarized above, the WG did not attempt a comprehensive review of all evidence relating lead exposure to health. Instead, the WG set out to answer the following questions:

1) Does available evidence support negative associations between children's measured blood lead levels and their health in the range < 10 µg/dL?

2) Are the observed associations likely to represent a causal effect of lead on health?

The work group established criteria as described in the methods section for published studies that would address the first question. In addition, the work group identified issues relevant to making causal inference from any observed associations. Identifying such issues is an essential step in interpreting evidence relevant to the WG charge. Human studies to assess potential health effects of environmental toxicants in general and lead in particular are, for the most part, observational studies. That is, the health status of participants is related to some measure of exposure, dose, or body burden that varies on the basis of environmental factors and not experimental manipulations by the investigator. For ethical reasons, the limited number of human experimental studies that evaluated causal relations of toxicant exposures to health usually involved attempts to reduce exposure or body burden and assess the impact on health status. Such studies of lead exposed children are rare, and to date none have focused on children with blood lead levels < 10 µg/dL.

Observational studies have inherent limitations and the potential to produce biased results. Biases from observational studies can obscure true causal effects of toxicant exposures and produce associations between toxicant exposures and health status when no causal relation is present. Thus, statistical associations from individual observational studies or multiple studies subject to similar biases cannot establish causal relationships, and additional, non-statistical criteria have been used to evaluate such evidence. Although causal criteria have been stated in various ways, the Surgeon General's Report on Smoking and Health (U.S. Public Health Service 1964) provides a useful set of criteria. They include:

- <u>The consistency of the association</u>. Is a similar association observed across studies with varying methods and populations?

- <u>The strength of the association.</u> The strength of an association is the extent to which the risk of a disease or a measure of health status varies in relation to exposure and can be expressed, for example, as a relative risk or regression coefficient. It is distinguished from the statistical significance of an association that reflects both the strength of the association and the sample size. An additional criterion, specificity of the association, is closely related to strength of

the association and is considered less important in the context of multifactorial health conditions.

- The temporal relationship of associated variables. Does the hypothesized causal exposure occur before the health outcome associated with it?

- Coherence of the association. Is the observed association consistent with other relevant facts including, for example, experimental animal studies and the descriptive epidemiology of the health condition under study?

Consistent with these criteria, the WG identified several issues specifically relevant to inferring causality from associations, or the lack of associations, of blood lead levels to health measures observed in studies of low-level lead exposure. These potential biases are not unique to studies of children with blood lead levels ≤ 10 µg/dL, e.g., Smith, 1989. The larger number of human and experimental animal studies, including primate studies, and the nature of associated health effects associated with higher blood lead levels have made it possible to conclusively demonstrate adverse health effects of lead. However, far fewer studies of possible health effects of blood lead levels < 10 µg/dL have been conducted, and the relative importance of some sources of bias may be greater at these lower levels. Therefore, the work group considered several issues, which are delineated in the discussion section, in interpreting the findings of available studies.

At the time of this review, a consortium of investigators from several longitudinal studies of lead exposure and cognitive function in children, were conducting a reanalysis of data pooled from these studies. A focus of the pooled reanalysis is studying the shape of the association between postnatal lead exposure at low levels and measured IQ (Bruce Lanphear, personal communication). These studies include serial measures of blood lead level, cognitive function, and a large number of potential confounders and thus represent stronger evidence than is available from cross-sectional studies. The WG reviewed published reports from individual cohort studies from which data were pooled, but the final results of that pooled reanalysis were not available for inclusion in the WG report.

On the basis of its charge, the WG did not develop policy recommendations or address questions relevant to such recommendations. Among such questions are the following:

1) Is it feasible to routinely measure blood lead levels in individual children and accurately and reliably classify them with respect to threshold BLLs < 10 µg/dL?

2) Are evidence-based interventions available to reduce blood lead levels and improve health of children who develop BLLs above such threshold values?

3) Would the benefits, if any, of testing and classifying children according to such threshold values outweigh any potential harm that might result?

4) Would setting a threshold below 10 µg/dL for initiating individual case management divert resources for services to children with higher blood lead levels?

5) What are other policy options for responding to concerns about health effects of lead at low levels of exposure?

6) Would policy recommendations be most appropriately directed at the population or at the individual level?

Such questions and policy decisions will, if appropriate, be considered by the full ACCLPP after reviewing the findings of this report.

Criteria for relevant studies

The WG initially considered then rejected limiting its review to studies for which published results provide direct comparisons between children with varying BLLs 10 µg/dL. Instead, the group decided that the large number of studies that have included IQ as an outcome could, collectively, indirectly support or refute the existence a threshold near 10 µg/dL for the blood lead-IQ association. The rationale for this approach is based on that used in a review and metaregression reported by Schwartz (1994) and restated below.

Suppose that, hypothetically, a threshold exists near 10 µg/dL, above which mean IQ decreases linearly with increasing blood lead, with a slope=x and below which mean IQ is not associated with blood lead (see Figure 1 - Hypothesized "true" relation A). In studies of children who have blood lead levels < 10, estimated slopes would, absent sampling error, be 0. For studies with all children having blood lead levels above the threshold, the estimated slope would, again ignoring sampling error, be x. Studies in which some children have blood lead above and others below the threshold, estimated slopes will vary between 0 and x as shown in Figure 1. Thus, if regression coefficients estimating the IQ-blood lead slope are less negative (approaching 0) in populations with lower mean blood lead levels than in populations with higher mean levels, a threshold near 10 would be suggested. The absence of such a trend or an increase in slopes with decreasing mean blood lead level of the population studied would provide evidence against such a threshold and in support of "true" relations B and C, respectively.

Because of this approach, studies that assess the association between blood lead and measured IQ were included in this review, even if (as was true in most cases) published results did not examine blood lead - IQ associations limited to the range of blood lead levels < 10 µg/dL. An additional reason for considering studies that measured IQ was the relationship of IQ

to other outcomes of policy and public health importance including educational success and earnings potential (Grosse et al. 2002). Because the McCarthy Scales of Children's Ability (MSCA) General Cognitive Index (GCI) was used in a number of studies to measure cognitive function in preschool children and because GCI and IQ scores have similar distributions, studies using GCI as an outcome were also included in this review.

The following criteria were used to select relevant studies to review for this report:

1) Blood lead levels were measured using graphite furnace atomic absorption spectrophotometry (GFAAS) or anodic stripping voltametry.

2) The study was published in English.

In addition,

For studies in which IQ or GCI was a measured outcome, the

study analyses included an assessment of the association between blood lead levels measured in children and IQ or GCI.

For studies in which IQ or GCI was not a measured outcome, the

study analyses included an assessment of the association between blood lead levels < 10 µg/dL measured in children and a health outcome. The assessment could either be formal (e.g., non-linear modeling, linear modeling restricted to populations with all or at least 95% of children had blood lead levels < 10 µg/dL, statistical comparison of two or more sub-groups with blood lead levels < 10 µg/dL) or informal (e.g., graphical display of results permitting visual assessment of blood lead-outcome relation in the range < 10 µg/dL).

Literature search

To identify potentially relevant articles, a comprehensive report published by the Agency for Toxic Substances and Disease Registry (ATSDR 1999) was reviewed first to identify cited articles that related to low-level lead exposure in children. The list of potentially relevant citations identified in the ATSDR report was supplemented by three computerized literature searches, using Dialog ® to search Medline, Toxfile, and other bibliographic databases. Search terms (see Appendix A) were chosen to identify articles reporting on blood lead measurements and one or more domains of health related to lead exposure including neurodevelopment, cognitive function, intelligence, behavior, growth or stature, hearing, renal function, blood pressure, heme synthesis, hematopoiesis, and Vitamin D metabolism. The first search spanned articles published from 1995 through 2002 and indexed as of September 2002 when the initial search was performed. The second search was performed in April 2003 and spanned the period 2002 through the search date. A third search, spanning the years 1990 through 1996 was

performed when a relevant article not cited in the ATSDR toxicological profile was identified by one of the work group members. In addition, potentially relevant articles were identified by work group members and through citations in articles identified previously. Abstracts were reviewed initially. If they were ambiguous or if they suggested the article was relevant, full articles were checked for relevance. Articles deemed relevant were abstracted for this report. Appendix A summarizes the number of possibly relevant references identified, full articles checked for relevance, and relevant articles abstracted and considered in the review.

Structured abstracts

For each relevant study, a structured study abstraction was performed that captured the following information: the study location, sample size, age at which blood lead was measured, age at which the outcome was measured, available information about the blood lead distribution, including mean or other measure of central tendency, variance, and % of participants with blood lead levels < 10 µg/dL, and the crude and adjusted regression coefficients relating blood lead to outcome, if available. If regression coefficients were not available, other measures of association reported, such as correlation coefficients, were noted, the type of model fit (linear, log linear, or other), and the covariates included in the adjusted model. Because some studies fit multiple blood lead-outcome models, (e.g. cohort studies with blood lead and IQ measured at multiple ages), relevant information about each model estimated was abstracted. For IQ studies, covariates measured and not included in adjusted models were recorded where available.

Review of Cohort Study Methods

Among relevant published results were those from cohort studies specifically designed and conducted to study the relation of blood lead levels to children's cognitive function and other health outcomes. Because these studies have the strongest and best-documented study designs to address the topic of this review, methods used for blood lead measurement and neuropsychological assessment were summarized for these studies. This information was collected from published studies; in some cases, the studies were supplemented by information provided through correspondence with the investigators.

Results

Studies relating postnatal lead exposure to IQ or General Cognitive Index

Studies in which IQ or GCI measured using the McCarthy Scales of Children's Abilities) were measured as an outcome and other criteria were met, included 25 published reports from 16 separate study populations. Results from these studies are summarized in Table 2 (full scale IQ and GCI), Table 3 (verbal IQ), and Table 4 (performance IQ). Within each table, results are grouped according to the age at blood lead measurement and age at outcome measurement; each table displays results sorted according to the measure of central tendency of the blood lead distribution. Because some studies used linear models (blood lead levels were untransformed)

and some used log-linear models (blood lead levels were log transformed) estimated regression coefficients were, where possible, used to calculate the estimated change in IQ (or GCI) corresponding to a blood lead increase from 5 to 15 µg/dL to allow for comparisons across studies. Covariates included in adjusted models are grouped into several broad domains that were addressed in most of the published studies.

Among studies that provided results for the size and direction of the estimated blood lead-Full Scale IQ (or GCI) associations regardless of statistical significance, a majority found both crude and adjusted associations to be consistent with an adverse effect – IQ decreases with increasing blood lead. In most cases, covariate adjustment attenuated, but did not eliminate these estimated associations. Findings for performance and verbal IQ were similar, with some studies showing stronger associations of lead with performance IQ and others with verbal IQ.

There are notable exceptions to this pattern, however. Results from the Cleveland cohort (Ernhart et al. 1987, 1988, 1989) indicated a crude inverse association between blood lead and IQ but no association with covariate adjustment. In the Cincinnati and Boston cohort studies, BLLs measured at or below 12 months of age showed no association or a slightly positive association with covariate-adjusted IQ (Dietrich et al. 1993; Bellinger et al. 1992). The estimated BLL-IQ association in the Kosovo cohort was strengthened substantially with covariate adjustment (Wasserman et al. 1997).

No trend toward attenuation of the blood lead-IQ (or GCI) relations across studies with decreasing average blood lead levels is evident (Figures 2 and 3). For two of these studies, analyses were presented that provide more direct information concerning the association between BLL and cognitive function at blood lead levels < 10. The steepest estimates of blood lead- IQ slope come from the Rochester (Canfield et al. 2003) and Boston cohort (Bellinger et al., 2003) analyses that were restricted to children whose measured blood lead level never exceeded 10 µg/dL. In each case, the estimated slopes are substantially larger than those estimated from the entire study population (Figure 4). Canfield et al. also report a non-linear model supporting a steeper blood lead-IQ slope at lower levels.

Most of the published studies included at least one measure of socio-economic status. All of the published results from cohort studies were adjusted for Home Observation for Measurement Environment (HOME) score and birth weight; all except the Costa Rica cohort were adjusted for a measure of maternal intelligence. Prenatal exposure to maternal smoking was adjusted in the majority of studies, whereas, only in the Port Pirie cohort was a measure of postnatal environmental tobacco smoke exposure included. Iron deficiency anemia was included as a covariate in results from the Costa Rica study, which found no association of lead and IQ; the inverse blood lead-IQ associations in the Rochester study (Canfield et al. 2003) and the Karachi study (Rahman et al. 2002) were adjusted for serum transferrin saturation and hemoglobin respectively. In addition, in the Kosovo study (Wasserman et al., 1997), alternative models were fit with adjustment for hemoglobin, and these showed no appreciable change in the lead coefficient.

It should be noted that not all studies reported regression coefficients that could be used to estimate the change in IQ associated with a BLL change of 5 to 15 µg/dL, and the overall pattern of results summarized above and in Figures 2 and 3 might have been altered had regression coefficients been available from all studies. For example, a member of the WG provided results of reanalysis of the data from the Costa Rica cohort, which showed no evidence of an inverse relation of BLL to IQ with adjustment for maternal IQ and other covariates used in the published result (Wolff et al. 1994; B Lozoff and A Wolff, personal communication).

Studies of health endpoints other than IQ and CGI

As noted earlier, more stringent criteria were required for inclusion of studies in this review if they assessed health endpoints other than general intelligence as measured by IQ or GCI. These studies are summarized in Table 5 and are described below.

Cognitive function

Lanphear et al.(2000) analyzed data on blood lead levels on performance on standardized tests of cognitive function of 4853 children age 6 through 16 years who were evaluated as part of the NHANES III survey, a multiphasic health interview and examination survey of a stratified probability sample of the U.S. population, carried out from 1988 through 1994. In this population, with a geometric mean BLL of 1.9 and 98% of children having BLL < 10 µg/dL, significant inverse relations were found between BLL and scores on the Wide Ranging Achievement test (WRAT) arithmetic and reading scores and on the WISC-R block design and digit span subscales. The relationships were strengthened (the slopes became more negative) as analyses were progressively restricted to children with lower blood lead levels. Stone et al. (2003) reanalyzed the data used by Lanphear et al. (2000). While the results they present are largely consistent with the findings of Lanphear et al., they provided a critique of the validity of the NHANES III data for evaluating lead-related impacts on neuropsychological development in children. Their critique did not provide results that could be summarized in the structured abstract formant used in this report, so a discussion of the Stone et al. critique is found in Appendix B.

Other neurobehavioral measures and visual function

Three reports (Altman et al. 1998; Walkowiak et al. 1998; Winneke et al. 1994) describe the relation of blood lead to several neurobehavioral measures and to visual function assessed in 384 school children 5 to 7 years of age in three cities in Eastern Gemany. Blood lead levels were generally low, with a geometric mean of 4.25 µg/dL and 95% of children having blood lead levels < 10 µg/dL. Walkowiak et al. 1998 reported a significant negative association between BLL and WISC vocabulary subscale scores and with continuous performance test false positive and false negative responses. Other measures inversely related to BLL included performance on a pattern comparison test, finger tapping speed (Winneke et al, 1994) and visual evoked potential interpeak latency (Altman et al. 1998). Mendelsohn and colleagues (1999) found a 6 point deficit in the Mental Developmental Index (MDI) of the Bayley Scales of Infant Development for children aged 12 to 36 months with BLL 10-24 µg/dL compared with children who had BLLs

< 10 µg/dL. A scatterplot of covariate-adjusted MDI vs. blood lead suggests the association continues at BLL<10.

Neurotransmitter metabolite levels

Among children ages 8 through 12 years with mean blood lead level of 3.95 µg/dL, an direct relation of PbB to higher urinary homovanillic acid, a neurotransmitter metabolite, was found for the subset of children with BLL > 5 µg/dL (Alvarez Leite et al., 2002).

Growth

Two studies examined the relation of blood lead levels < 10 µg/dL to somatic growth. Ballew et al. (1999) using the NHANES data, found that blood lead levels were inversely related to height and to head circumference among children 1 to 7 years of age. A birth cohort of children in Mexico had blood lead levels and head circumference assessed every 6 months from 6 to 48 months of age, during which time the median blood lead level varied from 7 to10 µg/dL (Rothenberg et al. 1999). Most postnatal blood lead measures were inversely correlated with covariate adjusted head circumference, with the strongest relation found between blood lead at age 12 months and head circumference at 36 months. Kafourou and colleagues (1997) reported a significant negative association between blood lead level and covariate-adjusted head circumference and height in a population of children with median BLL of 9.8, with a scatterplot suggesting the relation extends to BLL < 10 µg/dL.

Sexual maturation

Two studies, both based on analyses of the NHANES data, found an association between blood lead levels less than 10 and later puberty in girls. Selevan et al (2003) found that blood lead levels of 3 µg/dL, compared with 1 µg/dL were associated with significant delays in breast and pubic hair development in African American and Mexican girls. The trend was similar, but not significant, for non-Hispanic white girls. Age at menarche was also delayed in relation to higher blood lead levels, but the association was only significant for African-American girls. Wu et al. (2003) reported similar findings, also for girls in the NHANES III population but did not stratify the analysis by racial/ethnic group. Compared with blood lead levels 2.0 µg/dL and below, BLLs of 2.1-4.9 µg/dL were associated with significantly lower odds of attaining Tanner 2 stage pubic hair and menarche; whereas no overall association with breast development was noted.

Dental caries

In the NHANES III population, the odds of dental caries, comparing children age 5 to or through 17 years in middle tertile of the BLL distribution (range of BLLs 1.7-4.1) with those in the lowest tertile, were significantly elevated at 1.36 (1.01-1.83) (Moss et al. 1999). Gemmel et al., (2002) evaluated the association between blood lead levels and caries in 6-10 year old children from urban communities in eastern Massachusetts (mean PbB=2.9 µg/dL) and a rural

community (mean PbB=1.7 µg/dL) in Maine. They found a significant direct relation of blood lead level to caries in the former, but not the latter population in which a non-significant decrease in caries frequency was observed with increasing blood lead. In the urban population, the trend of increasing caries with PbB level was evident comparing children with 1, 2, and 3 µg/dL PbB.

Blood pressure and renal function

Among 66-month-old children in Kosovo, a graphs depicting adjusted mean systolic and diastolic blood pressure vs. blood lead level, showed no consistent trend across 4 groups of children (approximately 28 per group) with blood lead levels spanning a range from approximately 5 to 10 µg/dL (Factor Litvak et al. 1996). In a population of 12- to 15-year-old children living near a lead smelter and a control group, urinary retinal binding protein (U-RBP) was found to be significantly associated with PbB in a stepwise regression. When urinary RBP excretion was examined by BLL tertiles, significantly lower U-RBP was seen in the group with BLL <8.64 ug/dl compared with BLL 8.64-12.3.

Heme synthesis biomarkers

Roels et al. (1987) studied the relations of PbB to heme synthesis biomarkers and reported no evident threshold for inhibition of aminolevulinic acid dehydratase synthesis at PbB as low as 8-10 µg/dL, while the threshold for increasing erythrocyte protoporphyrin levels was evident in the range of 15-20 µg/dL, consistent with other studies, including two meeting criteria for inclusion in this report (Rabinowitz et al. 1986; Hammond et al. 1985).

Discussion

Question 1: Does available evidence support an inverse association between children's blood lead levels in the range < 10 µg/dL and children's health?

The weight of evidence clearly favors such an association for cognitive function. This conclusion is based on both indirect and direct evidence. Indirect evidence comes from the great majority of studies relating blood lead levels to standardized measures of overall cognitive function showing an inverse relation and no trend toward weaker associations in populations with lower BLL distributions. Two recent analyses of data from cohorts designed from the start to study the relation of blood lead to child development provide more direct evidence of such an association (Canfield et al. 2003; Bellinger et al. 2003). These studies showed that the inverse relation of BLL to cognitive function is present and indeed stronger at BLL <10 µg/dL compared with higher BLL. These studies suggest no threshold within the range of routinely measured blood lead levels below which no association was present. Several recent analyses of data from the NHANES III and other populations also provide direct evidence of associations that imply adverse impacts of lead on indicators of children's neurocognitive development, stature, head circumference, dental caries, and sexual maturation in girls, occurring at measured blood lead levels < 10 µg/dL. Though the number of studies providing direct evidence of associations at BLL < 10 µg/dL is limited and most are cross sectional, they provide convincing evidence of an association in the context of the much large number of studies that relate slightly higher levels of lead in blood to impairments of children's health.

Question 2: Are the observed associations likely to be causal?

With the weight of evidence clearly favoring an association between blood lead levels in the range < 10 µg/dL children and health and, indeed, suggesting that such relationships become steeper as blood lead levels decrease, the work group considered a number of issues that must be addressed in judging whether such associations are likely to be causal. These issues are discussed individually below followed by overall conclusions.

Biologic plausibility

Evidence from experimental animal and *in vitro* studies, which are not subject to confounding influences of concern in human observational studies, can establish causation and identify mechanisms that might be operative in humans. Therefore, an important consideration in judging whether associations between blood lead levels < 10 µg/dL and health outcomes are likely to represent causal relations is whether such causal relations are biologically plausible on the basis of experimental animal and *in vitro* studies. These studies can also help to assess potential dose-response relationships and thresholds, but extrapolation from *in vitro* and animal models to human health risk adds additional uncertainty.

Lead is the most extensively studied environmental neurotoxicant. Animal and *in vitro* studies have provided an abundance of information concerning biochemical and physiologic changes caused by lead. Along with clinical and epidemiologic data, this evidence has clearly established that lead is toxic to the developing and mature nervous system. These data have been extensively reviewed elsewhere (EPA 1986, ATSDR 1999, WHO 1995, Davis et al. 1990) and are not exhaustively reviewed here. Rather, this discussion highlights evidence concerning potential mechanisms of lead toxicity and data from animal studies that are relevant to the biologic plausibility of the toxicity of lead, especially to the developing nervous systems of children exposed at blood lead levels < 10 micrograms per deciliter.

Athough the precise mechanisms of action and their relative importance in different manifestations of lead toxicity are not known for certain, *in vitro* studies demonstrate that lead can interfere with fundamental biochemical processes. At the most basic level, many of the proposed mechanisms of lead toxicity involve binding to proteins and/or interference with calcium dependent processes (Goldstein 1993).

For some of the adverse health effects of lead, such as anemia, the lead-associated biochemical changes that contribute to the effect in humans are fairly well understood. Lead interferes with heme synthesis in part by binding to sulfhydryl groups in the enzyme amino levulinic acid dehydratase (ATSDR, 1999), which is especially sensitive to inhibition by lead (less than 0.5 micromoles per liter *in vitro*) (Kusell et al., 1978; Dresner et al., 1982). This inhibition causes delta amino levulinic acid, a potential neurotoxic agent, to accumulate. Lead also inhibits ferrochelatase, an enzyme catalyzing the incorporation of iron into protoporphyrin to form heme. This inhibition also may involve lead binding to protein sulfhydryl groups.

Although anemia and accumulation of protoporphyrin IX in erythrocytes are the most obvious consequence of impaired heme synthesis, this pathway could play a role in lead-related impairment of cellular function throughout the body (EPA 1986). By interfering with heme synthesis and perhaps by inducing enzymes that inactivate heme, lead can decrease the levels of heme in body tissues (Fowler et al. 1980). A reduction in the body heme pool may impair heme-dependent biochemical processes, such as cellular respiration, energy production and the function of the cytochrome p-450 monooxygenase system involved in detoxification of xenobiotics and in transformation of endogenous compounds such as vitamin D precursors (EPA 1986).

For other more complex health effects of lead, such as impaired neurocognitive development and behavior change, a number of plausible mechanisms have been demonstrated in animal and *in vitro* systems. Lead's impact on one or more biochemical systems needed for normal brain development and function could account for the neurobehavioral effects observed at low levels of exposure. Especially sensitive to lead *in vitro* is the activation of protein kinase C (PKC), a calcium dependent enzyme. Lead binds more avidly to PKC than its physiologic ligand, calcium, causing activation at picomolar concentrations *in vitro*. (Markovac and Goldstein, 1988). The interactions between lead exposure and PKC activity in the brain are complex; chronic lead exposure may reduce activity of PKC associated with cell membranes while increasing cytosolic PKC activity. Lead effects on PKC activity have been proposed to

mediate potential impacts of lead on cell growth and differentiation, including that of neural cells (Deng and Poretz, 2002), the blood-brain barrier, and long-term potentiation (a process related to memory) (Hussain et al, 2000). Lead also interferes with calcium-dependent control of neurotransmitter release at presynaptic nerve terminals. It may thereby interfere with signaling between neurons and possibly with development of neural networks. In animal and *in vitro* studies, lead has been shown to interfere with neurotransmitter systems, including inter with dopamine binding and the inhibition of N-methyl-D-aspartate (NMDA) receptor activity.

The large body of evidence from animal studies of lead exposure and neurodevelopment supports a causal effect that is persistent following exposure early in life and that generally parallels human studies in terms of the domains of function that are impaired. (WHO 1995) Concerning blood lead-effect relations, direct cross-species comparisons of blood lead levels cannot be made (Davis et al., 1990), and most animal studies demonstrating lead-related developmental neurotoxicity involved doses that produced blood lead levels well above 10 µg/dL. However, available studies provide strong evidence of adverse effects in animals with blood lead levels near 10 µg/dL. It should be noted that blood lead levels cited in animal studies generally involve mean levels achieved in experimental groups with individual animals varying, sometimes substantially, around that mean.

Non-human primates experimentally exposed to lead early in life demonstrate dose related impairments in learning and behavior (Bushnell and Bowman, 1979; Rice 1985; Levin and Boman 1986). One study, involving monkeys dosed during the first 200 days of life to achieve peak blood lead levels that averaged 25 and 15 µg/dL, showed deficits relative to control monkeys (average peak blood lead 3 µg/dL) at age 3 years on "discrimination reversal" tasks (the animals are taught to respond to a cue and then the cue is changed and the ability to learn the new cue, with and without irrelevant cues, is measured). At the time of testing, mean blood lead levels in the exposed groups had fallen to 13 and 11 µg/dL, respectively. Both exposure groups showed deficits, but in the lower exposed group the deficits were evident only with more complex tasks (e.g. including irrelevant cues) (Rice 1985). The same monkeys showed persistent impairments at 9 to 10 years of age (Gilbert and Rice, 1987). Experimental studies in rats have demonstrated behavioral effects at mean blood lead levels in the range of 10-20 µg/dL (Cory-Slechta et al. 1985; Brockel and Cory-Slechta, 1998).

There is uncertainty about the relationship of the tissue or cellular levels of lead linked to physiologic changes in animal and *in vitro* studies to the corresponding human blood lead level required to produce such levels at target sites. Although the majority (90 to 99%) of lead in whole blood is in red cells, plasma lead level is believed to better reflect lead transferred from bone stores and (Cake et al, 1996) available for transfer to target tissues. Because red cells have limited capacity to accumulate lead, the relation of blood lead to plasma or serum lead is non-linear with serum Pb increasing more rapidly at higher blood lead levels (Leggett 1993). In subjects with a mean blood lead level of 11.9 µg/dL, plasma lead levels ranged from 0.3-0.7% of whole blood lead levels (Hernandez-Avila et al. 1998). The relation of plasma serum levels in intact animals to tissue levels measured in *in vitro* models is probably more complex. It is also uncertain whether *in vitro* studies demonstrating possible mechanisms for low-level lead toxicity reflect mechanisms operative in the intact animal. For example, Zhao et al (1998) found that

lead interfered with PKC in choroid plexus endothelial cells in a dose dependent fashion over the concentration range range of 0.1-10 micromolar. However, no effect on choroid plexus PKC activity was seen in an in vivo model.

Conclusions: The fundamental nature of biochemical and physiologic changes linked to lead in *in vitro* and experimental animal studies do illustrate potential mechanisms for lead toxicity that might be operative in humans at very low exposure levels. Experimental animal studies support the biologic plausibility of adverse health effects of lead in children at blood lead levels near 10 µg/dL. However, firm conclusions concerning relations of health status of children to blood lead levels in the range < 10 µg/dL cannot be drawn from these studies because of limitations of extrapolating from *in vitro* systems to intact animals and from animals to humans and because of the limited amount of data available from studies of animals dosed to produce a range of blood lead levels less than 10 µg/dL. Data from primates, which can most readily be extrapolated to humans, are especially limited.

On the other hand, given the uncertainty in extrapolating across species, the fact that animal test systems cannot match the complexity of learning tasks faced by young children, and the relatively small relative difference in blood lead levels shown to be harmful in animals and those at issue in children, adverse health effects in children at blood lead levels < 10 µg/dL are biologically plausible.

Blood lead measurement

The precision and accuracy of blood lead measurements performed in an epidemiologic study will impact observed results. On the one hand, if blood lead levels are systematically over or underestimated, biases in estimated blood-lead response relationships and/or no effect thresholds will result. All blood lead measurements involve some random error, which, if a true blood lead-health relation exists, will tend to bias estimates of the relation toward the null (i.e. no effect) value. The quality of BPb measurements varies widely from one laboratory to another, between different analytical technologies and between different specimen collection techniques. In addition, laboratory performance for blood lead has improved markedly over the last 3 decades and continues to improve as new analytical technologies are developed. Each of these factors becomes important in assessing the quality of blood lead measurements used in published studies. In this section, specimen collection and laboratory factors that can effect blood lead precision and accuracy are considered.

The widespread industrial use and dispersal of lead, particularly during the last century, has ensured that it is a ubiquitous contaminant. Stringent procedures are therefore necessary to reduce environmental contamination of blood collection devices and supplies so that false positive results are avoided. Consequently, venous blood collected using evacuated tubes and needles certified as "lead-free" is considered the most appropriate specimen for BPb measurements. See National Committee for Clinical Laboratory Standards (NCCLS), 2001. However, collection of venous blood from pediatric subjects is sometimes difficult; thus, capillary blood from a finger puncture is used widely for screening purposes. Published studies have compared the quality of BPb results for capillary and venous specimens drawn

simultaneously (Schlenker et al. 1994; Schonfeld et al. 1994; Parsons et al. 1997). With stringent precautions, particularly rigorous hand washing, contamination errors can be held to around 4% or better (Parsons et al. 1997). So, although venous blood is preferable for epidemiologic studies of environmental lead exposure, use of capillary blood is acceptable if collected by staff specially trained in the technique using devices certified as "lead-free." Data should be provided showing an acceptably low rate of contamination errors and low mean bias in the capillary blood lead levels as collected using the study protocol.

There are currently three basic analytical approaches to blood lead measurement: atomic absorption spectrometry (AAS); anodic stripping voltammetry (ASV) and inductively coupled plasma mass spectrometry (ICP-MS). A thorough discussion of these analytical techniques is beyond the scope of this brief. A comprehensive assessment has been published by the National Committee for Clinical Laboratory Standards (NCCLS, 2001). Briefly, the older flame atomization AAS methods, which include MIBK-extraction and Delves cup, are less precise, with a detection limit near 5 µg/dL for Delves cup (Parsons et al. 1993), and are thus not well suited to examining BLL-health relations in the range < 10 µg/dL. The electrothermal atomization techniques based on the graphite furnace (ETAAS) are more precise and more sensitive and, therefore, have better detection limits, typically around 1.0 µg/dL. A direct comparison between ASV and ETAAS techniques (Bannon et al. 2001) shows that the latter has better precision and better accuracy. Nonetheless, when operated in experienced hands and with a robust quality control/quality assurance program that includes calibration standards traceable to the mole via isotope dilution mass spectrometry (ID-MS), ASV can deliver BPb measurements with accuracy and precision sufficient to examine health effects at BLL < 10 µg/dL (Roda et al. 1988).

In order to assess the accuracy and precision of blood lead measurements made for research purposes, investigators should provide information on the laboratory's performance in measuring external quality control samples and on the between-run standard deviation for routine quality control samples that span the relevant blood lead range for a given study.

Conclusions: The key considerations relevant to judging the accuracy and precision of BPb measurements in published studies include the type and quality of blood specimen collected, analytical methodology used by the laboratory, internal and external QA/QC procedures in place. For the purpose of studying the relation of blood lead to health endpoints at levels < 10 µg/dL, venous samples are preferred and capillary samples are acceptable with evidence of a rigorous protocol to control contamination errors. Acceptable analytic methods include electrothermal AAS, ASV, and ICP-MS. Information on laboratory performance (accuracy and precision) from external and internal quality control data should be provided.

Suitable measurement methods were required for studies to be included in this review. In addition, venous samples were used for most postnatal blood lead measurements in the relevant cohort studies (see Table 6) and others cited in this report. Given this and the blood lead quality control procedures reported in the most informative studies, it is highly unlikely that systematic errors in measurement in the relevant studies were sufficient to bias the observed blood lead

distributions enough that associations observed in the range < 10 µg/dL were attributable to blood lead levels above that threshold.

Blood lead age trend, tracking, and inference concerning blood lead - effect relations in children

Age-related changes in children's blood lead levels and within-child correlation of blood lead measured at different ages may influence observed relations of blood lead level to health at a given age. In addition, the biologic impact of lead in children is likely related not only to the blood lead level measured at any one time but may also be influenced by the ages at which a given level occurs and the duration of exposure.

Under most exposure scenarios, children's blood lead levels show a characteristic age trend. A newborn's blood lead level will largely reflect the blood lead level of its mother. Because adult women tend to have lower blood lead levels than young children, umbilical cord blood lead levels are generally lower than blood lead levels during childhood. During the latter half of the first year of life, however, children's blood lead levels begin to increase as the infant becomes more active, mobile, and exposed to ambient lead. The onset of ambulation during this period is likely to be important, as are play patterns that bring the child into contact with environmental media such as lead-contaminated dust and soils. Other factors include the increased hand-to-mouth activity of children, including the practice of eating "in place," i.e., in play areas. Physiologic factors, such as more efficient absorption of ingested lead in children compared to adults, and their greater food and air intake on a body weight basis might also contribute to the early postnatal rise in blood lead level

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The mean blood lead level within a study sample generally peaks between 18 and 36 months of age, and slowly declines over the next few years. This blood lead profile is seen among poor urban minority children (Dietrich et al., 2001) and among children living around a smelter (Tong et.al., 1996; see Figure 5). In cohorts with extremely high exposures, the blood lead decline might be very gradual (e.g. Wasserman et al., 1997). In the Cincinnati Study, the same general profile was evident in each of four strata defined by average lifetime blood lead level, suggesting that it is, to some extent, independent of the overall level of exposure. This blood lead profile has not been observed in all study cohorts, however. In the Boston Study, for example, mean blood lead level varied minimally, from 6.2 to 7.6, between birth and 5 years of age (Rabinowitz et al., 1984; Bellinger et al., 1991).

One implication of the typical profile is that maximum level is often associated with age, constituting an obstacle to an effort to identify age-specific vulnerability to lead toxicity. Compounding this challenge is that, under many exposure scenarios, particularly those involving higher exposures, intra-individual stability of blood lead level tends to be substantial. That is, blood lead level tends to "track," so that if, at time 1, child A has a higher blood lead level than child B, child A is likely to have a higher blood lead level than child B at time 2 as well. Thus, children's rank ordering tends to be similar over time even though, in absolute value, blood lead level rises and falls over the course of childhood. Again, however, the degree of intra-individual stability varies from cohort to cohort. In the Boston Study cohort, for instance, the extent was

limited; likely, it was due to the generally low blood lead levels of the children (Rabinowitz et al., 1984).

A blood lead level measured after 36 months of age will, on average, be lower than the blood lead level that would have been measured if a child's blood been sampled sometime during the 18 to 36 month period. Suppose, however, that the critical period with regard to producing an adverse health outcome is the 18 to36 month period, and that, in a study conducted post-36 months, an inverse association is noted between concurrent blood lead level and a health endpoint. If the concurrent blood lead level is the only index of lead exposure history available, basing a dose-effect assessment on it will, to the extent that the natural history of blood lead levels in the study cohort follows the canonical form illustrated above, result in an underestimate of the blood lead level responsible for any adverse health effects noted at the time of or subsequent to blood sampling. In other words, one will conclude that adverse health effects occur at lower blood lead levels than is the case. For instance, assume that the inverse association shown in Figure 6 holds between IQ and concurrent blood lead in a cross-sectional study of 6 year olds.

If, however, the blood lead level of each child was, on average, 5 µg/dL greater at age 2 than at age 6, and age 2 is the time of greatest toxicologic significance (i.e., it is age at which lead exposure produced the IQ deficit observed at age 6), then the dose-effect relationship that underlies the association seen at age 6 would be more accurately described as in Figure 7.

This dataset would thus not be informative with respect to the functional form of the dose-effect relationship at levels below 10 µg/dL insofar as (hypothetically) all children had a blood lead level greater than 10 at age 2.

Other uncertainties apply to interpreting blood lead-health associations (or lack of associations) observed at any point in time. First, the relation of age to vulnerability to lead toxicity is not well understood. Is blood lead level during the age period 18 to 36 months more toxicologically critical than a measure of cumulative lifetime exposure, such as the area under the curve or some other exposure index? Also, it is possible that the critical age varies with dose, health endpoint, or sociodemographic factors. Available studies do not provide consistent answers to these questions. For example, in the Boston cohort, blood lead at age 24 months was most strongly related to IQ at age 10 years (Bellinger et al,1992), while in the Port Pirie Cohort, the lifetime average blood lead level through age 5 years was most predictive of IQ at age 11 to 13 years.

If 18- to 36 months is the critical age of exposure, it should, in theory, be possible to "adjust" an observed blood lead distribution measured at age 6 by some function to reflect the downward trend in blood lead level with age and estimate the blood lead distribution at, e.g. age 2. It seems unlikely that a "one size fits all" adjustment would be appropriate for all children. Moreover, the appropriate adjustment is likely to be study site-specific (i.e., depend on the key exposure sources and pathways of a particular study cohort).

It would be possible to get a general sense of how accurately past peak exposure can be estimated for children in cross-sectional studies by using data collected in prospective studies in which blood lead was measured frequently during the period spanning birth to school-age. Examining the distribution of the differences between blood lead levels measured at ages 18 to 36 months and at age 6 would suggest the amount of exposure misclassification that would result from applying a constant adjustment factor.

Conclusions: Because of age trends in blood lead and the tendency of blood lead levels to "track" within individual children, inferences drawn from cross-sectional blood lead-health associations at a given age should be interpreted cautiously because of to the influence of likely higher blood lead levels occurring earlier in life. It may be possible to apply data on age trends and within-subject correlation of blood lead to estimate from an observed blood lead – health association the approximate relation to blood lead levels at an earlier age. However, because of differences between study populations in age trends and "tracking," any estimate of the earlier blood lead distribution will have considerable uncertainty. If the only relevant studies available based on cross-sectional data, such as the NHANES III, age trends and "tracking" of blood lead levels would represent a serious challenge to inferring a causal link between blood lead levels < 10 µg/dL and adverse health impacts. However, recently published results from two cohort studies (Canfield et al. 2003; Bellinger et al. 2003) showed inverse associations of BLLs measured early in life (6 to 24 months and 24 months, etc.) and later IQ among children whose measured BLL did not exceed 10 µg/dL. This makes it unlikely that associations observed in cross-sectional studies cited in this report are due solely to the impact of higher blood lead levels experienced earlier in life.

Quality of neurobehavioral assessments

As with blood lead (exposure) measurements, the accuracy, precision, and consistency of neurobehavioral assessments can influence observed blood lead-outcome relations. In order to judge whether the data from a study should be considered in characterizing the functional form of the dose-effect relationship at blood lead levels below 10 µg/dL, one would like to have access to the following information about the conduct of the neurobehavioral assessments:

- Assurance that examiners were blinded to all aspects of children's lead exposure histories.

- The assessment setting. Assessments can be standardized when carried out in a hospital, neighborhood health center, or community center, but may be difficult to standardize in a participant's home.

- Essentials of the process by which an examiner was trained, including the criterion used to certify an examiner (e.g., % agreement on an item-by-item basis with some gold standard, average difference in scores assigned compared to gold standard, correlation with gold standard in terms of scores assigned).

- The plan implemented for supervision of test administration over the course of data collection (e.g., periodic observation of test sessions, live or by videotape)

- The plan implemented for supervision of test scoring over the course of data collection (e.g., doubling scoring of a sample of protocols).

- The number of neurobehavioral examiners used over the course of data collection

- If more than one assessor was used, whether data analysis plan included evaluation of an "assessor" effect (i.e., as a main effect, as a modifier of lead's association with endpoints).

The Practice Committee of the American Academy of Clinical Neuropsychology, supports the use of non-doctoral level personnel in data collection for clinical neuropsychological evaluations (Brandt et al. 1999). While some have argued that neurobehavioral examiners should have professional qualifications (e.g., Kaufman, 2001, cites the need for a clinician with graduate-level training in psychometrics, neuropsychology, etc,), with rigorous training, supervision, and quality control, non-professionals can obtain good quality data.

Assuming blinding of examiners to blood lead levels, most problems with quality of neurobehavioral assessment would be expected to mask or underestimate true associations rather than create spurious ones. It is possible, for example, that use of non-professional examiners might introduce noise into the data, masking an association between toxicant exposure and performance. In one study of methyl mercury (MeHg) exposure (Grandjean et al., 1997), MeHg was inversely associated with children's scores on the Similarities subtest of the WISC-III among children tested by the supervising, PhD-level psychologist but not among children tested by the research assistant. On the other hand, it is difficult to imagine how use of non-professional examiners could introduce a positive bias in effect estimates (assuming that blinding was preserved).

Measurement quality problems causing bias of associations away from the null, without loss of blinding, are theoretically possible. If one examiner, for example, consistently yields lower scores than another and that examiner, without knowledge of blood lead, is assigned to assessments of a segment of the study population at higher risk for lead exposure. A spurious inverse association could be created between lead level and neuropsychological test scores.

Conclusions: The key considerations in judging the quality of neurobehavioral assessments in the research setting are the blinding of examiners to lead exposure history, the training and supervision of examiners, and the setting for examinations. If examiners are truly blinded, other data quality problems will generally bias estimated blood lead-outcome relations toward the null. Given that examiners were noted to blinded to blood lead levels cohort studies demonstrating associations (see Table 6) and the NHANES III survey, errors in measurement of

neuropsychological function are unlikely to have contributed to observed associations with blood lead levels < 10 µg/dL.

Potential Confounding Factors

Social Factors

Because socioeconomic factors influence both lead exposure and measured intelligence, the potential for reported subtle effects of lead on IQ and related measures of intellect to be attributable to confounding by socioeconomic factors warrants serious consideration (Bellinger et al., 1989). Key relations required for confounding to occur are almost certainly present – socioeconomic status (SES) has been shown to be related to blood lead levels, presumably because the neighborhoods and homes in which families of lower income reside are associated with higher levels of lead in soil and residences. Socioeconomic status is also clearly relateed to measures of intelligence, whether through parental stimulation, nutrition, or resources available in the home. With an inverse relationship between socioeconomic factors and lead levels (higher socioeconomic status predictive of lower lead levels) and a positive relationship between socioeconomic factors and measures of intelligence (higher socioeconomic status predictive of higher intelligence test scores), failure to adjust for the confounding effect of socioeconomic factors will result in confounding that overstates the harmful effect of lead on IQ because the socioeconomic effect will be mixed with any true effect of lead exposure. Confounding by social factors may be a concern for some other lead-associated health measures with social gradients such as height (Silventoinen 2003).

Data presented from most of the key studies strongly suggest that there is substantial confounding by socioeconomic factors, and even with adjustment for crude measures such as parental education and household income (Lanphear et al. 2000), the apparent lead effect on cognitive function is greatly reduced. Such a pattern in which adjustment for a crude proxy results in a substantial decrement in the magnitude of association would suggest that "residual confounding" may be present in the adjusted estimate of effect. If residual confounding is indeed present, then tighter control for confounding with more refined measures of the social environment, the apparent effect might well be further attenuated or eliminated (Savitz et al. 1989).

The following factors complicate this scenario:

1) Socioeconomic status is a very elusive construct to fully capture, far more complex than is reflected in parental education or income. It includes many aspects of economic means and associated lifestyle, so that adjustment for operational measures such as education or income is certain to be incomplete. Adjustment for an imperfect proxy measure of a confounder results in residual confounding (Greenland et al. 1985; Savitz et al. 1989).

2) As discussed above (see blood lead tracking), long-term lead exposure is imperfectly reflected in a current blood lead measure (Bellinger et al., 1989) or to

> some extent, even from a series of blood lead measures. Whatever physiologic effect it might produce, available evidence suggests that the impact is chronic and cumulative. Beyond what is reflected in a blood lead measure, socioeconomic status may be indicative of historical exposure and thus the observed effect of socioeconomic status would partly reflect an effect of lead exposure above and beyond the blood lead measure.

With a focus on blood lead levels of <10 µg/dl, the nature and magnitude of these associations is less clear. Measures of social advantage, including income and parental education, are associated with blood lead levels within the range of <10 µg/dl (e.g. Lanphear et al, 2000). But the relative importance of different aspects of socioeconomic status and the pathways by which they affect lead exposure are not entirely clear. It appears that the association between lower income and deterioration of paint in older housing contributes to variation in blood lead levels even in the range < 10 µg/dL. The increase in geometric mean blood lead associated with living in an older home is greater for children from low compared to middle income families (Pirkle et al, 1998). Nonetheless, with the elimination of lead in gasoline some time ago and the continued decline in the proportion of homes with leaded paint (Jacobs et al, 2002), it is possible that the relative importance of lead exposure sources is changing. It is also possible that the association of social factors with lead exposure is different for populations with blood lead levels < 10 µg/dL than for those above that threshold.

Several strategies have been applied to address the role of socioeconomic factors and isolate a non-specific effect of socioeconomic factors on IQ from an effect of lead exposure. First, populations can be sought or even constructed in which blood lead is not closely associated with socioeconomic status as demonstrated most clearly in the Boston cohort (Bellinger et al., 1987). In that population, all in a relatively low blood lead range for that time and the great majority of relatively advantaged socioeconomic status, there was a weak positive gradient between socioeconomic status and lead. The Kosovo cohort (Wasserman et al.1997) also departed from the usual trend in that the more socioeconomically advantaged of the two communities studied was the site of a lead smelter. As a result, adjustment for social and other covariates actually strengthened inverse relation of blood lead to IQ in that population.

Second, improved measures of socioeconomic factors have been applied to better control for non-specific effects. That is, by refining and decomposing the construct of socioeconomic status, it is possible to more fully adjust for the confounding dimensions such as nutrition, parental stimulation, attitudes towards achievement, etc., and not adjust for the aspects that primarily serve as a proxy for lead exposure, such as age of housing and neighborhood. One example among published research of refining and decomposing the construct of socioeconomic status, has been the use of the HOME scales to adjust for stimulation provided by caregivers. Use of HOME scales has in some cases further attenuated but not eliminated apparent lead-IQ associations.

A third approach has been to examine the possibility of confounding of the blood lead-IQ relation at low levels would be to conduct a formal statistical assessment of the extent to which the strength of the observed association across studies is varies in relation to control for relevant

confounders, using meta-regression, as was applied by Schwartz (1994). This approach could be refined to assess possible residual confounding. One challenge in performing such an analysis using published summary data is the difficulty in operationalizing measures of the tightness of SES adjustment while controlling for other aspects of study design that might influence blood lead- IQ slopes. An alternative approach is discussed in the research recommendations section.

Conclusions: On the basis of available evidence, it is likely that the observed associations between blood lead and cognitive function below 10 µg/dL are, at least in part, causal. This conclusion is supported by the following: 1) the studies showing the strongest relationship (Canfield et al. 2003; Bellinger et al. 2003) at low levels employed the HOME scale for adjustment, the best available measure for assessing the impact of the home environment on child development; 2) two cohorts, Kosovo and Boston, in which strong relations of blood lead to IQ have been found were characterized by a direct, rather than inverse, correlation of blood lead with social advantage; 3) diversity of geographic and social settings in which associations of children's blood lead and intelligence have been seen at blood lead levels – in both cases close to 10 µg/dL; and 4) animal data demonstrating effects of lead at blood lead levels near 10 µg/dL. At this point, the case for residual confounding by social environment is speculative, but available studies relating blood lead to cognitive function in children cannot entirely exclude the possibility that observed associations are at least partly influenced by it. Such a possibility does increase uncertainty about the actual strength and shape of blood-lead relationships at blood lead levels less than 10 µg/dL.

Iron Status

Iron deficiency could confound the relation of blood lead to neurodevelopmental status in some populations. The likelihood of such bias is related to the extent to which iron status was controlled in a given study and the prevalence of iron deficiency in a study population. Iron deficiency may impair neurodevelopment in a manner similar to low-level lead exposure and the populations at increased risk for iron deficiency and lead toxicity may overlap (Lozoff et al. 1991; Wasserman et al. 1999). However, the association between iron deficiency and blood lead is not consistent across populations (CDC, 2002). Therefore, the potential for iron to confound an association of blood lead with neurodevelopmental status will vary across populations, depending on both the prevalence of iron deficiency and its association with blood lead level.

Clinically, adequate assessment of iron status entails determination of hemoglobin or hematocrit and at least two other measures of iron status. Generally accepted definitions of iron deficiency and iron deficiency anemia depend on age- and sex-specific normal ranges. The iron status measures most commonly used are mean corpuscular volume (MCV), free erythrocyte protoporphyrin (FEP) or zinc protoporphyrin (ZPP), transferrin saturation, ferritin, and, more recently, transferrin receptor. The standard for defining iron deficiency is values indicating iron deficiency on at least two of these measures and/or response to iron therapy with an increase in hemoglobin to at least 10 g/L. The utility of ferritin in young infants is under debate, making it important that functional measures, such as MCV or ZPP be obtained. There are limitations of each measure (e.g., ferritin goes up with infection, MCV is down in hemoglobinopathies, etc.).

Although iron deficiency with low hemoglobin has been associated with later impairment of cognitive function, it is not certain which measure(s) of iron status are most strongly related to neurodevelopmental outcomes. The most consistent finding across longitudinal studies of children is the finding that anemia in early childhood is associated with poorer performance on tests of cognitive and motor development at school age (Grantham-McGregor et al. 2001). Thus, based on available evidence, measurement of hemoglobin would seem to be the single best predictor of iron deficiency-related neurodevelopmental problems. In studies of children with higher BLLs, controlling for hemoglobin is problematic because lead toxicity can reduce hemoglobin in the normal range or cause frank anemia. This is less of a concern in studies of children with blood lead levels < 10, a range in which no meaningful impact on hemoglobin levels has been observed.

Conclusions: Measurement of iron deficiency has been absent or suboptimal in most of the studies reviewed. Two studies in which iron status was controlled for using tranferrin saturation (Canfield et al, 2003) and serum ferritin (Lanphear et al. 2000) found strong inverse relations of blood lead to cognitive function, while a third study that controlled for the presence of iron deficiency anemia found the opposite (Wolf et al. 1994). Furthermore, iron deficiency anemia is the measure of iron status most clearly linked to impaired cognitive function, and it seems unlikely that the prevalence of iron deficiency anemia could be high enough in the populations showing the strongest inverse relations of blood lead to cognitive function (Canfield et al. 2003; Bellinger et al 2003; Lanphear et al. 2000) to entirely explain these associations. Finally, in Kosovo, following treatment of iron deficient children with iron supplements, no association of earlier hemoglobin levels with IQ at age 4 (Wassserman et al. 1994) or age 7 (Wasserman et al. 1997) was found. Thus it is unlikely that inverse associations between blood lead levels < 10 µg/dL and cognitive function are explained completely by iron deficiency.

Tobacco

Blood lead levels in children have been associated with exposure to environmental tobacco smoke (assessed by caregiver report or by urinary cotinine levels) in both general population surveys (Stromberg et al., 2003; Mathee et al., 2002; Lanphear et al., 2000) and in studies of children living near lead smelters (Willers et al.,1988; Baghurst et al., 1992; Baghurst et al., 1999). The explanation for this association is not entirely clear; possibilities include enhancement of lead uptake by environmental tobacco smoke (ETS), exposure to lead in ETS itself, or differences in cleaning practices or child supervision between households with and without smokers.

Maternal smoking during pregnancy has been associated with behavior problems and impaired cognitive development in children; fetal hypoxia is one possible contributing mechanism (Habek et al. 2000). Evidence for an effect of pre- or postnatal ETS exposure on neurodevelopment is less clear (Eskenazi et al. 1999). As with studies of lead and neurodevelopment, social factors may confound, at least in part, the association between maternal smoking and neurodevelopment (Baghurst et al. 1992). A child's prenatal exposure to maternal smoking or pre- or postnatal exposure to ETS could, if these are causally related to impaired neurodevelopment or other adverse health outcomes, confound the observed

associations of lead and health. In addition, if a relation between postnatal ETS and neurodevelopment is established, it is possible that lead exposure is a mediating factor.

Conclusions: Among the studies reviewed, most did not assess pre- or postnatal ETS as a possible confounding factor. Those that assessed tobacco at all controlled for maternal smoking during pregnancy. However, the two exceptions, Lanphear et al (2000) in which serum cotinine measurements were used to control for ETS and a study based on the Port Pirie cohort (Tong et al. 1996; Baghurst et al. 1992) in which reported postnatal parental smoking, provide no evidence that confounding by tobacco exposure accounts for the associations observed between blood lead and adverse health effects. Limitations in available studies leave some uncertainty as to what contribution, if any ETS might make to observed associations between BLL and health.

Causal Direction

Inference of causation from observational epidemiologic studies is sometimes complicated by the possibility that the health outcome under study could be a cause of the exposure or causally related to a third factor which itself is a cause of the exposure under study. Two possibilities are relevant to studies of the health effects of lead at low level.

Mouthing behavior

An important pathway of lead uptake by yong children is ingestion of lead-contaminated dust (Charney et al. 1980; Bornschein et al, 1985), presumably through mouthing of hands, surfaces, and objects on which the dust is deposited. Although mouthing behavior is difficult to measure, children with more reported mouthing behavior have higher blood lead levels in relation to environmental lead exposure (Lanphear et al. 1998; Bellinger et al. 1986; Baghurst et al. 1999). Pica (purposeful ingestion of non-food items) can be a consequence of impaired neurodevelopment and predispose to lead ingestion (Cohen et al. 1976; McElvaine et al. 1992), but the relation of variation in "normal" age-appropriate mouthing behavior to neurodevelopment is uncertain. However, in groups of children, average measured or caregiver reported mouthing has been shown to diminish with age (Juberg et al., 2001; Tulve et al., 2002). Nonetheless, it is unclear whether, at the individual level, more frequent mouthing behavior is a marker (independent of its effect on lead ingestion) for delayed neurodevelopment. If it were, then an association between blood lead level and impaired neurodevelopment would result, and failure to adjust for mouthing behavior would result in an overestimate of the blood lead effect. On the other hand, if measured mouthing behavior is associated with cumulative lead exposure above and beyond that reflected in measured blood lead levels, then controlling for mouthing behavior could amount to over control, underestimating the true effect of lead on neurodevelopmental measures.

Conclusions: At this point, no direct evidence supports reverse causation by mouthing behavior, and this hypothesis remains speculative. Arguing against this possibility, Tong et al. (1996) reported that an early measure of neurocognitive development, the Bailey MDI, was not predictive of later blood lead levels.

Calcium balance

Calcium balance changes in relation to growth during childhood and during the rapid expansion of bone mass during puberty and the pubertal growth spurt (Bronner et al, 1998; van Coeverden et al. 2002; Bailey et al, 2000); estradiol may influence bone mineral deposition in pubertal girls (Cadogan, 1998). It is possible that effect of skeletal growth and puberty on calcium balance could cause lower blood lead levels (Thane et al. 2001), just as the opposite changes in calcium balance during menopause appear to cause an increase in blood lead (Hernandez-Avila et al. 2000; Garrido Latorre et al. 2003).

Conclusions: Because human studies linking blood lead at levels < 10 µg/dL to delayed puberty and smaller stature are, with one exception, cross-sectional and evidence is limited on this topic, reverse causation via changes in calcium balance can not be ruled out as accounting for at least some of the observed associations.

Overall Conclusions

Because of the large number of studies that have assessed cognitive function as an outcome, the WG review and conclusions focus to a great extent on this health domain. The consensus of the WG is that the overall weight of available evidence supports an inverse association between blood lead levels in the range less than 10 µg/dL and the cognitive function of children and that the association more likely than not reflects, at least in part, a causal relation. However, the WG also concluded that the available evidence has a number of important limitations, including likely residual confounding by social environment, that raise uncertainty about the absolute strength and shape of the causal relation. Because of this, associations observed in the relevant population studies cannot be applied with any confidence to interpretation of BLLs measured in individual children at a single point in time. Thus, the WG does not believe that the individual children can be classified as "lead poisoned," as the term is used in the clinical setting, on the basis of the associations observed in studies reviewed for this report. The basis of the overall WG conclusions is discussed below and is followed by a summary of the important limitations in the available evidence.

This evidence for an adverse impact of BLLs < 10 µg/dL on cognitive function is bolstered by the consistency across both cross sectional and longitudinal studies in varied settings and by the lack of any trend towards a weaker association in studies with lower population mean blood lead levels. More recent studies and analyses best suited to examining this association (Canfield et al. 2003; Bellinger et al. 2003) have added to, rather than refuted, evidence for such an association noted in prior CDC guidance (1991). The WG explored other possible explanations (aside from causation) for these associations and concluded that none are likely to fully explain the observed data. The context of evidence from animal, in vitro, and human studies of adult populations, also supports the consensus of the WG conclusion that the observed associations most likely represent, at least in part, causal adverse impacts of lead on children's cognitive function at blood lead levels less than 10 µg/dL.

The greatest source of uncertainty in interpreting the relation of BLLs < 10 µg/dL to cognitive function is the potential for residual confounding by social factors. The conditions for residual confounding appear to be present: BLLs are strongly influenced by SES, SES is clearly related to measured cognitive function, and social factors that could influence BLL and cognitive function are difficult to measure precisely. Other sources of potential bias are, individually, less concerning than social confounding, but collectively they add to the overall uncertainty about the absolute strength and shape of the relation of BLL to impaired cognitive function. These include, random error in blood lead measurement and in a single BLL as a measure of chronic exposure, possible influence of factors that have not been fully addressed in published studies, including blood lead tracking and age trend, which limits cross-sectional studies in particular, tobacco smoke exposure, iron deficiency, and mouthing behavior. Error in measuring lead exposure would bias observed associations towards the null, while failure to adjust for the other factors noted would most likely bias observed associations away from the null.

The recently reported trend of asymptotically increasing slopes of lead-associated decrements in cognitive test scores at lower BLLs (Bellinger et al. 2003; Canfield et al. 2003; Lanphear et al. 2000) would be expected if residual confounding were operative as illustrated in figure 8. The graph on the left depicts a comparison of two groups of children who live in a high exposure setting. They differ, on average, with respect to aspects of the home and social environment that are not captured in measured covariates. This results in one group ingesting and absorbing twice as much lead and having, after adjustment for measured covariates, a mean IQ 1 point lower than the children raised in a more favorable environment. Assuming a roughly linear relation of lead intake to blood lead, the result is that one group has a mean blood lead twice as high, corresponding to a 10 µg/dL difference in blood lead and an estimated blood lead-IQ slope attributable to residual confounding of 0.1 IQ points per µg/dL. The figure on the right depicts the same hypothetical two populations living in a low exposure setting. The same imperfectly measured differences in social environment contribute to the equivalent covariate-adjusted difference in mean IQ, but in this case, although one group ingests twice as much contaminated dust as before, lower levels of lead contamination result in the two children having a blood lead difference of only 1 µg/dL in blood lead level. The result is an estimated blood lead-IQ slope attributable to residual confounding of 1.0 IQ points per µg/dL. In addition, a convincing and directly relevant biologic mechanism for such a dose response relation has yet to be demonstrated. Though this hypothetical example cannot demonstrate that residual confounding underlies the steep blood lead- IQ slopes observed at low levels, it does support the need for caution in interpreting the absolute value of the estimated effect sizes.

For other health endpoints other than cognitive function, including other neurologic functions, stature, sexual maturation, and dental caries available data favors associations consistent with adverse health effects at blood lead levels < 10 µg/dL. The available data for these other health endpoints, taken mostly from cross-sectional studies, are more limited and firm conclusions concerning causation cannot be made at this time.

Research Needs

Resolving residual confounding through observational studies

It may be somewhat easier to locate or configure populations in the <10 µg/dL range in which socioeconomic factors are not associated with exposure as compared to studies in a higher range in which more advantaged persons may be rare above 20 or 30 µg/dL. Configuring a cohort similar to the one in Boston or assembling one from the pieces of others already studied could be helpful in isolating socioeconomic and lead effects from one another. Another formal statistical approach that could be applied to pooled data across multiple studies is the application of a hierarchical modeling approach as proposed by Schwartz et al. (2003, in press).

Controlled intervention trials

While experimental designs can establish causation with greater confidence than observational studies, it would be unethical to intentionally expose some children to higher blood lead levels in a randomized controlled design. However, randomized trials in which interventions are tested for their ability to reduce BLLs in the range < 10 µg/dL or prevent their increase provide an opportunity to support or refute a causal relation of BLLs < 10 µg/dL to adverse health outcomes. Studies testing such interventions should measure covariates relevant to assessing health effects, allowing a test of the causal hypothesis should they be successful at sufficiently reducing blood levels.

Animal and in vitro studies to explore mechanisms and dose-response relations

While the overall evidence from animal or in vitro models supports the biologic plausibility of adverse effects of lead at blood lead levels < 10 µg/dL, the WG is unaware of directly relevant animal or in vitro studies that demonstrate a steeper slope for adverse effects of lead exposure at lower blood lead levels than observed at higher levels. Demonstrating such a relationship in experimental studies and identifying possible mechanisms would increase confidence in a causal interpretation of the observed blood lead-response relations in studies such as Canfield et al. (2003).

Table 1. Lowest blood lead level (BLL) considered elevated by CDC and the US Public Health Service

Year and Reference	BLL (μg/dL)
1971 (Surgeon General)	40
1975 (CDC)	30
1978 (CDC)	30
1985 (CDC)	25
1991 (CDC)	10

Table 2. Summary of studies estimating association of postnatal PbB with Cognitive Function

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Study Population* (ref., type, n)	PbB Age	Outcome Age #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
	(<= 2 years)	(>= 4 years)												
Kosovo (193, L ,332)	24 months	# 4 years	21.8 (GM)	not stated	-5 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home
Port Pirie (13, L ,537)	24 months	# 4 years	21.3 (GM)	-12.3 (log10)^	-5.3 (log10)^	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight, Gestation	Marital Status, Maternal Age	unspecified		Mother		Postnatal Factors, Birth Order, Birth Type, Birth Problems, Child's Sex, Residence in Regions, Medication Used by Child, Child's Medical History, mother's work site
Port Pirie (13, L ,537)	15 months	# 4 years	20.9 (GM)	-6.8 (log10)^	-1.7 (log10)	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight, Gestation	Marital Status, Maternal Age	unspecified		Mother		Postnatal Factors, Birth Order, Birth Type, Birth Problems, Child's Sex, Residence in Regions, Medication Used by Child, Child's Medical History, mother's work site
Port Pirie (5, L ,367)	15 months	11-13 years	20.9 (GM)	-6.8 (ln)^	-2 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Port Pirie (37, L ,494)	Lifetime avg. 2 years	7 years	16.6-20.5 (means of 2nd & 3rd quartiles) (GM)	not stated	-5.1 (ln)^	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Kosovo (193, L ,332)	18 months	# 4 years	20.0 (GM)	not stated	-2.3 (log10)	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home

= McCarthy GCI, all unmarked are full-scale IQ measures.
* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis.
^ statistically significant (p < 0.05)

Study Population* (ref., type, n)	PbB Age	Outcome Age #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
Port Pirie (37, L ,494)	Lifetime avg. 15 months	7 years	14.3-18.0 (means of 2nd & 3rd quartiles) (GM)	not stated	-4.4 (ln)^	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Kosovo (193, L ,332)	12 months	# 4 years	17.2 (GM)	not stated	-3.6 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home
Cincinnati (2, L ,253)	Mean 15-24 months	6.5 years	17.1	-1.3	-0.2		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Cleveland (4, L ,149)	2 years	4 years 10 months	16.70	r=-.38^	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Sydney (7, L ,318)	Mean 18,24 months	# 48 months	15.8 (GM)	not stated	not stated	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.		Gestation		total 48 mo		Mother		
Sydney (7, L ,318)	Mean 6,12 months	# 48 months	15.2 (GM)	not stated	not stated	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.		Gestation		total 48 mo		Mother		
Kosovo (193, L ,332)	6 months	# 4 years	15.0 (GM)	not stated	-2 (log10)	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home

= McCarthy GCI, all unmarked are full-scale IQ measures.
* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis.
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
Port Pirie (13, L ,537)	6 months	# 4 years	14.5 (GM)	-7.2 (log10)^	-4.1 (log10)	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight, Gestation	Marital Status, Maternal Age	unspecified		Mother		Postnatal Factors, Birth Order, Birth Type, Birth Problems, Child's Sex, Residence in Regions, Medication Used by Child, Child's Medical History, mother's work site
Costa Rica (22, L ,184)	12-23 months	5 years	11.0	r=+.06	not stated									
Cincinnati (2, L ,253)	Mean 3-12 months	6.5 years	10.6	-2.2	0.1		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Mexico City (17, L ,112)	Mean 6-18 months	# 36-60 months	10.1 (GM)	not stated	mean square = 87.81 (neg) (ln)	Family socioeconomic level, Mat. Edu.		Birth Weight				Mother		Postnatal Factors, Birth Order, Child's Sex
Cleveland (4, L ,122)	6 months	4 years 10 months	9.99	r=-.06	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Boston (20, L ,170)	18 months	# 57 months	8.0	-3.3 (ln)^	-1.8 (ln)	Hollingshead index of Social Class		Birth Weight	Family Structure, Marital Status, Res Changes, Day Care	total	Child	Mother		Birth Order, Child's Sex, School Grade, Medication Used by Child
Boston (20, L ,170)	12 months	# 57 months	7.8	-2.4 (ln)	-1.6 (ln)	Hollingshead index of Social Class		Birth Weight	Family Structure, Marital Status, Res Changes, Day Care	total	Child	Mother		Birth Order, Child's Sex, School Grade, Medication Used by Child

= McCarthy GCI, all unmarked are full-scale IQ measures.
* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis.
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
Boston (1, L ,116)	18 months	10 years	7.8	-2.8	-1.2	Hollingshead Four-Factor Index of Social Class			Family Stress, Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	12 months	10 years	7.7	-2	0	Hollingshead Four-Factor Index of Social Class			Family Balance, Family Stress, Marital Status	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Parents' Sense Competence, Birth Order, Child's Sex
Boston (20, L ,170)	24 months	# 57 months	7.0	-3.4 (ln)^	-3.2 (ln)^	Hollingshead index of Social Class		Birth Weight	Family Structure, Marital Status, Res Changes, Day Care	total	Child	Mother		Birth Order, Child's Sex, School Grade, Medication Used by Child
Rochester (19, L ,172) [all]	avg in infancy - 6-24 months	5 years	7.0	-9.7^	-5.3^	yearly household income, Mat. Edu.	Tobacco use during pregnancy (user/nonuser)	Birth Weight		total	Mother	Mother	serum transferrin saturation	Child's Sex
Boston (20, L ,170)	6 months	# 57 months	6.8	0.3 (ln)	0.3 (ln)	Hollingshead index of Social Class		Birth Weight	Family Structure, Marital Status, Res Changes, Day Care	total	Child	Mother		Birth Order, Child's Sex, School Grade, Medication Used by Child
Boston (1, L ,116)	6 months	10 years	6.7	-2	-1.3	Hollingshead Four-Factor Index of Social Class			Marital Status	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	24 months	10 years	6.5	-7.1^	-5.8^	Hollingshead Four-Factor Index of Social Class			Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Cincinnati (2, L ,253)	10 Days	6.5 years	5	-1	-0.3		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex

= McCarthy GCI, all unmarked are full-scale IQ measures.
* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis.
^ statistically significant (p < 0.05)

Study Population* (ref., type, n)	PbB Age	Outcome Age #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
Boston (219, L ,not stated)	24 months	10 years	not stated	not stated	-15.6^									
Boston (214, L ,148)	24 months	10 years	< 8	not stated	-5.8^	Hollingshead Four-Factor Index of Social Class			Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Rochester (19, L ,105) [<10 group]	avg in infancy - 6-24 months	5 years	not stated	-15.8^	-9.2	yearly household income, Mat. Edu.	Tobacco use during pregnancy (user/nonuser)	Birth Weight		total	Mother	Mother	serum transferrin saturation	Child's Sex
	(>2 - <4 years)	(>= 4 years)												
Kosovo (193, L ,332)	36 months	# 4 years	24.1 (GM)	not stated	-4.5 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home
Kosovo (193, L ,332)	42 months	# 4 years	23.2 (GM)	not stated	-5 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home
Kosovo (193, L ,332)	30 months	# 4 years	22.1 (GM)	not stated	-4.6 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home
Port Pirie (37, L ,494)	Lifetime avg. 3 years	7 years	17.4-21.7 (means of 2nd & 3rd quartiles) (GM)	not stated	-5.3 (ln)^	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Port Pirie (13, L ,537)	36 months	# 4 years	19.5 (GM)	-12 (log10)^	-6.3 (log10)^	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight, Gestation	Marital Status, Maternal Age	unspecified		Mother		Postnatal Factors, Birth Order, Birth Type, Birth Problems, Child's Sex, Residence in Regions, Medication Used by Child, Child's Medical History, mother's work site

= McCarthy GCI, all unmarked are full-scale IQ measures.
* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant (p < 0.05)

Study Population* (ref., type, n)	PbB Age	Outcome Age #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
Port Pirie (5, L ,372)	3 years	11-13 years	19.3 (GM)	-10.8 (ln)^	-4.2 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Cleveland (4, L ,155)	3 years	4 years 10 months	16.70	r=-.31^	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Cincinnati (2, L ,253)	Mean 27-36 months	6.5 years	16.3	-2.6^	-1.3		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Sydney (7, L ,318)	Mean 30,36 months	# 48 months	12.4 (GM)	not stated	not stated	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.		Gestation		total 48 mo		Mother		
Mexico City (17, L ,112)	Mean 24-36 months	# 36-60 months	9.7 (GM)	not stated	mean square = 101.62 (neg) (ln)	Family socioeconomic level, Mat. Edu.		Birth Weight				Mother		Postnatal Factors, Birth Order, Child's Sex
Port Pirie (5, L ,326)	Lifetime avg. 3 years	11-13 years	not stated	-10.4 (ln)^	-4.7 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Kosovo (193, L ,332)	48 months	# 4 years	25.1 (GM)	not stated	-4.5 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex, language spoken in home

= McCarthy GCI, all unmarked are full-scale IQ measures.
* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis.
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
Lavrion, Greece (21, X ,509) [cov. model b]	primary school children - not specified years	primary school children - not specified years	23.7	-3.76^	-2.66^	Mat. Edu., Pat. Edu., Pat. Occ.			Family Structure			Both		Birth Order, History Alcohol Abuse, father's age
Lavrion, Greece (21, X ,509) [cov. model c]	primary school children - not specified years	primary school children - not specified years	23.7	-3.76^	-2.7^	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight	Family Structure, Marital Status, Life Events			Both		Birth Order, Birth Problems, Child's Age, Child's Medical History, History Alcohol Abuse, father's age, bilingualism
Lavrion, Greece (21, X ,509) [cov. model d]	primary school children - not specified years	primary school children - not specified years	23.7	-3.76^	-2.6^	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight	Family Structure, Marital Status, Life Events			Both		Birth Order, Birth Problems, Child's Sex, Child's Age, Residence in Regions, Child's Medical History, History Alcohol Abuse, Mouthing Behavior, father's age, bilingualism
Lavrion, Greece (21, X ,509) [cov. model e]	primary school children - not specified years	primary school children - not specified years	23.7	-3.76^	-2.4^	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight	Family Structure, Marital Status, Life Events			Both		Birth Order, Birth Problems, Child's Age, School Grade, Child's Medical History, History Alcohol Abuse, father's age, bilingualism
Port Pirie (37, L ,494)	Lifetime avg. 4 years	7 years	17.6-21.5 (means of 2nd & 3rd quartiles) (GM)	not stated	-5.1 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Port Pirie (37, L ,494)	Lifetime avg. 7 years	7 years	15.7-19.7 (means of 2nd & 3rd quartiles) (GM)	not stated	-4.1 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex

= McCarthy GCI, all unmarked are full-scale IQ measures.
* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant (p < 0.05)

ne #	ne #	Mean PbB (ug/dL)	Estimated Delta for PbB 5 -> 15		Covariates in Model								
			Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental Intelligence	Iron Status	Other
		19.4	r=-.33 (ln)^	r=-.32 (ln)^	income, Mat. Edu., Pat. Edu.								Child's Sex, Assessment Site, Child's Medical History
		17.1 (GM)	not stated	-5.3	Mat. Edu., Pat. Occ.								Child's Sex, Child's Age
		16.4 (GM)	-9.6 (log10)^	-2.6 (log10)	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight, Gestation	Marital Status, Maternal Age	unspecified		Mother		Postnatal Factors, Birth Order, Birth Type, Birth Problems, Child's Sex, Residence in Regions, Medication Used by Child, Child's Medical History, mother's work site
		16.08	-4.3^	-6.3^								haemoglobin	child's height-for-age
		14.3 (GM)	-9.8 (ln)^	-4.4 (ln)^	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
		14.1 (GM)	-12.7 (ln)^	-4.7 (ln)^	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
		14.0	-3.1^	-1.5		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
		11.8	-4.2^	-2.3^		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex

ll-scall-scale IQ measures.
tionational, M=Meta analysis.

Table 3. Summary of studies estimating association of postnatal PbB with performance scale IQ

DRAFT FOR DISCUSSION PURPOSES ONLY. DO NOT CITE OR QUOTE.

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
	(<= 2 years)	(>= 4 years)												
Port Pirie (5, L ,367)	15 months	11-13 years	20.9 (GM)	-5.7 (ln)^	-0.7 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Port Pirie (37, L ,494)	Lifetime avg. 2 years	7 years	16.6-20.5 (means of 2nd & 3rd quartiles) (GM)	not stated	-2.6 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Port Pirie (37, L ,494)	Lifetime avg. 15 months	7 years	14.3-18.0 (means of 2nd & 3rd quartiles) (GM)	not stated	-2.5 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Cincinnati (2, L ,253)	Mean 15-24 months	6.5 years	17.1	-2^	-1		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Cleveland (4, L ,149)	2 years	4 years 10 months	16.70	r=-.34	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Child Stress, Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Costa Rica (22, L ,184)	12-23 months	5 years	11.0	r=+.05	not stated									
Cincinnati (2, L ,253)	Mean 3-12 months	6.5 years	10.6	-3.9^	-1.6		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Cleveland (4, L ,122)	6 months	4 years 10 months	9.99	r=-.02	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Boston (1, L ,116)	18 months	10 years	7.8	not stated	0	Hollingshead Four-Factor Index of Social Class			Family Stress, Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	12 months	10 years	7.7	not stated	1.4	Hollingshead Four-Factor Index of Social Class			Family Balance, Family Stress, Marital Status	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Parents' Sense Competence, Birth Order, Child's Sex
Boston (1, L ,116)	6 months	10 years	6.7	not stated	0.3	Hollingshead Four-Factor Index of Social Class			Marital Status	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	24 months	10 years	6.5	not stated	-3.9	Hollingshead Four-Factor Index of Social Class			Family Stress, Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Cincinnati (2, L ,253)	10 Days	6.5 years	5	-4	-2.2		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Boston (214, L ,148)	24 months	10 years	< 8	not stated	-3.9	Hollingshead Four-Factor Index of Social Class			Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Port Pirie (37, L ,494)	Lifetime avg. 3 years	7 years	17.4-21.7 (means of 2nd & 3rd quartiles) (GM)	not stated	-3.1 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Port Pirie (5, L ,372)	3 years	11-13 years	19.3 (GM)	-10.3 (ln)^	-4.6 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Cleveland (4, L ,155)	3 years	4 years 10 months	16.70	r=-.28	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Child Stress, Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Cincinnati (2, L ,253)	Mean 27-36 months	6.5 years	16.3	-3.4^	-2.2^		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Port Pirie (5, L ,326)	Lifetime avg. 3 years	11-13 years	not stated	-8.6 (ln)	-3.5 (ln)	Pat. Occ.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
Lavrion, Greece (21, X ,509)	primary school children - not specified years	primary school children - not specified years	23.7	not stated	-2.3	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight	Family Structure, Marital Status, Life Events			Both		Birth Order, Birth Problems, Child's Age, Child's Medical History, History Alcohol Abuse, father's age, bilingualism
Port Pirie (37, L ,494)	Lifetime avg. 4 years	7 years	17.6-21.5 (means of 2nd & 3rd quartiles) (GM)	not stated	-3.6 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Port Pirie (37, L ,494)	Lifetime avg. 7 years	7 years	15.7-19.7 (means of 2nd & 3rd quartiles) (GM)	not stated	-2.5 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Mexico City II (23, X ,139)	7-9 years	7-9 years	19.4	r=-.24 (ln)^	r=-.28 (ln)^	income, Mat. Edu., Pat. Edu.								Child's Sex, Assessment Site, Child's Medical History
Port Pirie (5, L ,368)	5 years	11-13 years	14.3 (GM)	-7.9 (ln)^	-4.1 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Port Pirie (5, L ,326)	Lifetime avg. 11-13 years	11-13 years	14.1 (GM)	-11.9 (ln)	-5.2 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
Cincinnati (2, L ,253)	Mean 39-48 months	6.5 years	14.0	-4.3^	-2.7^		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Cincinnati (2, L ,253)	Mean 51-60 months	6.5 years	11.8	-5.5^	-3.8^		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Port Pirie (5, L ,360)	7 years	11-13 years	11.6 (GM)	-9.4 (ln)^	-4.2 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Sassuolo, Italy (8, X ,211)	7-8 years	7-8 years	10.99 (GM)	r = -0.100 (log10)	not stated									
San Luis Potosi, Mexico (9, X ,39) [reference group]	6-9 years	6-9 years	9.73 (GM)	r=+.04 (ln)	r=-.10 (ln)	Bronffman Index of Socioeconomic Status, Mat. Edu., Pat. Edu.								Child's Sex, Child's Age
San Luis Potosi, Mexico (9, X ,41) [exposed group]	6-9 years	6-9 years	8.98 (GM)	r=-.08 (ln)	r=+.005 (ln)	Bronffman Index of Socioeconomic Status, Mat. Edu., Pat. Edu.								Child's Sex, Child's Age

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Port Pirie (5, L ,326)	11-13 years	11-13 years	7.9 (GM)	-6.8 (ln)^	-2.2 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning	unspecified		Mother		
Boston (1, L ,116)	57 months	10 years	6.3	not stated	-4.4	Hollingshead Four-Factor Index of Social Class		Birth Weight	Family Stress, Marital Status, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	10 years	10 years	2.9	not stated	-1.7	Hollingshead Four-Factor Index of Social Class		Birth Weight	Family Stress, Marital Status, Day Care, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Kosovo (194, L ,261)	Mean AUC7 years	7 years	age7=21.2; cumulative age7=1.21	not stated	-4.5 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex
Port Pirie (5, L ,326)	Lifetime avg. 7 years	11-13 years	not stated	-9.6 (ln)	-4.7 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
Port Pirie (5, L ,326)	Lifetime avg. 5 years	11-13 years	not stated	-9.4 (ln)	-4.8 (ln)	Pat. Occ.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
Cincinnati (2, L ,253)	Mean 66-72 months	6.5 years	not stated	-7.5^	-5.2^		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex

(Other) (Other)

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant (p < 0.05)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Cleveland (4, L ,212)	Mean 0.5 - 3 years	4 years 10 months	9.99 @ 6 months & 16.70 @ both 2 yrs & 3 yrs)	r=-.25	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Cincinnati (2, L ,253)	Lifetime avg. 72 months	6.5 years	not stated	-4.3	-2.6		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant (p < 0.05)

Table 4. Summary of studies estimating association of postnatal PbB with verbal scale IQ

DRAFT FOR DISCUSSION PURPOSES ONLY. DO NOT CITE OR QUOTE.

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
	(<= 2 years)	(>= 4 years)												
Port Pirie (5, L ,367)	15 months	11-13 years	20.9 (GM)	-7 (ln)^	-3.2 (ln)^	Daniel's Scale of Prestige of Occupations in Australia			Family Structure, Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Port Pirie (37, L ,494)	Lifetime avg. 2 years	7 years	16.6-20.5 (means of 2nd & 3rd quartiles) (GM)	not stated	-6.4 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Port Pirie (37, L ,494)	Lifetime avg. 15 months	7 years	14.3-18.0 (means of 2nd & 3rd quartiles) (GM)	not stated	-5.5 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Cincinnati (2, L ,253)	Mean 15-24 months	6.5 years	17.1	-0.3	0.2		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Cleveland (4, L ,149)	2 years	4 years 10 months	16.70	r=-.37	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Costa Rica (22, L ,184)	12-23 months	5 years	11.0	r=+.06	not stated									
Cincinnati (2, L ,253)	Mean 3-12 months	6.5 years	10.6	0	1.2		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Cleveland (4, L ,122)	6 months	4 years 10 months	9.99	r=-.05	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Boston (1, L ,116)	18 months	10 years	7.8	not stated	-2	Hollingshead Four-Factor Index of Social Class			Family Stress, Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	12 months	10 years	7.7	not stated	-1.3	Hollingshead Four-Factor Index of Social Class			Family Balance, Family Stress, Marital Status	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Parents' Sense Competence, Birth Order, Child's Sex
Boston (1, L ,116)	6 months	10 years	6.7	not stated	-2.4	Hollingshead Four-Factor Index of Social Class			Marital Status	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	24 months	10 years	6.5	not stated	-6.3^	Hollingshead Four-Factor Index of Social Class			Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Cincinnati (2, L ,253)	10 Days	6.5 years	5	-0.1	1.1		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Boston (214, L ,148)	24 months	10 years	< 8	not stated	-6.3^	Hollingshead Four-Factor Index of Social Class			Marital Status, Res Changes, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
	(>2 - <4 years)	(>= 4 years)												
Port Pirie (37, L ,494)	Lifetime avg. 3 years	7 years	17.4-21.7 (means of 2nd & 3rd quartiles) (GM)	not stated	-6.3 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant (p < 0.05)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Port Pirie (5, L ,372)	3 years	11-13 years	19.3 (GM)	-9.3 (ln)^	-2.9 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Structure, Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Cleveland (4, L ,155)	3 years	4 years 10 months	16.70	r=-.37	not stated	Mat. Edu.	Cigarettes per day, Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse
Cincinnati (2, L ,253)	Mean 27-36 months	6.5 years	16.3	-1.4	-0.4		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Port Pirie (5, L ,326)	Lifetime avg. 3 years	11-13 years	not stated	-10.2 (ln)	-5.1 (ln)	Pat. Occ.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
		(>= 4 years)												
Lavrion, Greece (21, X ,509)	primary school children - not specified years	primary school children - not specified years	23.7	not stated	-2.52	Mat. Edu., Pat. Edu., Pat. Occ.		Birth Weight	Family Structure, Marital Status, Life Events			Both		Birth Order, Birth Problems, Child's Age, Child's Medical History, History Alcohol Abuse, father's age, bilingualism
Port Pirie (37, L ,494)	Lifetime avg. 4 years	7 years	17.6-21.5 (means of 2nd & 3rd quartiles) (GM)	not stated	-5.5 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex
Port Pirie (37, L ,494)	Lifetime avg. 7 years	7 years	15.7-19.7 (means of 2nd & 3rd quartiles) (GM)	not stated	-4.7 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu., Pat. Edu.	Parental smoking	Birth Weight	Family Structure, Maternal Age	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex

* L=Longitudinal cohort, X=Cross-sectional, M=Meta-analysis
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Mexico City II (23, X ,139)	7-9 years	7-9 years	19.4	r=-.24 (ln)^	r=-.19 (ln)^	income, Mat. Edu., Pat. Edu.								Child's Sex, Assessment Site, Child's Medical History
Port Pirie (5, L ,368)	5 years	11-13 years	14.3 (GM)	-9.2 (ln)^	-4.1 (ln)^	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Port Pirie (5, L ,326)	Lifetime avg. 11-13 years	11-13 years	14.1 (GM)	-11.9 (ln)	-4.3 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
Cincinnati (2, L ,253)	Mean 39-48 months	6.5 years	14.0	-1.4	-0.2		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Cincinnati (2, L ,253)	Mean 51-60 months	6.5 years	11.8	-2.2	-0.7		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
Port Pirie (5, L ,360)	7 years	11-13 years	11.6 (GM)	-8.7 (ln)^	-3.1 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status			Mother		
Sassuolo, Italy (8, X ,212)	7-8 years	7-8 years	10.99 (GM)	r = -0.101 (log10)	not stated									
San Luis Potosi, Mexico (9, X ,39) [reference group]	6-9 years	6-9 years	9.73 (GM)	r=+.04 (ln)	r=+.07 (ln)	Bronffman Index of Socioeconomic Status, Mat. Edu., Pat. Edu.								Child's Sex, Child's Age
San Luis Potosi, Mexico (9, X ,41) [exposed group]	6-9 years	6-9 years	8.98 (GM)	r=-.12 (ln)	r=-.25 (ln)	Bronffman Index of Socioeconomic Status, Mat. Edu., Pat. Edu.								Child's Sex, Child's Age

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant ($p < 0.05$)

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Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Port Pirie (5, L ,326)	11-13 years	11-13 years	7.9 (GM)	-6.3 (ln)^	-2.6 (ln)	Daniel's Scale of Prestige of Occupations in Australia			Family Functioning, Maternal Psychopathological Status	unspecified		Mother		
Boston (1, L ,116)	57 months	10 years	6.3	not stated	-0.7	Hollingshead Four-Factor Index of Social Class		Birth Weight	Family Stress, Marital Status, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Boston (1, L ,116)	10 years	10 years	2.9	not stated	-5.9	Hollingshead Four-Factor Index of Social Class		Birth Weight	Family Stress, Marital Status, Day Care, Maternal Age	scales V & VI @ 120 mo, total @ 57 mo	Child	Mother		Child Stress, Birth Order, Child's Sex
Kosovo (194, L ,259)	Mean AUC7 years	7 years	age7=21.2; cumulative age7=1.21	not stated	-3.4 (log10)^	Mat. Edu.		Birth Weight	Family Structure, Maternal Age	unspecified	Child	Mother		Child's Sex
Port Pirie (5, L ,326)	Lifetime avg. 5 years	11-13 years	not stated	-10.8 (ln)	-5.5 (ln)	Pat. Occ.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
Port Pirie (5, L ,326)	Lifetime avg. 7 years	11-13 years	not stated	-10.5 (ln)	-4.7 (ln)	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence
Cincinnati (2, L ,253)	Mean 66-72 months	6.5 years	not stated	-3.3^	-1.2		Cigarette consumption during pregnancy	Birth Weight, Birth Length		unspecified		Mother		Child's Sex
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cleveland (4, L ,212)	Mean 0.5 - 3 years	4 years 10 months	9.99 @ 6 months & 16.70 @ both 2 yrs & 3 yrs)	r=-.29	not stated	Mat. Edu.	Maternal cigarettes/day	Birth Weight, Gestation	Authoritarian Family Ideology	total (mean of 1, 2, 3, and 4 yrs 10 mos)	Child	Mother		Medication/drug Use, Maternal Alcohol Consumption, Birth Order, Child's Sex, History Alcohol Abuse

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant ($p < 0.05$)

Study Population* (ref., type, n)	PbB Age	Outcome Age	Mean PbB (ug/dL)	Estimated Delta IQ for PbB 5 -> 15		Covariates in Model								
				Crude	Adj	SES	Smoking	Fetal Growth	Family Environment	HOME	Race	Parental IQ	Iron Status	Other
Cincinnati (2, L ,253)	Lifetime avg. 72 months	6.5 years	not stated	-1.3	-0.1	Daniel's Scale of Prestige of Occupations in Australia, Mat. Edu.	Parental smoking habits	Birth Weight	Family Structure, Family Functioning, Marital Status, Maternal Age, Life Events	unspecified		Mother		Breast Feeding, Feeding Method, Birth Order, Child's Sex, Child's Age, School Grade, School Absence

* L=Longitudinal cohort, X=Cross-sectional, M=Meta analysis
^ statistically significant (p < 0.05)

Table 5. Studies of health endpoints other than IQ or GCI in relation to BLLs < 10 µg/dL

Study Population	Health Outcome	Age PbB	Age Outcome	PbB Distribution	Covariates	Results on BLL-outcome association less than 10
[29] X - NHANES III (n=4853)	Cognitive function	6-16 years	6-16 years	Geometric mean 1.9 µg/dL, 98% < 10 µg/dL	gender, race/ethnicity, poverty, region, parent/caregiver education and marital status, serum ferritin, serum cotinine.	Signficant inverse relationships between BLL and WRAT arithmetic, WRAT reading, WISC R block design, WISC-R digit span. For all but block design, regression slopes became more negative with restriction of analyses to children with bll < 10, < 7.5, < 5.0 and < 2.5 µg/dL.
[27] X - Leipzig, Gardelegen, Duisberg, Germany (n=384)	Attention, sensorimotor function, and cognitive function	5-7 years	5-7 years	4.25 µg/dL (GM), 95 %ile 9 µg/dL	For WISC vocabulary and block design: Study area, visual acuity and contrast sensitivity, parental education, sex, breastfeeding, height, nationality. For NES2 pattern comparison, pattern memory, tapping, simple reaction time, and continuous performance test: study area, visual acuity and contrast sensitivity, age, parental education, sex, birthweight, smoking in pregnancy, number of siblings, height, computer familiarity.	Significant negative association between WISC vocabulary and CPT results. Associations strongest in Gardelegen, community with lowest mean PbB.
[18] X – Leipzig, Gardelegen, Duisberg, Germany (n=367)	Neuobehavioral and Neurophysiologic function	6 years	6 years	Median 5 µg/dL, 95 %ile < 10 µg/dL	For NES2 tapping, benton (pattern memory), reaction time, pattern comparison: age, sex, parental education, study area. For Visual Evoked Potentials: age, gender, study area.	Significant negative association of log transformed blood lead with tapping speed and with pattern comparison. No significant association of log-transformed blood lead level with visual evoked potential peak latencies.
[28] X – New York (n=68)	Mental development	12-36 months	12-36 months	Mean= 10.3 µg/dL	Receives public assistance, maternal education, HOME - Stim Q, child race, maternal IQ, anemia or low MCV, birth order, sex, age	Significantly lower Bayley MDI for children ≥ 10 µg/dL vs < 10; scatterplot of adjusted MDI vs BLL suggests relation linear relation continues at BLL < 10

Study Population	Health Outcome	Age PbB	Age Outcome	PbB Distribution	Covariates	Results on BLL-outcome association less than 10
[216] X - - Leipzig, Gardelegen, Duisberg, Germany (n = 746)	NES1 – Tapping Test and Pattern Recognition	5 and 6 years	5 and 6 years	Median = 5 ug/dl and 95th percentile of overall frequency distribution for PbB was <10	Maternal education, child's sex, child's age	Authors report that after adjustment for confounders a significant deficit for tapping and pattern comparison in relation to BLL($p<.05$) was found, but no regression coefficient or dose-response analyses are presented..
[31] X - Leipzig, Gardelegen, Duisberg, Germany (n=384)	Visual function	5-7 years	5-7 years	4.25 µg/dL (GM), 95 %ile 9 µg/dL	Child's Age, Assessment site, Birth Weight, Child's Medical History, head circumference, child weight, quality of fixation	Visual evoked potential interpeak latencies were significantly prolonged in relation to PbB for one of three visual stimuli tested and non-significantly prolonged for a second stimulus. No significant association between PbB and contrast sensitivity was seen.
[109] X - unstated (n=)	Neurotransmitter and neuroendocrine levels	8.5 - 12.3 years	8.5 - 12.3 years	mean = 3.95		No significant correlation overall between PbB and serum prolactin (Pro-S) or urinary homovanillic acid HVA-U. Analysis performed on only those children PbB> 5 ug/dl showed a weak but stat direct relation to PbB.
[40] X - NHANES III (n=4391)	Stature and head circumference	1-7 years	1-7 years		ethnic group, iron status, dietary intake, medical history, sociodemographic factors, and household characteristics	Significant inverse relation of bll to stature and head circumference. estimated decrease of 1. 57 cm in stature and 0.52 cm in head circumference for each 10 micrograms/dL increase in BLL
[154] L - Mexico City (n=119-199)	Head Circumference	every 6 months from 6-48 months	every 6 months from 6-48 months	Medican postnatal varied from 7-10 µg/dL	Birth Problems, Child's Race, maternal head circumference, head circumference at birth	Ln of blood lead at 12, 18, and 24 months significantly related to head circumference at 36 months; Ln of blood lead at 12 months signifcantly related to head circumference at 42 months. Most other partial correlations between postnatal blood were negative. Plot of coavariate adjusted head circumference at 36 months vs. Ln blood lead at 12 months shows inverse relation that appears to continue below 10 µg/dL

Study Population	Health Outcome	Age PbB	Age Outcome	PbB Distribution	Covariates	Results on BLL-outcome association less than 10
[94] X – Lavrion, Elefsina, Loutraki Greece	Somatic growth, including head circumference, height, and chest circumference	6-9 years	6-9 years	Mean = 12.3 ug/dl, Median = 9.8 ug/dl	Paternal education, paternal occupation, child's sex, child's age, iron status, assessment site, father's height, mother's height	Significant negative association of BLL and head circumference and height with scatterplot suggesting relation continues below 10 µg/dL.. No significant association with chest circumference.
[169] X - NHANES III (n= 2186 girls: 1964 with pubic hair stage, 1986 with breast development stage and 1796 with age at menarche.) (African Amer)	Pubertal development in girls	8-18 years	8-18 years	Geometric means: Non-Hispanic whites 1.4; African Americans 2.1; Mexican Americans 1.7. greater than 5: 2.7%, 11.6% and 12.8%, respectively	family income ever smoke 100 cigarettes Child's Age, Iron Status, Child's Medical History, height, BMI, age squared For age at menarche: height Family income, ever smoke 100 cigarettes Child's Age, Iron Status, Child's Medical History, height, BMI, age squared	Blood lead levels of 3 ▯g/dL, compared with 1 ▯g/dL were associated with significant delays in breast and pubic hair development in African American and Mexican girls. The trend was similar, but not significant, for non-Hispanic white girls. Age at menarche was also delayed in relation to higher blood lead levels, but the association was only significant for African-American girls.
[201] X - NHANES III (n=Sample I: 1706 ages 8-16 years with pubic hair and breast development info; Sample II: 1235 girls aged 10-16 had info on menarche) (all)	Pubertal development in girls	8-16 years	8-16 years	98.5% < 10; 54.3% 0-2.0	Poverty income ratio, family size, metro residence, Child's Age, Child's Race, BMI	Compared with blood lead levels 2.0 ▯g/dL and below, blls of 2.1-4.9 were associated with significantly lower odds of attaining tanner 2 stage pubic hair (OR=0.48, 95% CI 0.25-0.92) and menarche (OR=0.42, 95% CI 0.18-0.97); no significant association with breast development was noted.

Study Population	Health Outcome	Age PbB	Age Outcome	PbB Distribution	Covariates	Results on BLL-outcome association less than 10
[120] X - NHANES III (n=24901)	Dental Caries	2+ years	2+ years	Geometric means: age 2-5 yrs 2.9; 6-11 years 2.1; 12+yrs 2.5; 74-88% of participants with bll < 5 in each age group	Poverty Income Ratio, Mat. Edu. exposure to cigarette smoke Child's Sex, Child's Age, Child's Race, Assessment site, Child's Medical History, days since last dental visit, usual freq of dental visit	Comparing children 5-17 years of age in middle the tertile of BLL (range of BLLs 1.7-4.1) with lowest tertile), odds ratio for dental caries was 1.36 (1.01-1.83)
[272] X Boston&Cambridge MA and Farmington ME (n=543)	Dental Caries	6-10 years	6-10 years	Means: Cambridge/Boston 2.9 µg/dL, Farmington 1.7 µg/dL	Age, sex, family income, education of female guardian, ethnicity, maternal smoking, tooth brushing frequency, tooth brush bristle hardness, gum chewing	In Cambridge/ Boston number of carious surfaces increased significantly with log PbB in linear regression and in graph comparing children with PbB of 1, 2, and 3 µg/dL. In Farmington, non-significant decrease in carious surfaces with increasing PbB
[78] L - Kosovo (n=281)	Blood pressure	66 months	66 months	K. Mitrovica: mean=37.3 mcg/dL (sd=12.0); Pristina: mean=8.7 mcg/dL (sd=2.8)	For Systolic blood pressure: Birth Order, Child's Sex, Child's Race, height, BMI; For diastolic blood pressure: Birth Order, Child's Race	Figures showing adjusted mean systolic and diastolic blood pressure for 10 groups with approximately equal numbers in each ordered by blood lead shows no consistent trend among the 4 across a range of bll approximately 5-10 ug/dL
[150] X - Belgium (n=143)	Heme Synthesis Biomarkers	10-13 years	10-13 years	Means: Boys: < 1 km: 28.7 µg/dL (SD=8); 2.5 km: 15.6 (2.9); urban: 10.6 (2.0); rural: 9.2 (2.3) Girls: < 1 km: 20.7 (7.6); 2.5 km: 9.8 (3.8); urban: 9 (2.0); rural: 8.7 (1.7)	not specified	Dose-effect relationships are plotted for FEP, ALAD, and ALAU. No threshold evident for ALAD inhibition. Authors state if it exists it must be below 8-10 ug/dl. A PbB 5threshold for increasing FEP evident at 15-20 µg/dL.
[144] L – Boston (n=249 originally recruited; 201 at 2 years)	Heme Synthesis Biomarkers	6-24 months	6-24 months	Mean 7 µg/dL	not specified	No relation of incidence of elevated erythrocyte protoporphyrin levels to blood lead levels below 15 µg/dL

Study Population	Health Outcome	Age PbB	Age Outcome	PbB Distribution	Covariates	Results on BLL-outcome association less than 10
[86] L – Cincinnati (n=165)	Heme Synthesis Biomarkers	6-30 months	6-30 months	Not presented	None presented, crude results only	Significant positive association reported for FEP and ZPP and ln transformed BLL at all ages. Threshold for relationship at B:: between 15 and 20 μg/dL.
[215] X – Pribam, Czech Republic (n=246)	Renal function	12-15 years	12-15 years	Mean ranged from 8.39 ug/dl in girls in the control area to 14.9 ug/dl in boys in polluted area 2	None presented, crude only reported	Urinary RBP was found to be significantly associated with PbB in a stepwise regression. When urinary RBP excretion was examined by BLL tertiles, significantly lower U-RBP was seen in the group with BLL <8.64 ug/dl compared with BLL 8.64-12.3.

NOTE: Complete citations for these references appear in the alphabetical list above.

Journal ID	First Author	Date	Title
1	Bellinger DC	1992	Low-level lead exposure, intelligence and academic achievement: A long-term follow-up study
2	Dietrich KN	1993	The developmental consequences of low to moderate prenatal and postnatal lead exposure: Intellectual attainment in the Cincinnati Lead Study Cohort following school entry
3	Ernhart CB	1988	Low-level lead exposure and intelligence in the preschool years
4	Ernhart CB	1989	Low-level lead exposure in the prenatal and early preschool periods: Intelligence prior to school entry
5	Tong, SL	1996	Lifetime exposure to environmental lead and children's intelligence at 11-13 years: The Port Pirie cohort study
6	Bellinger DC	2002	Low-level lead exposure and early development in socioeconomically advantaged urban infants
7	Cooney GH	1989	Low-level exposures to lead: the Sydney lead study
8	Bergomi M	1989	Relationship between lead exposure indicators and neuropsychological performance in children
9	Calderon J	2001	Exposure to arsenic and lead and neuropsychological development in Mexican children
11	Al-Saleh I	2001	Relationships between blood lead concentrations, intelligence, and academic achievement of Saudi Arabian schoolgirls
12	Fulton M	1987	Influence of blood lead on the ability and attainment of children in Edinburgh
13	McMichael AJ	1988	Port Pirie Cohort Study: Environmental exposure to lead and children's abilities at the age of 4 years
14	Ernhart CB	1987	Low-level lead exposure in the prenatal and early preschool periods: Early preschool development
15	Bellinger DC	1988	Low-level lead exposure, social class, and infant development
16	Winneke G	1990	Results from the European Multicenter Study on lead neurotoxicity in children: Implications for risk assessment
17	Schnaas L	2000	Temporal pattern in the effect of postnatal blood lead level on intellectual development of young children
18	Winneke G	1994	Neurobehavioral and neurophysiological observations in 6-year-old children with low lead levels in East and West Germany
19	Canfield RL	2003	Intellectual impairment in children with blood lead

Journal ID	First Author	Date	Title
			concentrations below 10 ug per deciliter
20	Bellinger DC	1991	Low-level lead exposure and children's cognitive function in the preschool years
21	Hatzakis A	1987	Psychometric intelligence and attentional performance deficits in lead-exposed children
22	Wolf AW	1994	No evidence of developmental ill effects of low-level lead exposure in a developing country
23	Munoz H	1993	Blood lead level and neurobehavioral development among children living in Mexico City
24	Shen XM	1992	The adverse effect of marginally higher lead level on intelligence development of children: A Shanghai Study
25	Silva PA	1988	Blood lead, intelligence, reading attainment, and behavior in 11-year-old children in Dunedin, New Zealand
26	Sovcikova E	1997	Effects on the mental and motor abilities of children exposed to low levels of lead in Bratislava
27	Walkowiak J	1998	Cognitive and sensorimotor functions in 6-year-old children in relation to lead and mercury levels: Adjustment for intelligence and contrast sensitivity in computerized testing
28	Mendelsohn A L	1999	Low-level lead exposure and cognitive development in early childhood
29	Lanphear BP	2000	Cognitive deficits associated with blood lead concentrations <10 ug/dL in U.S. children and adolescents
31	Altmann L	1998	Visual functions in 6-year old children in relation to lead and mercury levels
37	Baghurst PA	1992	Environmental exposure to lead and children's intelligence at the age of 7 years. The Port Pirie Cohort Study
40	Ballew C	1999	Blood lead concentration and children's anthropometric dimensions in the third National Health and Nutrition Examination Survey (NHANES III), 1988-1994
49	Bellinger DC	1995	Interpreting the literature on lead and child development: The neglected role of the 'experimental system'
78	Factor-Litvak P	1996	Blood lead and blood pressure in young children
86	Hammond PB	1985	Dose-effect and dose-response relationships of blood lead to erthryocytic protoporphyrin in young children
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144	Rabinowitz MB	1986	Occurrence of elevated protoporphyrin levels in relation to lead burden in infants
150	Roels HA	1987	Evaluation of dose-effect and dose-response relationships for lead exposure in different Belgian population groups (fetus, child, adult men, and women)
154	Rothenberg SJ	1999	Pre- and postnatal lead effect on head circumference: A case for critical periods
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218	Dietrich KN	1990	Lead exposure and neurobehavioral development in later infancy
219	Bellinger DC	2003	Correspondence: Intellectual impairment and blood lead levels
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