Environmental determinants of different Blood Lead Levels in children: a quantile analysis from a nationwide survey.

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Abstract

Background: Blood Lead Levels (BLLs) have substantially decreased in recent decades in children in France. However, further reducing exposure is a public health goal because there is no clear toxicological threshold. The identification of the environmental determinants of BLLs as well as risk factors associated with high BLLs is important to update prevention strategies. We aimed to estimate the contribution of environmental sources of lead to different BLLs in children in France.

Methods: We enrolled 484 children aged from 6 months to 6 years, in a nationwide cross-sectional survey in 2008-2009. We measured lead concentrations in blood and environmental samples (water, soils, household settled dusts, paints, cosmetics and traditional cookware). We performed two models: a multivariate generalized additive model on the geometric mean (GM), and a quantile regression model on the 10th, 25th, 50th, 75th and 90th quantile of BLLs.

Results: The GM of BLLs was 13.8 µg/L (=1.38 µg/dL) (95% Confidence Intervals (CI): 12.7-14.9) and the 90th quantile was 25.7 µg/L (CI: 24.2-29.5). Household and common area dust, tap water, interior paint, ceramic cookware, traditional cosmetics, playground soil and dust, and environmental tobacco smoke were associated with the GM of BLLs. Household dust and tap water made the largest contributions to both the GM and the 90th quantile of BLLs. The concentration of lead in dust was positively correlated with all quantiles of BLLs even at low concentrations. Lead concentrations in tap water above 5 µg/L were also positively correlated with the GM, 75th and 90th quantiles of BLLs in children drinking tap water.

Conclusions: Preventative actions must target household settled dust and tap water to reduce the BLLs of children in France. The use of traditional cosmetics should be avoided whereas ceramic cookware should be limited to decorative purposes.

Keywords: blood lead, lead exposure, dust, water, soil.

1. Introduction

Blood lead levels (BLLs) in young children have considerably declined in developed countries over the past 15 years. The geometric mean of BLLs in children decreased from 36 to 15 µg/L between 1996 and 2009 in France (Etchevers et al. 2013). Similar BLLs have been reported in Germany (Becker et al. 2013), the USA (CDC 2013), Croatia, the Czech Republic, Poland, Slovakia, Slovenia (Hruba et al. 2012) and Sweden (Stromberg et al. 2008) in recent years.

Many scientific publications have shown adverse health effects associated with BLLs below 50 µg/L (=5 µg/dL) (National Toxicology Program 2012) and there is currently no defined toxicity threshold (Canfield et al. 2003;Jusko et al. 2008;Lanphear et al. 2005). As a consequence, the German Federal Environmental Agency and the Centers for Disease Control and Prevention (CDC) have recently revised the blood lead 'levels of concern' of 100 µg/L. It was lowered from 100 µg/L to 35 µg/L (Wilhelm et al. 2010) in Germany and from 100 µg/L to 50 µg/L (CDC 2012) in the USA. Similarly, in France, a reduction of the current level of 100 µg/L to an as-yet undetermined threshold is under revision.

Since the removal of lead from gasoline, residential sources have become the biggest sources of lead exposure for children in developed countries (Lanphear et al. 2003). Levallois *et al.* (Levallois et al. 2013) and Oulhote *et al.* (Oulhote et al. 2011;Oulhote et al. 2013) recently demonstrated that exposure to several sources of lead including tap water, home and exterior dust and soil is associated with BLLs in children.

It is essential to evaluate the contribution of each individual source to BLLs in children both to design prevention strategies and to limit environmental exposure. Such prevention strategies must target both children with low BLLs (the most frequent) and children with elevated BLLs. The identification of environmental factors that contribute to elevated BLLs will facilitate both the design of effective screening programs and strategies to remove these sources. Identification of the contributors to low BLLs is important because they contribute to the main burden of IQ loss (Lanphear et al. 2005) and have the largest economic impact (Pichery et al. 2011).

The first objective of the study was to identify the contribution of lead sources to BLLs in young children living in France 1) for the whole population (corresponding to the geometric mean) and 2) for the most exposed children (corresponding to the 90th quantile of BLLs). The second objective was to compare the contribution of dust and tap water lead levels at different points of the BLL distribution (geometric mean, 10th, 25th, 50th, 75th and 90th quantiles of BLLs).

2. Methods

2.1. Population and sampling

Between 2008 and 2009, the French Institute for Public Health Surveillance (InVS) implemented a nationwide (n=3831) cross-sectional survey to estimate BLLs in children (6 months to 6 years of age) in France (Etchevers et al. 2013). Between November 2008 and August 2009, the Scientific and Technical Building Institute (CSTB) carried out a nested environmental survey in homes of a random subsample of 484 children in mainland France (Etchevers et al. 2013;Lucas et al. 2012). Hereafter, only the main features will be recalled. We used a two-stage probability sample design: in the first stage, the primary sampling units were hospitals and in the second stage, we included hospitalized children. The hospitals were stratified by administrative regions and the risk of lead poisoning, the extent of old and poor housing in the catchment area, and industrial activity related to lead. Hospitals in high risk areas were intentionally oversampled. The sampling weights were then adjusted by post-stratification based on auxiliary variables (region, sex, age and eligibility for complementary free health insurance (CMUc)) to increase the precision of estimates and to make the sample more representative of the population (Lumley T 2010). The participation was 83% for hospitals. The participation for parents was 97% at hospitals and 62% at home.

2.2 Data and sample collection

Children gave venous blood samples (1.5 mL) during the hospital stay. At each child's home, we interviewed one adult who was living with the child, about demographic, housing and behavioral characteristics and we sampled residential sources of lead. In each dwelling, we collected wipe samples of floor dust from a 0.1 m^2 surface area of the floor where the child was reported to play, in up to five rooms (U.S.HUD 2002). In addition, we collected one or two dust samples in the entrance hall and in the landing for apartments. If the child was reported to play outside, in a garden or playground in close vicinity to the home, the ground was sampled by coring (2 cm deep) for soil surfaces or by dust wiping (0.1 m^2) for hard surfaces. We collected a 2 L tap water sample after a 30 min stagnation time of water in the pipework. The water samples were homogenized and were poured into a 0.25 L flask acidified with 1% of HNO3 to ensure a pH < 2. We performed paint measurements with portable X-ray fluorescence (XRF) lead-based paint analyzers (Niton) on each part of the room (wall, door, and window) accessible to the child, except on new parts of the room. Finally, if the family agreed, we also collected traditional cosmetics (kohl) or dishes known to be potential sources of lead.

2.3 Chemical analyses

2.3.1 Blood lead levels

Blood lead levels were analyzed by inductively coupled plasma mass spectrometry (ICP-MS). The blood samples were diluted (1:10) with an aqueous matrix modifier solution (0.2%

butanol, 0.1% Triton and 1% nitric acid). The limit of quantification (LOQ) was 0.037 µg/L. In all cases, BLLs were above the LOQ. All blood samples with a BLL greater than 80 µg/L were analyzed a second time to confirm the result. Quality control procedures were performed: blanks and internal quality controls from reference materials (Utak blood samples of 27.91 µg/L and 394.92 µg/L) were analyzed for every 10 samples. External quality control procedures included participation in the AFSSAPS (French Agency for medical care safety) interlaboratory control (2007 and 2009) and the use of external samples from the INSPQ (National Institute of Public Health of Quebec). The external control test was considered successful if there was less than 10% difference between the expected and observed values.

2.3.2 Lead measurements in environmental samples, kohl and traditional cookware

We analyzed environmental samples for lead content using an ICP-MS (Agilent Technology) 7500ce equipped with a quadrupole mass filter and an octopole reaction cell. We analyzed all environmental samples (except for water) for leachable (regulatory method in France) and total lead content (Le Bot et al. 2010;Le Bot et al. 2011). The LOQ were 1 µg/L for water, 1 µg/m² (0.09 mg/ft²) for leachable lead in dust and 2 µg/m² (0.19 mg/ft²) for total lead in dust. For soil, the LOQ were 0.5 µg/g and 1.3 µg/g, for leachable and total lead respectively. For traditional cosmetic (kohl), we used the same leachable digestion method as for soil. The LOQ was 1.3 µg/g. For traditional cookware, leachable lead was measured by contact with acetic acid (4%) for 24 hours at room temperature (ISO 7086-1 2000). The LOQ was 1 µg/L. Quality control was performed with analytical blanks and standard reference materials SRM 2583 and SRM 2584 for dust, certified reference material CRM 013-050 for paint, CRM SS2 for soil and kohl, and the National Institute of Standards and Technology NIST 1643 for water and traditional cookware. Control samples were included in all digestion series or analyses series (for water) to determine lead concentration in a manner identical to that of the real samples. The lab has French accreditation (Comité Français d'accréditation (COFRAC)) for the analysis of lead in water and dust. The intra-laboratory relative standard deviation for lead in all types of sample was lower than 10%.

2.4 Statistical analyses

We used two different modeling approaches: 1) a generalized additive model (GAM) of expected geometric mean of BLLs to quantify the risk factors for the whole population and 2) quantile regressions for expected 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} quantiles of BLLs to study risk factors of specific areas of the BLLs distribution. In the GAM model, we included the following variables: lead levels in interior dust, dust from common areas of the building, tap water, soil, playground dust, paints, cookware ceramics, traditional cosmetics (kohl, surma, tiro), along with children's sex, children's age, environmental tobacco smoke (ETS) exposure, tap water consumption and parents' occupational exposure to lead. In the quantile regression models, we removed some covariates (i.e. lead in paints, ceramics, traditional cosmetics, ETS) that were collinear with other risk factors at the 90^{th} quantile of BLLs due to the absence or quasi-absence of these risks factors in children.

The construction of the variables is presented in Appendix A.

BLLs were natural log-transformed to ensure proper distribution of the residuals. We transformed environmental lead concentrations to their cubic root to address the high degree of skewness. In the GAM model, the variables age, tap water, interior dust, dust from indoor common areas concentrations were included as penalized smoothing splines to capture possible non-linearity with BLLs; the other variables were introduced as linear terms. In the quantile regression models, the variables age, interior dust and tap water concentrations were introduced as natural spline functions with three degrees of freedom to potentially adjust for non-linearity, whereas the other variables were introduced linearly. We performed analysis on the complete data set (434 children), with no missing data for the included variables.

For the sake of simplicity, we presented the increase in BLLs associated with a change of the environmental lead concentration from its 25th or 50th percentile to its 95th percentile and from its 25th or 50th percentile to its 99th percentile to assess the contribution of each environmental component to BLLs. The estimated increases are presented for the geometric mean (GM) for GAM analyses and for the 90th quantile of BLLs for quantile regressions. A variable was considered as a risk factor if its estimated increase was positive. Evidence of the association was assessed both in terms of 95% confidence interval and consistency with published results. Using the GAM and quantile regression models, we predicted the GM, 10th, 25th, 50th, 75th and 90th quantiles of BLLs for lead concentrations in dust and tap water to construct dose-response relationship curves (Figure 1).

We used the survey package (Lumley T 2011) in the R software (R : a Language and Environment for Statistical Computing 2012) to account for the complex sampling design and the sampling weight of each participant. We carried out the quantile regressions with the quantreg package (Koenker R 2012).

The results in this manuscript are for total lead. The results for leachable lead are available in Appendix B.

3. Results

3.1 Characteristics of the study population and environmental factors

The estimated blood and environmental lead concentrations are described in Table 1. They were determined by Lucas *et al.* (Lucas 2012) for paints, dust and soil. The population-weighted geometric mean BLL was 13.8 µg/l and the 95th percentile was 32.8 µg/l.

Insert Table 1

About 21% of children were exposed to indoor passive smoking (Table 2), and 10% were exposed for more than 2 hours/day. Thirteen percent of parents used traditional cookware and 1.5% used ceramics releasing lead. Approximately 3% of families declared the use of traditional cosmetics from their native countries; 0.8% used cosmetics containing lead. Twenty one percent of parents were potentially exposed to lead during their work or hobbies.

The distribution of children's age, sex and passive smoking in this sub-sample was similar to those estimated in the original sample selected at hospital (Etchevers et al. 2014).

Insert Table 2

3.2 Associations between environmental exposure and BLLs

3.2.1 Associations between environmental sources and geometric mean of BLLs

The geometric mean of BLLs was associated with all potential sources included in the model. However, the precision of the estimate was low (the confidence interval contained 0) for dust from indoor common areas, exterior playground soil, ETS and the use of cosmetics releasing lead. An association between BLLs and dust from common areas and paints in good condition was only detected for a change from their 25th percentile to their 99th percentile, although the precision of this estimate was low. The geometric mean of BLLs was associated with traditional ceramic cookware (+56% in GM), traditional cosmetics releasing lead (+43% in GM), floor dust from inside homes (+33% in GM with a range of 3 [0.3 µg/ft²] to 62 µg/m² [6 µg/ft²]), tap water (+44% in GM with a range of 1 to 14 µg/L), and outdoor playground dust (+33% in GM with a range of 0 to 187.5 µg/m² [17 µg/ft²]).

Insert Table 3

3.2.2 Associations between environmental sources and the quantile 90th of BLLs

The risk factors of the 90th quantile (25.7 µg/L) of BLLs are displayed in Table 4. BLLs ≥ the 90th quantile were associated with dust from the household interior and indoor common areas and with tap water, for both children drinking tap or bottled water. Precision was lower for tap water and dust from indoor common areas than for household dust. High BLLs were estimated for high levels of exposure to these factors (99th quantile).

Insert Table 4

3.2.3 Predicted BLLs according to exposure to household dust and tap water

For the two main risk factors (household dust and tap water) we plotted separately the concentration-response relationship for the geometric mean and the 10th, 25th, 50th, 75th, 90th quantiles of BLLs (Figure 1). For each prediction, the contribution of other factors was set arbitrarily to zero. . The zone shaded in grey shows the 95% confidence interval of the estimated geometric mean.

Insert Figure 1

Lead loadings in interior floor dust were positively correlated with all quantiles of BLLs. The higher the BLLs were, the higher the contribution of lead loadings from interior floor dust was. Low and median BLLs (10th to 50th quantile) increased with increasing dust lead loadings between 1 and 60 µg/m² (5.6 µg/ft^2). The 75th and 90th quantiles increased until 200 µg/m² (18.6 µg/ft^2) and tended to reach a plateau or to decrease above 200 µg/m². This decrease of BLLs may be explained by the high uncertainty for the high dust lead loadings. The geometric mean did not follow this pattern and BLLs were still positively correlated with dust lead loadings above 200 µg/m². The highest BLL predicted by exclusively interior floor dust did not exceed 21 µg/L.

The presence of lead in tap water was positively correlated with all quantiles of BLLs in children drinking tap water. Tap water lead concentrations higher than 5 µg/L affected the geometric mean and elevated BLLs (75th and 90th quantile) and concentrations higher than 10 µg/L affected the lower quantiles (10th and 25th). For children drinking tap water with a lead concentration of 10 µg/L, the predicted GM BLL was 15 µg/L and the predicted 90th quantile of BLLs was 19 µg/L. The highest levels of water lead exposure (between 30 and 50 µg/L) contributed to predict BLLs between 36 to 55 µg/L, if we consider no contribution from other sources. Additionally, BLLs of the 90th quantile were positively correlated with tap water lead concentrations in children drinking bottled water, most probably due to the use of leaded tap water for food preparation and cooking (Triantafyllidou and Edwards M. 2011). BLLs of the geometric mean and the 75th quantile tended to increase for water lead concentrations higher than 20 µg/L in children drinking bottled water. A water lead concentration of 10 µg/L was associated with a GM BLL of 11 µg/L and a BLL of 17 µg/L for the more exposed (90th quantile of BLLs).

4. Discussion

The aim of this study was to estimate the contribution of environmental sources of lead on the geometric mean and 90th percentile of BLLs and to compare, for tap water and dust, the relationship between its concentration and BLLs at different points of the BLLs distribution. Household dust and tap water were the main predictors of both the geometric mean and 90th quantile of BLLs. Playground soil and dust affected the geometric mean of BLLs but not the 90th quantile of BLLs. We also found a strong association between ceramic cookware, traditional cosmetics and the geometric mean of BLLs in children.

4.1 Environmental determinants of BLLs

4.1.1 Interior floor dust

The concentration of lead in household dust was positively correlated with all quantiles of BLLs and this was the main risk factor for all quantiles of BLLs studied in our study. We demonstrated that lead loadings much lower than the current American standard of 40 µg/ft² (430 µg/m²) were positively correlated with BLLs: for example they increased the 90th quantile of BLLs by 75% for a change from 4 µg/m² to 62 µg/m² (6 µg/ft²) and by 96% for a change from 4 µg/m² to 172 µg/m² (16 µg/ft²). Approximately 5% of children were exposed to lead loadings in dust above 62 µg/m² (6 µg/ft²) and 1% to levels above 172 µg/m² (16 µg/ft²). The geometric mean of BLLs estimated in the American NHANES study (1999-2004) was higher (20.3 µg/L) than our estimate here (Dixon et al. 2009); nonetheless, we found that interior dust lead loading had a similar contribution on BLLs at dust levels below 34.4 µg/m² (3.2 µg/ft²). Above 34.4 µg/m², the contribution of dust was lower in our study than in that of the NHANES. A more recent study in Montreal (Canada) also reported a weak association between BLLs >18 µg/L (75th quantile in their study) and floor dust >13 µg/m² (Levallois et al. 2013).

4.1.2 Dust from indoor common areas

Although lead concentrations in dust from indoor common areas were nearly four times higher (GM = 32.2 µg/m²) than in household dust (GM=8.7 µg/m²), its contribution was only observable for the 1% most exposed children in the geometric mean (Table 3), the 75th quantile (data not shown) and the 90th quantile (Table 4). The estimates for the extreme quantiles of BLLs had a high uncertainty due to the small number of children in our sample (114). As few as 8 out of 114 children declared spending time in common areas; dust from the common area may be an indirect source of exposure. Indeed, dust from landings has been demonstrated to be the major contributor to lead in interior floor dust (Lucas et al. 2014).

4.1.3 Tap water

Lead in drinking water was an important exposure pathway in our study with a contribution of water lead concentrations above 5 µg/L on the geometric mean, 75th and 90th quantiles of BLLs for consumers and on the 90th quantile for non-consumers. All BLLs were also positively correlated with concentrations of lead in tap water exceeding the current 2013 European standard of 10 µg/L (Council of the European Union 1998); it concerned three percent of French children in 2009. Moreover we reported that high lead water exposure alone can be responsible for elevated BLLs: the 90th predicted quantile of BLLs reached 50 µg/L with a water lead concentration of 42 µg/L and 35 µg/L with a water lead concentration of 29 µg/L. However, the correlation between high levels of lead in water and BLLs has a high uncertainty (based on few children). Concerning the tap water values below LOQ (58%) included as raw data, we performed a sensitivity analysis in a non-weighted GAM using a multiple imputation on values of tap water <LOQ to assess a potential bias on the estimates. The estimated risk associated to tap water exposure with multiple imputation was similar to the one estimated with missing data or with replacement of values by raw data (data not shown). If, as observed by Triantafyllidou *et al* (Triantafyllidou et al. 2013) at higher lead water concentrations, water lead measurements were underestimated in our study due to samples transfer, the strength of the association between lead in water and blood would be overestimated. The effect of tap water has been studied previously (Brown and Margolis 2012;Lanphear et al. 1998a;Levallois et al. 2013;Miranda et al. 2007;Renner 2010). These results are consistent with those of Levallois *et al.* who reported that lead concentrations > 3.27 µg/L influenced the 75th quantile of BLLs (17.8 µg/L) (Levallois 2013). We noticed also that elevated BLLs were influenced by indirect consumption (through food preparation and cooking) but with a lower impact than for children drinking tap water. It demonstrated that water lead exposure can be reduced by consumption of exclusively bottled water. Fertmann *et* *al* have shown that consuming bottled water for drinking and cooking during 11 weeks reduced maternal median blood lead exposure from 32 to 20 µg/L (Fertmann et al. 2004). We found a similar decline on the 90th quantile of BLLs between children drinking tap water versus bottled water.

4.1.4 Exterior soil and dust

The geometric mean of BLLs was 18% higher at exterior dust lead concentrations of 32 µg/m² than at 0 µg/m² and was 33% higher at 187 µg/m². Playground dust also affected the 10th, 25th and 75th quantile of BLLs (data not shown). However we did not have enough statistical power with only 53 dust samples to model the relationship between the quantiles of BLLs and exterior dust with high precision. Nevertheless, we can assume that the contribution of exterior dust to the GM was underestimated, given that dust in indoor common areas must have captured a part of the contribution of the exterior dust (Lucas et al. 2014).

Lead in soil only influenced the geometric mean and the 50th quantile of BLLs. Lead content in soil increased the GM of 13% for a change from 0 to 251 mg/kg and 16% for a change from 0 to 407 mg/kg; however, there was no statistical evidence. Even above the current U.S. federal hazard standard of 400 mg/kg (1.4% of exterior play areas are above this threshold in France), the contribution is weak, probably because the effect of soil may have also been captured by household dust.

Studies have demonstrated an association between soil (and sometimes exterior dust from play areas) and BLLs for high lead concentrations in soils (Lanphear et al. 1998a;Lanphear et al. 1998b;Lanphear et al. 2002). However, few studies assessed the contribution of soil at similar lead concentrations.

4.1.5 Interior lead-based paints

Leaded paint in good condition was associated with a 13% increase in geometric mean BLL for a variation between the 25th and the 99th quantile. Paints may be either a direct source of exposure when children make contact with the walls or an indirect source of exposure through dust. Studies have demonstrated an association between high BLLs and leaded paints (Gulson et al. 2013;Lanphear et al. 1998b;Schwartz and Levin 1991) whereas a more recent study that did not find this relationship when an adjustment was made for dust and tap water (Levallois 2013).

4.1.6 Cosmetics and ceramics

Ceramics and cosmetics were associated with an increase in the GM of BLLs (56% for ceramics and 43% for traditional cosmetics releasing lead). The association was detectable for lead levels above the LOQ, which was 1 µg/L for ceramics and 0.13 mg/g for traditional cosmetics. Therefore, we demonstrate an association for a lead content far below the 4 mg/L current European legislation for food container materials (JORF 2006). The range of lead concentrations leached from ceramics was 7 to 2 380 000 µg/L (only two dishes exceeded 4 mg/L) and five out of 14 sampled ceramics were tagines. We observed a similar association (27% increase in GM) for families who declared using traditional ceramic cookware, which was not tested for lead release (13% of families overall). Lead was detectable in nine out of 16 kohl samples, mainly originating from Maghreb and Egypt, even though lead is forbidden in cosmetics in France. This exposure involved 3% of families (only mothers). Previous cases of lead exposure involving lead-glazed ceramics and kohl were identified among the 690 children screened in France (Inserm and InVS 2008) and in neonates in three maternity wards in the surroundings of Paris in 2004 (Yazbeck et al. 2007). Traditional cosmetics, such as surma and kohl, are also associated with high levels of lead exposure in children in the countries where they are frequently used (Al-Saleh et al. 1999;Goswami 2013;Nuwayhid et al. 2003;Rahbar et al. 2002) and in sporadic cases in the US (CDC 2004;CDC 2013b).

4.1.7 Environmental tobacco smoke

Although our results seem to confirm the influence of ETS on BLLs as already demonstrated by Mannino *et al.* (Mannino et al. 2003), Dixon *et al.*(Dixon et al. 2009) and Apostolou *et al.* (Apostolou et al. 2012), the relationship we observed was not statistically significant. We also found no trend between the duration of exposure to smoking indoors and BLLs. In addition this relationship did not remain when we added free complementary health insurance (CMUc) to the model as a proxy of poverty (data not shown).

4.1.8 Parent's occupational risk

We did not find a relationship between parents' occupation and BLLs. However the list of occupational activities was very general and 21% of parents declared activities related to lead exposure.

4.2 Limitations

First, a potential selection bias due to hospital recruitment could persist despite the consideration of the sampling weights and the post-stratification through the use of auxiliary information (available in the census). A residual bias may persist if some characteristics of the sampled children are highly correlated to blood lead levels and are not take into account in the sampling design or in the post-stratification. Following post-stratification, the proportions of complementary free health insurance (CMUc)-covered children, children and mothers born abroad and parents' occupational categories were essentially similar for the estimate for the population and national census data (Insee 2012). So, in fine, the potential selection bias, if any, seems minimal.

Second, although the quantile regression was more powerful than logistic regression, we did not have a sufficient sample size to study all the risk factors for extreme BLLs and the precision of the estimates was low.

And finally the design of the study did not allow us to assess past exposure of the children, food contribution, or exposure sources outside the home such as nursery, primary school or day care center.

5. Conclusion

This study provided insights into the many determinants of BLLs in a nationally representative sample of children with a large range of measures sources of exposure and harmonized data collection. We found that tap water, floor dust, cookware and cosmetics containing lead had a substantial contribution on the BLLs of children in France. For dust, even very low dust lead loadings had a noticeable contribution on BLLs and thus attempts to reduce dust lead loadings towards zero would be very beneficial for a large proportion of children. Furthermore, lead in dust had a greater contribution on elevated BLLs than on low BLLs; therefore, such measures would also benefit to the most exposed children. Most household tap water had a lead concentration lower than the current European standard; however, water remains a risk factor for elevated BLLs. Further reduction in lead concentration is necessary to limit the risk of lead exposure in children (Scientific Committee on Health and Environmental Risks (SCHER) 2011) and also pregnant woman as fetal death can occur at very low levels of water lead exposure (Edwards 2014). Protective measures as water lead filters use or exclusion of tap water consumption should be provided until the complete lead pipes removal. Exposure to cosmetics and dishes containing lead were also prevalent and were associated with an increase in BLLs. The use of such cosmetics should be avoided and traditional dishes should be limited to decorative purposes as far as possible.

The prevention of lead exposure is still a major goal for public health considering the absence of a clear toxicological threshold and the risk of exposure from low levels of lead in environmental sources.

Appendix A and B: Supplemental material

The Appendix A defines the construction of the variables included in the models. The Table B.5 describes the environmental risk factors of lead exposure in children in France for leachable lead. The Table B.6 displays the results of the quantile regression model for the 90th quantile of Blood Lead Levels for leachable lead.

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Conflict of interest: All authors declare they have no current or potential competing financial interests.

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Table 1: Estimated lead levels in blood and environmental sources of exposure, France 2008-2009.

	n	Min	P25	Median	P75	P95	Max	AM	GM
Blood lead levels (µg/L)	484	2.6	9.8	13	20.1	32.8	307.8	21.4	13.8
Interior floor dust (µg/m²)[a]	470	<2	3.7	8.3	18.9	62.1	796	19.6	8.7
Dust from indoor common areas (µg/m²)[b]	114	<2	18	25.2	43.7	384.1	6271	128.2	32.2
Tap water (µg/L)[c]	472	<1	<1	<1	2	6.1	74	1.9	<1
Exterior playground soil (mg/kg)[d]	315	1.7	17.3	27.2	60.2	253.8	3408	73.6	33.9
Exterior playground dust (µg/m²)[d]	53	<2	17	32.2	99	393.2	3225	96	44.4
Presence of lead in deteriorated household paint[e]	484	0	0	0	0	0	5.6	0.03	_
Presence of lead in household paint in a good condition[f]	484	0	0	0	0	0.52	19.5	0.2	_

n: number of children in the sample with no missing value, P25: 25th percentile, P75: 75th percentile, P95: 95th percentile, AM: arithmetic mean, GM: geometric mean

[a] Arithmetic mean of rooms frequented by the child with dust values below LOQ replaced by LOQ/2.
[b] Arithmetic mean of indoor common areas
[c] Tap water values below LOQ were replaced by raw data.
[d] Where the child plays
[e] Sum(XRF sum of deteriorated paint/surface of each room) per dwelling
[f] Sum(XRF sum of paint in a good condition/surface of each room) per dwelling

Table 2: Demographic and behavioral characteristics of children aged 6 months to 6 years, France 2008-2009.

		n	Estimated percentage
Child's age (years)	0.5 - < 1	71	9.7
	1	108	17.1
	2	93	14.6
	3	84	12.7
	4	62	27.1
	5	42	12.8
	6	24	6
Child's sex	Female	229	52.5
	Male	255	47.5
Parents smoking at home	Never	367	78.8
	< 1h/day	36	6.4
	1-2h/day	30	5.1
	2-5h/day	25	6.8
	>5h/day	17	2.9
Exposure to traditional ceramic cookware	Not used by family or measure of lead release <LOQ	414	87.3
	Used by family, but no measure of lead release available	59	11.2
	Used by family, measure of lead release >LOQ	11	1.5
Exposure to traditional cosmetics	Not used by family, or measure of lead release <LOQ	459	96.6
	Used by family, but no measure of lead release available	17	2.6
	Used by family, measure of lead release >LOQ	8	0.8
Parents' occupational risk	No	364	79.3
	Yes	120	20.7
Tap water consumption	No	210	39.5
	Yes	274	60.5

Table 3: Associations between environmental lead sources and geometric mean of blood lead levels in children in France in 2008-2009.

Quantitative variables												
	Percentiles				% increase (95% CI[a]) of BLL for a change in lead source from *p0* to *p1* percentile *(p0-p1)*							
Lead concentration by source of exposure	25	50	95	99	p25-p95		p25-p99		p50-p95		p50-p99	
Interior floor dust (µg/m²)	3.7	8.3	62.1	172.4	33	(14 ; 55)	34	(3 ; 74)	16	(0 ; 35)	17	(-10 ; 52)
Dust from indoor common areas (µg/m²)[b]	0	0	92.4	562.0	4	(-12 ; 22)	21	(-13 ; 70)	4	(-12 ; 22)	21	(-13 ; 70)
Tap water (µg/L) children drinking tap water	0.4	0.9	5.1	13.9	8	(-9 ; 28)	36	(2 ; 82)	14	(-2 ; 33)	44	(8 ; 92)
children drinking bottled water	0.4	0.8	6.0	21.0	-13	(-30 ; 7)	-11	(-38 ; 28)	-12	(-28 ; 28)	-10	(-37 ; 29)
Exterior playground soil (mg/kg)[c]	0	18.8	250.7	407.1	13	(-8 ; 35)	16	(-9 ; 42)	8	(-5 ; 21)	10	(-6 ; 27)
Exterior playground dust (µg/m²)[c]	0	0	32.1	187.5	18	(4 ; 32)	33	(8 ; 58)	18	(4 ; 32)	33	(8 ; 58)
Sum(XRF sum of deteriorated paint/surface of each room) per dwelling	0	0	0	0.9	0	_	0	_	0	_	5	(-7 ; 20)
Sum(XRF sum of paint in a good condition/surface of each room) per dwelling	0	0	0.5	3.3	2	(-2; 7)	13	(-15 ; 45)	2	(-2 ; 7)	13	(-15 ; 45)
Categorial variables												
			% increase (95% CI[a]) of BLL									
Parents smoking at home			**Never**		**< 1h/day**		**1-2h/day**		**2-5h/day**		**>5h/day**	
			Reference		7	(-19 ; 43)	18	(-12 ; 58)	10	(-32 ; 79)	13	(-23 ; 65)
Exposure to traditional ceramic cookware			**No[d]**		**Possible[e]**		**Yes[f]**					
			Reference		27	(7 ; 50)	56	(4 ; 132)				
Exposure to traditional cosmetics			**No[d]**		**Possible[e]**		**Yes[f]**					
			Reference		4	(-31 ; 56)	43	(-4 ; 113)				
Parents' occupational risk			**No**		**Yes**							
			Reference		-1	(-14 ; 14)						

[a] 95% Confidence Interval

[b] Concentrations set to 0 if indoor common areas were absent

[c] Concentrations set to 0 if the child did not play outside. The value for the exterior playground was set to 0 for soil if a hard surface was sampled and was set to 0 for dust if soil was sampled.

[d] Not used by family or measure of lead release <LOQ

[e] Used by family but no measure of lead release available

[f] Used by family, measure of lead release >LOQ

Table 4: Associations between environmental risk factors of lead exposure sources and the 90th quantile of blood lead levels in children in France in 2008-2009.

		Percentiles				% increase (95% CI) of BLL for a change in lead source from *p0* to *p1* percentile *(p0-p1)*							
Lead concentration by source of exposure		**25**	**50**	**95**	**99**	**p25-p95**		**p25-p99**		**p50-p95**		**p50-p99**	
Interior floor dust (µg/m^2)		3.7	8.3	62.1	172.4	75	(29 ; 139)	96	(30 ; 195)	50	(20;87)	67	(18 ; 137)
Dust from indoor common areas (µg/m^2)[b]		0	0	92.4	562.0	13	(-13 ; 45)	26	(-23 ; 104)	13	(-13;45)	26	(-23 ; 104)
Tap water (µg/L)	children drinking tap water	0.4	0.9	5.1	13.9	35	(-2 ; 85)	55	(-10 ; 167)	25	(-10;73)	43	(-13 ; 135)
	children drinking bottled water	0.4	0.8	6.0	21.0	36	(-7 ; 98)	66	(-18 ; 238)	26	(-5;67)	55	(-23 ; 209)
Exterior playground soil (mg/kg)[c]		0	18.8	250.7	407.1	-7	(-29 ; 21)	-9	(-35 ; 28)	-6	(-23;16)	-8	(-30 ; 22)
Exterior playground dust (µg/m^2)[c]		0	0	32.1	187.5	-5	(-24 ; 18)	-9	(-37 ; 34)	-5	(-24;18)	-9	(-37 ; 34)

[a] Confidence Interval

[b] Concentrations set to 0 if indoor common areas were absent

[c] Concentrations set to 0 if the child did not play outside. The value for the exterior playground was set to 0 for soil if a hard surface was sampled and was set to 0 for dust if soil was sampled.

Table B.5: Associations between environmental risk factors of lead exposure sources and geometric mean of blood lead levels in children in France in 2008-2009 (leachable lead).

Quantitative variables												
	Percentiles				**% increase (95% CI[a]) of BLL for a change in lead source from *p0* to *p1* percentile *(p0-p1)***							
Lead concentration by source of exposure	**25**	**50**	**95**	**99**	**p25-p95**		**p25-p99**		**p50-p95**		**p50-p99**	
Interior floor dust ($\mu g/m^2$)	3.0	6.5	47.8	91.3	38	(17 ; 62)	44	(14 ; 82)	22	(5 ; 42)	27	(1 ; 61)
Dust from indoor common areas ($\mu g/m^2$)[b]	0	0	56.7	412.2	0	(-14 ; 16)	16	(-17 ; 61)	0	(-14 ; 16)	16	(-17 ; 61)
Tap water ($\mu g/L$) children drinking tap water	0.4	0.9	5.1	13.9	7	(-10 ; 27)	36	(1 ; 82)	13	(-3 ; 32)	44	(8 ; 92)
children drinking bottled water	0.4	0.8	6	21	-14	(-30 ; 7)	-12	(-39 ; 28)	-13	(-28 ; 28)	-11	(-38 ; 28)
Exterior playground soil (mg/kg)[c]	0	12.2	190	359.6	11	(-9 ; 31)	13	(-11; 38)	6	(-5 ; 18)	9	(-7 ; 26)
Exterior playground dust ($\mu g/m^2$)[c]	0	0	21	155.2	16	(4 ; 28)	30	(7 ; 54)	16	(4 ; 28)	30	(7 ; 54)
Sum(XRF sum of deteriorated paint/surface of each room) per dwelling	0	0	0	0.9	0	_	0	_	0	_	5	(-7 ; 19)
Sum(XRF sum of paint in a good condition/surface of each room) per dwelling	0	0	0.5	3.3	2	(-2 ; 7)	14	(-14 ; 46)	2	(-2 ; 7)	14	(-14 ; 46)
Categorial variables												
					% increase (95% CI[a]) of BLL							
Parents smoking at home			**Never**		**< 1h/day**		**1-2h/day**		**2-5h/day**		**>5h/day**	
			Reference		7	(-22 ; 45)	17	(-14 ; 60)	7	(-37 ; 81)	14	(-23 ; 65)
Exposure to traditional ceramic cookware			**No[d]**		**Possible[e]**		**Yes[f]**					
			Reference		28	(8 ; 52)	54	(6 ; 124)				
Exposure to traditional cosmetics			**No[d]**		**Possible[e]**		**Yes[f]**					
			Reference		7	(-32 ; 67)	44	(-10 ; 129)				
Parents' occupational risk			**No**		**Yes**							
			Reference		0	(-14;15)						

[a] 95% Confidence Interval

[b] Concentrations set to 0 if indoor common areas were absent

[c] Concentrations set to 0 if the child did not play outside. The value for the exterior playground was set to 0 for soil if a hard surface was sampled and was set to 0 for dust if soil was sampled.

[d] Not used by family or measure of lead release <LOQ

[e] Used by family but no measure of lead release available

[f] Used by family, measure of lead release >LOQ

Table B.6: Results of the quantile regression model for the 90th quantile of Blood Lead Levels in children, France 2008-2009 (leachable lead).

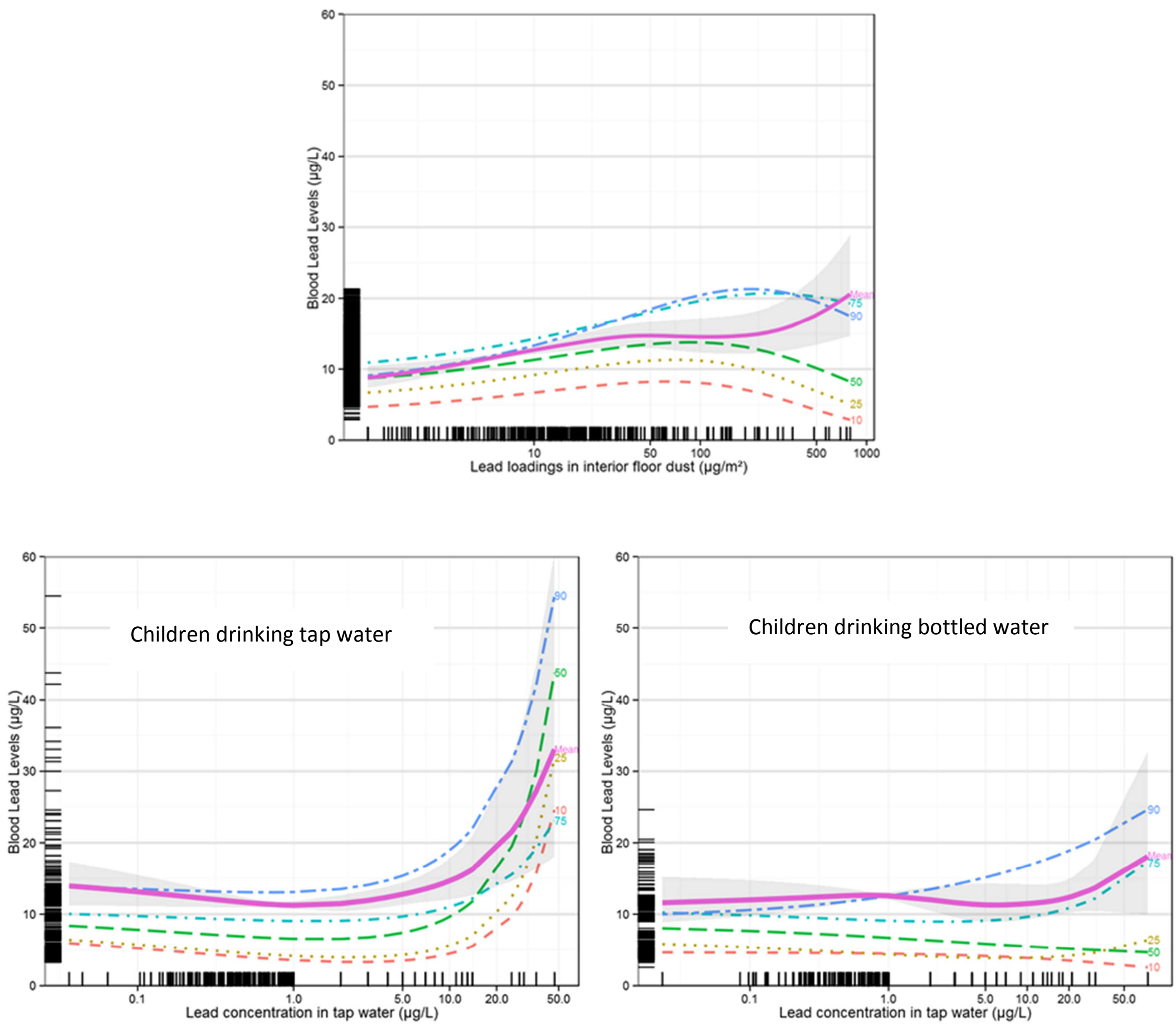
Lead concentration by source of exposure		Percentiles 25	50	95	99	% increase (95% CI) of BLL for a change in lead source from *p0* to *p1* percentile *(p0-p1)* p25-p95		p25-p99		p50-p95		p50-p99	
Interior floor dust (µg/m²)		3.0	6.5	47.8	91.3	67	(23 ; 125)	104	(36 ; 204)	44	(17 ; 77)	76	(25 ; 148)
Dust from indoor common areas (µg/m²)[b]		0	0	56.7	412.2	17	(-10 ; 50)	35	(-18 ; 120)	17	(-10 ; 50)	35	(-18 ; 120)
Tap water (µg/L)	children drinking tap water	0.4	0.9	5.1	13.9	24	(-6 ; 65)	81	(-2 ; 237)	23	(-2 ; 55)	79	(-2 ; 227)
	children drinking bottled water	0.4	0.8	6.0	21.0	33	(-5 ; 87)	57	(-17 ; 196)	24	(-3 ; 59)	46	(-22 ; 173)
Exterior playground soil (mg/kg)[c]		0	12.2	190.0	359.6	-10	(-33 ; 21)	-13	(-41 ; 29)	-8	(-26 ; 15)	-11	(-35 ; 23)
Exterior playground dust (µg/m²)[c]		0	0	21.0	155.2	1	(-19 ; 27)	3	(-31 ; 53)	1	(-19 ; 27)	3	(-31 ; 53)

[a] Confidence Interval

[b] Concentrations set to 0 if indoor common areas were absent

[c] Concentrations set to 0 if the child did not play outside. The value for the exterior playground was set to 0 for soil if a hard surface was sampled and was set to 0 for dust if soil was sampled.

Figure 1: Predicted mean and 10th, 25 th, 50 th, 75 th and 90 th quantiles of blood lead levels as a function of the lead levels in floor dust and tap water, France 2008-2009.



Appendix A_ Description of the selected variables introduced in the models

We averaged lead loadings of floor dust samples that were collected in rooms frequented by the child in each home. In the absence of an indoor common area, dust lead levels were set to 0. We introduced an interaction between water lead concentrations and tap water consumption. We used two variables for the exterior playground because the main outdoor play area was either a hard surface (providing loadings expressed in µg/m²) or soil (providing concentrations in mg/kg). When the soil was collected from a hard surface, the lead concentration in soil was set to 0 mg/kg, and vice versa. The presence of lead in paints was expressed as the sum of the XRF measurements in each room divided by the room's surface. The measures were added up by dwelling depending on the condition of the paint ("deteriorated" in the presence of chalking or chipping or in "good condition" in the presence of traces of shocks or micro-cracking). For glazed ceramics or traditional cosmetics we constructed a variable with three categories: 1) no exposure (the family either does not use ceramic cookware or traditional cosmetics, or lead released from their use is below LOQ), 2) use with no available measure for lead released from these sources, 3) use with a concentration of lead release above the LOQ. The parents' occupational risk of lead exposure was assessed by a questionnaire, using a list of occupations and professional activities defined by toxicological experts.

No values below LOQ were observed for outdoor dust and soil concentrations. Values below LOQ were assigned a value of LOQ/2 for indoor dust (1.8% of values in homes, 0% in common area). For tap water values below LOQ (53%) or LOD (18%), we included raw data despite their high uncertainty. We favored this method over a replacement by a single value (e.g. LOQ/2 or LOD/2) to avoid biased variance estimates and distorted inferences (Lubin et al. 2004).