The impact of childhood lead exposure on adult personality: Evidence from the United States, Europe, and a large-scale natural experiment

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Childhood lead exposure has devastating lifelong consequences, as even low-level exposure stunts intelligence and leads to delinquent behavior. However, these consequences may be more extensive than previously thought because childhood lead exposure may adversely affect normal-range personality traits. Personality influences nearly every aspect of human functioning, from well-being to career earnings to longevity, so effects of lead exposure on personality would have far-reaching societal consequences. In a preregistered investigation, we tested this hypothesis by linking historic atmospheric lead data from 269 US counties and 37 European nations to personality questionnaire data from over 1.5 million people who grew up in these areas. Adjusting for age and socioeconomic status, US adults who grew up in counties with higher atmospheric lead levels had less adaptive personality profiles: they were less agreeable and conscientious and, among younger participants, more neurotic. Next, we utilized a natural experiment, the removal of leaded gasoline because of the 1970 Clean Air Act, to test whether lead exposure caused these personality differences. Participants born after atmospheric lead levels began to decline in their county had more mature, psychologically healthy adult personalities (higher agreeableness and conscientiousness and lower neuroticism), but these findings were not discriminable from pure cohort effects. Finally, we replicated associations in Europeans. European participants who spent their childhood in areas with more atmospheric lead were less agreeable and more neurotic in adulthood. Our findings suggest that further reduction of lead exposure is a critical public health issue.

personality traits | environment | lead | toxins | personality development

Childhood lead exposure causes substantial physical and psychological problems. Among other deficits, children exposed to even low amounts of lead have lower intelligence quotients (IQs) (1, 2), drop out of school more often (3), and are more likely to exhibit conduct problems (4). In response to research highlighting the devastating consequences of lead exposure, US and European governments severely curbed lead emissions throughout the late 20th century, and blood lead levels in the population dropped by 93.6% from 1970 to 2016 (5). Despite this improvement, low-level lead exposure continues to cause population-wide problems (6–8). Researchers have estimated that further reduction of lead exposure could save US society 1.2 trillion dollars by reducing crime and delinquency (8), which is over a quarter of the 2020 US federal budget. However, the costs of lead exposure may be even greater than this trillion-dollar estimate because lead exposure, even at low levels, may impact people's personality traits [i.e., habitual patterns of thought, feeling, and behavior (9)]. By affecting broad personality traits, even low levels of lead exposure in the general population would have profound consequences for societal happiness, health, and wealth (10–12).

Little is known about the link between lead exposure and nonclinical personality traits. A single study to date has examined associations between childhood lead exposure and adult personality among a cohort of 579 New Zealanders (13). Blood lead levels were collected at age 11, when 90% of the sample had clinically high levels of blood lead by modern standards (>5 μg/dL). As adults, those with higher childhood blood lead levels were less agreeable, less conscientious, and more neurotic. These three personality domains are emblematic of psychological maturity (14) and indicative of a psychologically healthy personality (15). These results provide initial evidence for a negative association between lead exposure and a healthy adult personality. However, it is unclear whether these findings generalize to other geographic regions or to younger age groups who generally have had lower levels of lead exposure. More importantly, this correlational study did not address whether lead exposure actually causes personality trait differences.

To address these questions, we examined associations between personality traits and childhood atmospheric lead exposure in over 1.5 million US and European adults (see Fig. 1 for an analysis

Significance

Childhood lead exposure causes lifelong psychological problems, which may be more extensive than previously thought. In a sample of over 1.5 million people, we found that US and European residents who grew up in areas with higher levels of atmospheric lead had less adaptive personality profiles in adulthood (lower conscientiousness, lower agreeableness, and higher neuroticism), even when accounting for socioeconomic status. These effects were driven by participants ages 20 to 39. In a natural experiment, reductions of leaded gasoline in the United States following the 1970 Clean Air Act corresponded with increases in psychologically healthy personality traits. These results suggest that even low-level lead exposure may adversely impact personality traits, harming the well-being, longevity, and economic prospects of millions of people.

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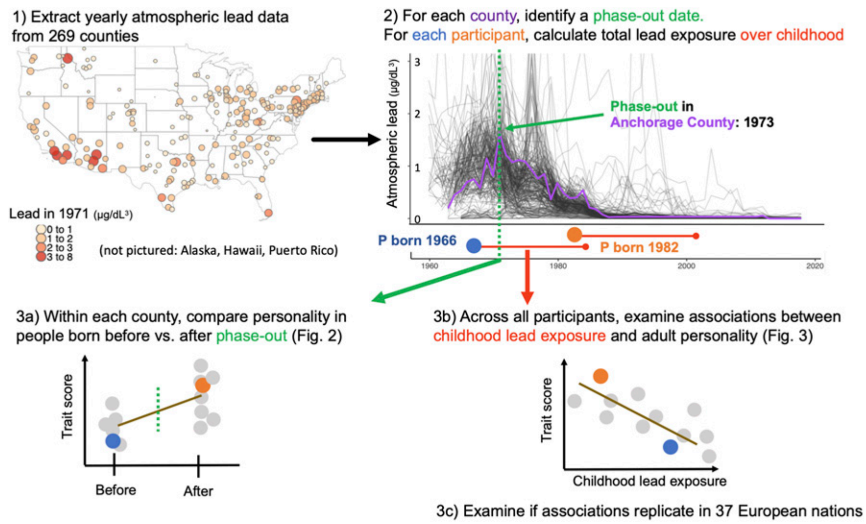

Fig. 1. Analysis flowchart.

flowchart). In an online survey unrelated to lead exposure, participants completed a personality questionnaire and provided their childhood zip code as well as the number of years they lived there. We estimated each participant's atmospheric lead exposure over the course of their childhood by linking these data to Environmental Protection Agency (EPA) measurements of atmospheric lead collected since 1960 by lead monitoring stations in 269 US counties. Across the late 20th century, atmospheric lead was by far the leading cause of blood lead levels, allowing us to use atmospheric lead as a measure of lead exposure (16).

In the present research, we tested three sets of preregistered hypotheses (https://www.osf.io/w7xd3). First, we examined associations between childhood atmospheric lead exposure and adult personality traits in the United States. Second, we examined whether lead exposure caused changes in personality traits using a natural experiment: the historical phase out of lead-based products in the United States that began in the 1970s (5). Specifically, we compared the personality profiles of individuals born before versus after each county's reduction in atmospheric lead levels. Lead reduction occurred in different years in different counties, allowing us to disentangle cohort effects (e.g., changes beginning in 1971) from effects tied specifically to the date of lead reduction in a given county. Critically, the reduction of atmospheric lead was driven by changes in petroleum company production and distribution rather than local policy changes, decoupling the timing of lead reduction from other county-level variables. By comparing personality trait levels within a county before and after an event that occurred at a date unrelated to potential confounds, we were able to rule out third-variable, cohort, and reverse causality effects and thus naturalistically investigated whether lead reductions caused changes in personality traits (see ref. 17). Finally, to test our third hypothesis, we examined whether associations between childhood lead exposure and personality differences generalized to Europe. In Europe, lead was phased out later than in the United States (18), and atmospheric lead was measured slightly differently, providing a robust test of whether lead–personality associations are generalizable. European atmospheric lead data were measured by a network of monitoring stations and then estimated as a continuous distribution across 37 nations for each year since 1990. We estimated each European participant's childhood lead exposure using the weighted distance from the four nearest atmospheric lead monitoring stations and examined whether this measure of lead exposure predicted their personality traits as measured in the online personality survey completed in adulthood. In sum, this suite of analyses provided a rigorous, precise, and generalizable series of tests of links between childhood lead exposure and adult personality in a sample that is highly diverse in terms of geography, age, and level of atmospheric lead exposure.

We hypothesized that lead exposure would be associated with lower agreeableness, conscientiousness, and openness to experience, and higher neuroticism. These predictions were based on past research on lead exposure and clinical problems. For example, childhood lead exposure increases risk for both general and specific psychopathology (13). Psychopathology is tied closely to the Big Five personality domain of neuroticism, which encompasses anxiety, depressiveness, and volatility (19). Similarly, conduct disorders and delinquency can be conceptualized as clinically low levels of agreeableness, a domain spanning warmth and empathy, and conscientiousness, which measures achievement striving, orderliness, and impulse control (20). Together, neuroticism, conscientiousness, and agreeableness are emblematic of psychological maturity—neuroticism decreases across adolescence and adulthood, while conscientiousness and agreeableness increase (21), and these three domains predict a host of valued outcomes in the domains of work and love (11, 12). Additionally, because lead exposure is associated with disrupted cognitive functioning (1, 2, 6), we hypothesized that childhood lead exposure would also be associated with lower openness to experience, a Big Five personality domain that measures intellect, creativity, and curiosity (22).

Finding associations between childhood lead exposure and adult personality traits in this large, multicohort sample would expand our understanding of the historical and ongoing effects of lead exposure. Specifically, because the average adult had a blood lead level of 13 µg/dL in the 1970s (5), an amount that is now twice the cutoff for clinical attention, millions of people born from the 1930s (when leaded gasoline became popular worldwide) to the mid-1970s (when it was phased out) may have had their personalities adversely affected. If these associations persist at low levels of exposure, current generations may still be experiencing lifelong consequences from lead exposure (18, 23). Even a small association between lead exposure and personality, when aggregated across millions of people and their countless decisions and behaviors influenced by personality, could have large effects on societal well-being, productivity, and longevity (10, 24, 25).

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Results

Associations between Atmospheric Lead Exposure and Personality in the United States. First, we conducted a series of regressions to examine the associations between US participants' atmospheric lead exposure across their first 18 y of life and each of the Big Five personality traits in adulthood, adjusting for age and socioeconomic status (SES; *SI Appendix*, Table S6). Consistent with our hypotheses, greater lead exposure predicted lower levels of adulthood agreeableness ($B = -0.031$, 99% CI [−0.034, −0.027]) and conscientiousness ($B = -0.079$, 99% CI [−0.083, −0.076]). However, contrary to hypotheses, lead exposure did not significantly predict neuroticism at $P < 0.001$ ($B = 0.002$, 99% CI [−0.002, 0.006]) and was predictive of higher openness ($B = 0.010$, 99% CI [0.006, 0.014]). Finally, lead exposure predicted higher levels of extraversion ($B = 0.021$ 99% CI [0.017, 0.025]).

These findings were generally robust to alternate specifications (Table 1 and *SI Appendix*, Tables S7–S11), which each provided additional information about the nature of associations between lead exposure and personality. Although SES is usually considered as a confounder of the association between lead exposure and negative psychological outcomes, associations were not affected by the removal of SES as a covariate. In fact, participants who lived in higher-income counties were only exposed to slightly less atmospheric lead on average ($r = -0.04$), which replicates the small effect found in Reuben et al. (13). Past research has found that the effects of lead on IQ are nonlinear, with stronger negative effects at lower levels of lead exposure (1). We found a similar pattern indicating that associations between lead exposure and personality were stronger among people with lower levels of lead exposure (<0.25 μg/L^3 per year) than people with higher levels of exposure. College students make up a large portion of our sample and are disproportionately high SES and high on openness (26). When removing them from our analyses, lead exposure was no longer significantly associated with openness, but associations with all other traits were unaffected. At many lead monitoring sites, data collection was discontinued when atmospheric lead levels fell. We originally imputed these missing data to match national trends in overall atmospheric lead decline. When we instead imputed this missing data under the highly conservative assumption that atmospheric lead levels stayed constant afterward, associations were smaller in magnitude, but the pattern of significant results was not affected. Finally, people may have been exposed to atmospheric lead from nearby counties. However, accounting for atmospheric lead from counties within 50 miles of a person's home county did not improve our prediction of personality traits.

Notably, associations between childhood lead exposure and adult personality varied across age groups (Fig. 2 and *SI Appendix*, Tables S12–S16). When stratifying participants into 10-y age groups, the effects of lead exposure on agreeableness and conscientiousness were driven by strong associations among adults in their 20s and 30s at the time of personality measurement, whereas associations between lead exposure and agreeableness and conscientiousness were not significant in older groups. Furthermore, although associations between lead exposure and neuroticism were null in the complete sample, lead exposure predicted higher adult neuroticism among adults in their 20s ($B = 0.047$) and 30s ($B = 0.023$) in line with our hypotheses. This variation across age groups raises the possibility that main effects were driven by age differences in personality rather than the effects of differing lead exposure. When we explored this by mean-centering personality

Table 1. Associations between childhood atmospheric lead exposure and adult personality traits across model specifications

Sample	Test	Preregistered	Ext.	Agr.	Con.	Neu.	Ope.	Full results in *SI Appendix* Table
United States	Preregistered covariates	Yes	0.022*	**−0.030***	**−0.079***	*0.002*	*0.009**	S6
	Additional covariates requested in revision		0.003	**−0.009***	**−0.016***	**0.009***	*−0.001*	S17–S21
	Not controlling for SES	Yes	0.021*	**−0.030***	**−0.079***	*0.002*	*0.007**	S7
	Among participants with higher exposure	Yes	0.010*	*−0.004*	**−0.016***	*−0.007*	*0.016**	S8
	Among participants with lower exposure	Yes	0.045*	**−0.190***	**−0.300***	**0.074***	*0.031**	S9
	Excluding college students	Yes	0.025*	**−0.022***	**−0.077***	*−0.003*	*0.001*	S10
	Alternate missing data imputation method	Yes	0.004*	**−0.004***	**−0.011***	*−0.00003*	*0.002**	S11
	Lead–age interaction, age <20†		0.050	*0.024*	*0.021*	*0.003*	*0.050*	S22
	Lead–age interaction, age 20 to 29		−0.007	**−0.091***	**−0.063***	**0.061***	*−0.007*	S22
	Lead–age interaction, age 30 to 39†		0.008	**−0.041**	**−0.054**	**0.018**	*0.008*	S22
	Lead–age interaction, age 40 to 49†		0.016	*−0.001*	**−0.018**	*−0.013*	*0.016*	S22
	Lead–age interaction, age 50+†		0.010	*−0.002*	*0.003*	*−0.004*	*0.010*	S22
	Lead–region interaction, Northeast		0.030*	**−0.040***	**−0.106***	*0.006*	*0.036**	S23
	Lead–region interaction, West†		0.026	**−0.025**	**−0.065**	*0.000*	*0.002*	S23
	Lead–region interaction, Southwest†		0.035	**−0.059**	**−0.137**	**0.020**	**−0.012**	S23
	Lead–region interaction, Midwest†		0.017	**−0.047**	**−0.122**	*0.006*	*0.025*	S23
	Lead–region interaction, Southeast†		0.030	**−0.029**	**−0.094**	**0.012**	*−0.003*	S23
Europe	Preregistered covariates	Yes	0.005	**−0.049***	*0.014**	**0.025***	*0.079*	S6
	Not controlling for SES	Yes	−0.011*	**−0.061***	*−0.003*	**0.054***	*0.077**	S32
	Only participants nearby lead measurement	Yes	0.001	**−0.038***	*0.012**	**0.022***	*0.072**	S33
	Excluding college students	Yes	0.008*	**−0.050***	*0.017**	**0.024***	*0.079**	S34

Ext. = Extraversion. Agr. = Agreeableness. Con. = Conscientiousness. Neu. = Neuroticism. Ope. = Openness. * = $P < 0.001$. Each row summarizes standardized multiple regression coefficients of interest from one set of models. Bold text indicates that the effect was as hypothesized. Italic text indicates that the effect was not as hypothesized. The column for Extraversion is not marked because we did not make any hypotheses about this trait.

†For interaction parameters, effects are calculated by the difference from the reference group (20 to 30 y olds and northeastern US residents) rather than the difference from 0, preventing use of significance asterisks. For these models, we marked results according to directionality and effect size, with $B \geq 0.01$ considered the threshold for a meaningfully large effect.

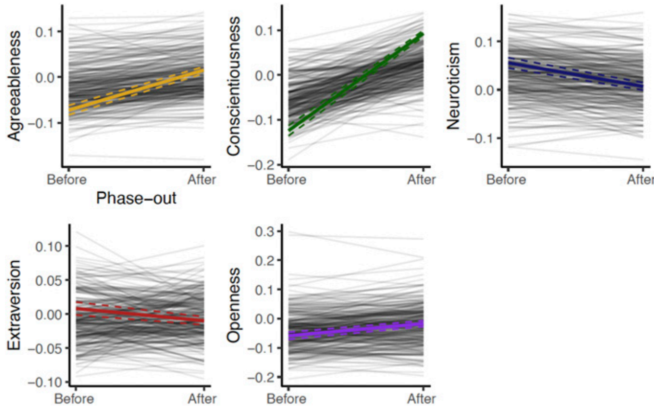

Fig. 2. Change in personality before and after lead phase out in 269 US counties (n = 1,219,290). Colored lines depict the model-implied before–after shift in personality traits across all counties, with a dashed 95% CI. The gray lines depict model-implied shifts in each county. The scores are standardized.

data for each age group, significant effects persisted, suggesting that age differences in personality did not explain associations between lead exposure and personality.

We also conducted additional analyses that were requested in review (Table 1 and *SI Appendix*, Tables S17–S24). The results indicated that the main effects of lead exposure on agreeableness and conscientiousness were robust to additional controls for SES, age, and geography, though associations were smaller in magnitude with covariates added. This reduction in effect size may be partially attributable to simultaneously controlling for age group, age, and year born because time accounted for a substantial portion of variance in lead exposure. Furthermore, associations with openness and extraversion were no longer significant when additional controls were added. Although associations between lead exposure and neuroticism were null in our preregistered analyses, lead exposure predicted higher neuroticism when additional controls were added (B = 0.009, 95% CI [0.004, 0.014]). Additional interaction analyses again indicated that the effects of lead exposure varied across age groups, following the same patterns as in age-stratified analyses. These analyses also indicated that associations between lead exposure and personality persisted but differed slightly in magnitude across geographic regions. One consistent geographic pattern emerged: associations between lead exposure and agreeableness, conscientiousness, and neuroticism were stronger in the southwestern United States than in other regions.

Personality Trait Shifts in Each US County following Lead Phase Out. We next examined whether people born in each county after atmospheric lead reduction began differed in their personality trait scores from those born before lead reduction. Preliminary analyses justified our use of lead phase out as an exogenous shock to the environment, as there was substantial variation in the year that lead reduction began across US counties (M = 1973, SD = 4.27 y, range = 1964 to 1995), and each county's date of reduction was not associated with its median household income (r = 0.06, P = 0.297).

To investigate shifts in personality traits following lead reduction at the county level, we estimated a multilevel model in which participants nested in each of 269 US counties were born either before or after the date when atmospheric lead began to decline in that county. Supporting our hypotheses, participants born after declines began were on average more agreeable (B = 0.088, 99% CI [0.075,0.101]), conscientious (B = 0.217, 99% CI [0.201, 0.233]), open to experience (B = 0.042, 99% CI [0.026, 0.057]), and less neurotic (B = −0.049, 99% CI [−0.062, −0.036]). Additionally, these participants were less extraverted (B = −0.018, 99% CI [−0.032, −0.004]). These results are presented in Fig. 2 and *SI Appendix*, Table S25. Most individual counties also followed this overall trend, but follow-up tests indicated that personality traits shifted more strongly in some counties than in others. This can be seen in the varying slopes of the gray lines in Fig. 2.

We then conducted additional preregistered tests to examine the conditions under which these findings held (*SI Appendix*, Tables S26–S30). Overall, these tests provided further evidence that lead reduction accounted for these shifts in personality traits. First, we ruled out that the observed shifts in personality were driven by people born many years before or after reduction began by restricting the analyses to participants born ±10 y after reduction or ±20 y after reduction. We also ruled out that findings were driven by the large number of college students in our sample, as findings did not differ when excluding these participants. We then tested the effect of adding in time lags to the date of phase out. Adding in a 5-y lag to the date of reduction decreased the strength of associations between lead and personality, and adding in a 10-y lag decreased the strength associations even further and flipped the sign of the conscientiousness and openness associations. These results suggested that effects were strongest and most consistent when estimating no lag between each county's date of lead reduction and its corresponding shift in personality traits.

Finally, we investigated whether personality shifts could be completely dissociated from cohort effects by examining personality shifts when we set all counties' dates of lead reduction to 1971, the date that the Clean Air Act was instituted nationwide, instead of estimating a unique date of reduction for each county. If we were to find that personality shifts corresponded to each county's unique date of lead reduction but were unassociated with chronological year, it would provide reasonable evidence that lead exposure caused these shifts. When we estimated a model in which lead reduction was set to 1971, shifts in conscientiousness became more pronounced compared to base results, but shifts in neuroticism were no longer significant (*SI Appendix*, Table S31). Additionally, shifts in openness and extraversion flipped in sign. Because shifts in personality were tied both to chronological year and to the county-specific date of lead phase out, both cohort effects and lead reduction remain plausible causal drivers of observed personality shifts in each county. In other words, lead exposure may be responsible for observed shifts in personality, but other changes that occurred in the 1970s may alternately, or additionally, be responsible.

Associations between Atmospheric Lead Exposure and Personality in Europe. Last, we examined whether results found in the United States generalized to 37 European nations. We conducted a series of regressions to examine the associations between the average atmospheric lead from 1990 to 2015 at each European participant's childhood postal code and their personality traits in adulthood, adjusting for age and SES. In line with our hypotheses, greater atmospheric lead exposure was associated with lower adult agreeableness (B = −0.049, 99% CI [−0.053, −0.045]) and higher neuroticism, (B = 0.025, 99% CI [0.021, 0.029]). However, inconsistent with our hypotheses, lead exposure was associated with higher adult conscientiousness (B = 0.014, 99% CI [0.010, 0.018]) and openness (B = 0.079, 99% CI [0.075, 0.083]). Lead exposure was also predictive of higher extraversion (B = 0.005, 99% CI [0.001, 0.009)]. These results are shown in Table 1 alongside the findings in the US sample. For all traits except conscientiousness, findings in the United States and Europe were in the same direction.

We then conducted additional preregistered tests, which indicated that our findings were robust to alternate specifications. (Table 1 and *SI Appendix*, Tables S32–S34). Again, associations did not differ when excluding college students. Associations were also unchanged when excluding participants who grew up >0.25° latitude or longitude from the nearest atmospheric lead measurement and therefore had less precise estimates of atmospheric lead exposure. However, when removing SES controls, associations between lead and conscientiousness were no longer significant, and associations between lead and extraversion were now negative, suggesting that in the European but not US sample, SES was associated with both lead exposure and personality trait scores.

Discussion

We conducted a rigorous, precise, and generalizable series of tests to examine whether childhood atmospheric lead exposure predicted adult personality traits in over 1.5 million people across the United States and 37 European nations. Supporting our preregistered hypotheses, we found that participants with greater childhood exposure to atmospheric lead grew up to have less mature and less healthy personalities in adulthood. People with higher levels of childhood lead exposure were less agreeable, less conscientious (in the US sample), and more neurotic (among younger participants). However, inconsistent with our hypotheses, people with greater atmospheric lead exposure grew up to be more open to experience. We also conducted a natural experiment to test whether lead caused these personality trait differences. Supporting our hypotheses, we found that people born in each US county after atmospheric lead reduction began had healthier, more mature personality profiles. They were more agreeable, more conscientious, more open to experience, and less neurotic. Follow-up tests suggested that these personality shifts could have been caused by lead reduction and/or other unmeasured changes in the United States that occurred in the early 1970s.

Psychological Implications. Each successive wave of research on the effects of lead exposure has identified broader and more pernicious harms. In this study, we tapped into a recent wave that has begun to demonstrate the many ways in which low-level lead exposure may impair everyday functioning. Our results replicated and extended those by Reuben and colleagues (13), indicating that the effects of lead on personality traits were pervasive: across the majority of tests, samples, and nations, children exposed to greater levels of atmospheric lead grew up to become more anxious, depressed, and emotionally less friendly, warm, and compliant, and less organized, disciplined, and goal striving. In other words, atmospheric lead exposure was associated with a broad array of unhealthy personality traits. This pattern of findings helps explain observed links between lead exposure and clinical problems. Low levels of agreeableness and conscientiousness have been related to a suite of behavioral issues, including substance misuse, criminal behavior, risky sex, and aggression (20), and high levels of neuroticism have been found to be at the heart of virtually all mental health problems (19). Though many people exposed to low levels of lead may not develop these clinical issues, they may at increased risk for similar changes at a subclinical level.

These broad harms were not confined to only those with high levels of lead exposure. We found significant deleterious effects of childhood lead exposure on adult personality even among those exposed to low amounts of atmospheric lead (<0.25 $\mu g/L^3$ per year). In fact, associations between lead exposure and unhealthy personality traits were even stronger among this low-exposure group, a nonlinear pattern that has also been found in research on lead and cognitive development (1). These findings suggest that there seems to be no "safe" level of lead exposure for personality. Overall, the results of this study and past research paint a clear picture: people with greater exposure to lead have less mature, less healthy personalities.

Societal Implications. To the extent that lead exposure affects personality traits, the societal cost of lead exposure may be massive because lead effects may accumulate over time, across many personality traits, and among huge numbers of people. Although the effects we found were small by conventional standards (average $r = \sim 0.05$), even slight changes to personality are likely to have snowballing consequences, as personality influences a lifetime of daily thoughts, emotions, and behavioral choices (11, 25). For example, a person who is exposed to low levels of atmospheric lead and thus becomes even slightly less agreeable may have hundreds more negative interpersonal interactions over the years, impacting their school performance, job prospects, and each of their personal and professional relationships. However, lead exposure is not solely associated with lower agreeableness: our results suggest that these gradually snowballing effects may occur across the personality trait domains of agreeableness, conscientiousness, and, to some extent, neuroticism, providing a broad psychological arena for lead exposure to affect many different aspects of a person's life. Furthermore, these effects may apply to broad swaths of the population. Millions of people born in the mid-20th century were exposed to high levels of atmospheric lead from leaded gasoline, and, although lead exposure is now much lower on average, an estimated 400,000 children in the United States still have clinically high levels of lead (>5 $\mu g/dL^3$) in their blood (8).

Unfortunately, the ongoing harms of lead exposure disproportionately burden vulnerable populations. Although there is now much less lead in the atmosphere (5), it remains in the topsoil and groundwater, especially in industrial urban areas that are generally lower income and less educated (26). This remaining lead is especially "sticky" and remains in the environment for many years if not removed, exerting negative effects that can persist across generations (27, 28). The disproportionate costs borne by low SES individuals make the further reduction of lead exposure an issue of social justice and equity.

Past research has estimated that lead exposure costs the United States 1.2 trillion dollars, which does not include costs incurred through negatively affecting personality traits (8). The societal costs of psychologically unhealthy personality traits are substantial: for example, low conscientiousness reduces the worldwide life expectancy by an estimated 1.3 y and reduces disability-free life expectancy by an estimated 1 y (29), and people in the top 25% of neuroticism cost an estimated 1.4 billion additional dollars per million people in excess healthcare burden, which is 2.5 times more than the cost of mental disorders (24). As we improve and broaden our understanding of the psychological harms of lead exposure, estimates of lead's true costs may skyrocket.

Limitations and Future Directions. Our investigation greatly expanded the scope of knowledge about the effects of lead exposure on personality traits, but some important limitations require attention. Although atmospheric lead represents the major contributor to blood lead levels throughout the 20th century (5, 18), there is not a one-to-one correspondence between atmospheric exposure and blood lead levels, and this measurement imprecision may have biased our effect sizes downward. Future research that accounts for lead exposure from other sources, such as leaded paint, pipes, and soil, may be better able to estimate the true negative effect of lead on personality. Additionally, our research focuses on a particular historical period in Western culture, covering the years when atmospheric lead was reduced through a phase out of leaded gasoline. Research in other cultural contexts, as well as in specific subpopulations with high lead exposure [such as the many people exposed to leaded drinking water in Flint, Michigan (23)], is needed to better understand the generalizability of our findings. Specifically, research in different cultural contexts could more fully disentangle lead reduction from other societal changes that occurred in the 1970s United States, such as the

PSYCHOLOGICAL AND COGNITIVE SCIENCES

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Vietnam War, the introduction of no-fault divorce, and the ascendance of feminism.

Though the majority of our analyses supported our preregistered hypotheses, there were some anomalous results that challenged our conclusions. These findings can serve as useful directions for future investigation. First, not all associations were in the direction we predicted. Associations between lead exposure and openness were generally positive, which contradicted our hypotheses, and associations between lead exposure and conscientiousness were robustly negative across all geographic regions of the United States but positive or null in Europe. Future research is needed to better understand which personality traits are negatively associated with lead exposure and identify the boundary conditions on these associations. A second major limitation was that associations between lead exposure and personality traits varied across age groups. Though we found robust negative effects among those aged 20 to 39 y old, lead exposure did not predict personality trait levels in older participants. These findings echo those of the other study to date that has examined associations between lead exposure and personality traits, which found significant effects in a cohort of 38 y olds (13). These findings speak to a need for future longitudinal research to disentangle whether the effects of lead exposure on personality traits are indeed confined to specific age groups, cohorts, or time periods (30).

Conclusion

Low-level childhood lead exposure is pervasively associated with psychological dysfunction, and we found that greater lead exposure predicts a less mature, psychologically healthy personality trait profile in adulthood. Despite worldwide reduction in lead exposure, hundreds of thousands of children may continue to experience the negative effects of lead on personality traits (7, 8).

Widespread reductions of blood lead levels over the late 20th century showed that lead exposure can be directly influenced by government regulations on corporate lead emissions (5). However, the United States has recently rolled back some of these regulations (31), putting future generations at risk for increased exposure to lead. Research on the psychological effects of lead exposure suggest that these rollbacks will lead to long-term harm that greatly outweigh any short-term benefits. Rather, further restrictions on lead emissions are needed to maximize human flourishing.

Materials and Methods

Sample and Measures Personality data for this study came from the Gosling–Potter Internet Personality Project (GPIPP; https://www.thebigfiveproject.com/), an internet study of over eight million people from around the world. The data collection efforts of the GPIPP have been declared exempt from approval by the Institutional Review Board (IRB) of the University of Texas, Austin (IRB number: 2004–10-0073). Since the early 2000s, visitors to the GPIPP website have completed personality questionnaires and given consent for their data to be used for research purposes. Previous research has demonstrated that US GPIPP participants are broadly representative of the racial composition of the US general population: 71.7% identified as White/Caucasian whereas 9.4% identified as Black and 2.9, 8.2, 1.1, and 5.0% identified as Asian, Hispanic, Mixed, or Other (32, 33). This sample is also representative of population size and social class membership of each US state, although it contains a greater proportion of college students than the general population does. Across European nations, GPIPP participants were also more likely to be college students, and there were proportionally fewer participants from southeastern European nations (see https://osf.io/qzjtm/ for complete information).

GPIPP participants completed the Big Five Inventory (BFI), a widely used 44-item index of the Big Five personality domains: extraversion, agreeableness, conscientiousness, neuroticism, and openness to experience (9). For each item, participants reported the degree to which they agreed with a short phrase (e.g., "I am someone who tends to be lazy") using a five-point rating scale (1, disagree strongly to 5, agree strongly).

Atmospheric lead levels for the United States came from the EPA and covered the years 1960 to 2018. At each lead measurement site, atmospheric lead was measured at multiple times throughout each year in micrograms per cubic liter. We averaged measurements within each year across each county's measurement sites and included data from all 269 counties with lead measurements from 1972 or earlier where there was sufficient data to calculate a date of lead reduction. Atmospheric lead levels for Europe come from the European Monitoring and Evaluation program and cover the years 1990 to 2015. Lead was estimated yearly as a continuous distribution across Europe in nanograms per cubic liter. In this study, we include lead data from the 37 European nations with GPIPP participants. To control for SES, we adjusted for county-level median annual household income in the United States and country-level gross domestic product per capita in Europe as well as parental education reported by GPIPP participants.

Methods. To test associations between lead exposure and personality in the United States, we included GPIPP participants who spent most of their childhood (10 or more years) in one of the 269 counties with sufficient lead data. We included only those participants who were born in the county after atmospheric lead data collection began (n = 1,104,455). For each participant, we estimated cumulative atmospheric lead exposure from living in that county over their first 18 y of life (see https://www.osf.io/w7xd3 for complete details and Fig. 1 for a visualization). We then conducted an ordinary least squares (OLS) regression for each Big Five trait to test whether childhood lead exposure predicted adult personality. Specifically, we estimated the following equation:

$$\begin{aligned}\text{Personality trait score} = b_0 + b_1 * \text{childhood lead exposure} + b_2 * \text{age}\\ + b_3 * \text{median county household income}\\ + b_4 * \text{parent attended college.}\end{aligned}$$

For each trait, we also tested whether it was necessary to account for spatial dependencies by conducting a test of Moran's I, which indicated that error terms were not spatially correlated ($ps > 0.001$).

We also conducted a series of additional analyses requested in review. These analyses were therefore not preregistered. First, we examined associations between lead exposure and personality traits when adding in additional controls: zip-code level median household income, zip-code level percent of the population that is non-Hispanic White, year born, decade age group (dummy coded), and geographic region of the United States (dummy coded into five regions). Then, we examined whether age group and geographic region interacted with lead exposure to predict personality trait scores.

To test personality trait shifts after each county's reduction in atmospheric lead levels, we included GPIPP participants who spent most of their childhood (10+ years) in one of the 269 counties with sufficient lead data, regardless of their date of birth (n = 1,219,290). For each county, we estimated the year after which lead levels dropped steadily by examining trends in atmospheric lead over time (see https://www.osf.io/w7xd3 for complete details). For each Big Five trait, we estimated a multilevel model to test whether participants born before versus after the date of lead reduction exhibited different levels of personality traits. In this model, participants were nested within counties and were assigned a time of either 0 (born before phase out) or 1 (born after phase out). The model included two random parameters, which varied across counties: intercepts (baseline average scores) and trait shifts (the extent to which traits changed after phase out) and controlled for age effects. Specifically, for county i, we estimated the following equation:

$$\begin{aligned}\text{Level 1: Personality trait score}_i = b_{0i} + b_{1i} * \text{born before/after phaseout}\\ + b_2 * \text{age} + e_i\end{aligned}$$

$$\begin{aligned}\text{Level 2: } b_{0i} &= \pi_{00} + \pi_{0i}\\ b_{1i} &= \pi_{10} + \pi_{1i}\end{aligned}$$

,

where π_{00} is the average trait score across counties, π_{0i} is the difference between the county's trait score and the average trait score, π_{10} is the average change in personality after the phase out across counties, and π_{1i} is the difference between the county's change after date of phase out and the average change after phase out.

To test associations between lead exposure and personality traits in Europe, we included all GPIPP participants who spent most of their childhood in a European nation where atmospheric lead levels were calculated. Unlike the US atmospheric lead data, which was collected at the county level, European lead data were modeled as a continuous distribution across latitude and longitude. Therefore, we calculated each participant's childhood lead exposure using the weighted distance from the four nearest lead measurement sites to their childhood postal code. Atmospheric lead data were collected in Europe beginning in 1990, which restricts our ability to model change in lead levels over time. However, because lead levels demonstrated high stability (r = 0.66 over 15 y), we estimated each participant's atmospheric lead exposure using the average yearly atmospheric lead levels over 1990 to 2015 at their childhood postal code (see https://www.osf.io/w7xd3 for complete details). For each Big Five trait, we conducted an OLS regression, as specified above, to test whether childhood lead exposure predicted adult personality after controlling for age and SES.

Data Availability. Preregistration documents, analysis syntax, and summary statistics grouped by US county and European country are available at https://www.osf.io/qzjtm/ (34). The individual-level data used in this study are proprietary; reasonable requests for access to the individual-level data will be granted by contacting S.D.G. (gosling@psy.utexas.edu). Deviations from the preregistration and descriptive information for study variables can be found in *SI Appendix*.

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