Lead Exposure and the Perpetuation of Low Socioeconomic Status

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1. Introduction

This paper addresses two questions: do socioeconomic status and family circumstance mediate the adverse effects of childhood lead exposure, and if so, why? Although these questions might seem better suited to a public health literature, understanding how early-life conditions mitigate or worsen the adverse consequences of environmental insults has important economic implications. In particular, answering these questions can help us explain the economics of human capital formation and the continuity of human capital stocks across generations. Recent economic research documents how gaps in cognitive and behavioral skills early in life persist into adulthood and how those gaps explain a large portion of the observed the black-white wage deficit (Neal and Johnson 1996; Carneiro et al. 2005). The significance of such premarket factors in sustaining social and economic inequality has prompted Heckman (2008) to call for policy interventions designed specifically for very young at risk children. Blanden et al. (2007) suggest that cognitive and non-cognitive skills partly explain the persistence in income inequality observed across generations.

Recent research implicates family structure and parental education in shaping the accumulation of human capital among children and perpetuating cognitive and educational disparities across generations. Black et al. (2010) show that unexpected changes in family size as caused by the birth of twins adversely affects intelligence, but other types of variation in the number of siblings have little impact on cognitive ability. Using health as a proxy for childhood health and nutrition and controlling for family-specific fixed effects with sibling pairs, multiple studies demonstrate that childhood health is a strong and significant predictor of adult well-being, including educational attainment and cognitive ability.[1] A parallel line of research uses birthweight as an indicator of health early in life and finds similar patterns (Black et al. 2007). Overall, it appears that children from poor socioeconomic backgrounds are more adversely affected by poor health, not because they have greater difficulty recovering from those shocks, but because they receive a greater number of them (Case, Lubotsky, and Paxson 2002; Currie and Stabile 2003). This research suggests that as children age, physiological insults accumulate and cognitive disparities widen.

Among economists, there has been surprisingly little attention given to the possibility that environmental health could even partly explain the propagation of cognitive disparities across socioeconomic groups (see Currie et al. 2013; Reyes 2007). Yet there are many intuitive reasons to believe that children from disadvantaged families would be more vulnerable to environmental degradation than other groups, including residential choice and location, overall health, diet, housing, and access to medical care (Needleman et al. 1990; Moodie et al. 2013). Accordingly, in this paper, we consider how and to what extent environmental lead exposure helped propagate socioeconomic differences in cognitive skills and educational attainment. The novelty of our effort resides not only in the question we consider, but also in the data we construct and the estimating strategy we employ, the combination of which allows us to identify and exploit a source of random variation in lead exposure. Our data set consists of individuals who have been matched across census and military records, and this allows us to estimate the long-term effects of lead exposure across socioeconomic groups, and in turn

[1]See, for example, Case and Paxson (2009 and 2011).

speaks directly to the question of how health insults accumulate over time. By the same token, it is often difficult to cleanly identify the effects of environmental lead exposure because exposure is in part a function of socioeconomic characteristics that might also influence intelligence and decisions to invest in education (Reyes 2007). This same phenomenon also confounds attempts to isolate and compare the consequences of lead exposure across socioeconomic groups.

Following a series of recent papers,[2] we use a quasi-natural experiment that generates random variation in the amount of lead in drinking water. Our analysis builds two bodies of research: first, the engineering concept of plumbosolvency; the second on factors that can mitigate the adverse effects of lead on neurological development. The first body of research suggests that water-related lead exposure is affected by the pH of drinking-water supplies in a non-monotonic way: for alkaline water sources (i.e., those with a pH greater than 7) increased pH is associated with greater lead uptake from the interior of lead water pipes and fixtures, while for acidic water supplies (i.e., those with a pH less than 7) increased pH is associated with reduced lead uptake from pipes and fixtures. The second body of research we exploit suggests that cognitive stimulation, like that likely provided in higher SES homes, reduces lead's adverse effects.

Given this research, we hypothesize that the long-term development of children from disadvantaged social backgrounds would be more sensitive to deviations in drinking water pH

[2](e.g., Troesken 2008; Clay, Troesken, and Haines 2010; and Ferrie, Rolf, and Troesken 2011)

than the development of children from advantaged backgrounds. We test this hypothesis by exploring an intelligence-related outcome (assignment to the Army Air Corps) among a newly compiled sample of recruits from World War II who have been linked to Census records that allow us to identify and control for various early life conditions, including the pH of their drinking water. The results are generally consistent with this hypothesis, as assignment to the air corps among recruits from disadvantaged socioeconomic groups drops off more sharply than air corps assignment among advantaged groups as the pH of early-life drinking water moves away from neutrality.

We also run a placebo test that allows us to rule out the possibility that the non-monotonic relationship we exploit is somehow correlated with unobservables. Specifically, if it was lead that was driving the non-monotonic relationship we observe it should apply most strongly in cities that use lead service pipes to distribute their water; it should not be observed, or only be observed in an attenuated form, in cities that do not use lead service pipes. The reason for this is that service pipes were the primary source of lead in public water supplies. Our results indicate that the hypothesized non-monotonicity in outcomes and pH levels applies to only cities with lead pipes. Cities without lead exhibit an attenuated non-monotonic relationship between outcomes and pH levels. That there is often a mild non-monotonic relationship for cities without lead reflects the fact that even in cities without lead water pipes, there was still lead to be found in household plumbing fixtures and pipes.

2. Water, Lead, and the Propagation of Intellectual Disparities

2.A. Lead as a Neurotoxin in Children

Although lead's effects are multisystemic, it is best known for its neurotoxicity. Exposure affects individuals throughout the lifespan: individuals who are exposed to lead can experience immediate symptomatology and also store in their bones lead that can affect their blood levels years later. Young children are more susceptible to lead than adults because of their smaller weight and developing systems. Risk will vary, however, depending upon the individual, the circumstances, and the amount of lead consumed. Recently, a specific polymorphism (*DRD2 Taq IA*) was identified as a genetic factor mediating the impact of lead exposure on intelligence (Roy et al. 2011). Individuals with the homozygous variant (A1) experienced an IQ drop of nine points for a one-log unit increase in blood lead levels, while individuals with the wild-type allele (A2) experienced only a four point drop for the same size increase in blood lead levels. This polymorphism "disrupts the protective effect of hemoglobin on cognition and may increase the susceptibility to the deficits in IQ due to lead exposure." (Roy et al. 2011, p. 144).

The effects of lead on children at low blood concentrations had been thought to be insignificant: at blood-lead levels below 10 μg/dl, variation in blood-lead levels were seen as having no effect on their intelligence. But recent research by Canfield et al. (2003) and Lanphear et al. (2000 and 2005) indicates that the marginal or incremental effects of increased lead exposure are greatest at the lowest levels of exposure, holding constant the child's age, levels long believed to have been safe. This new evidence suggests that IQ declines at a decreasing rate as lead exposure rises. There is, in particular, a rapid degradation in IQ at blood-lead levels below 10 μg/dl and a less rapid, though continuing, decline after this threshold has been reached.[3]

Lead's impact on the central nervous system stems mainly from its ability to mimic calcium, which is essential for effective neurotransmission. Lead mimics calcium because it has the same ionic structure: both lead and calcium are positively charged, with a valence of two. Lead also disrupts calcium homeostasis in cells, causing a build up of calcium in the cell and triggering premature cell death. In addition, because lead binds to cellular membranes at lower concentrations than calcium, it often clings to the relevant proteins and enzymes "more tightly" than calcium (Godwin 2001).

To appreciate lead's neurotoxic effects, it is useful to clarify the mechanisms that underlie effective neurotransmission. Neurotransmission builds on two cellular functions: exocytosis and endocytosis. Through exocytosis, cells release large molecules and particles, and through endocytosis other cells absorb the secreted material. In nerve cells, lead disrupts exocytosis—the release of neurotransmitters—and it does so in an asymmetric fashion. It enhances the release of spontaneous neurotransmitters, and inhibits the release of stimulated neurotransmitters. Put simply, lead exposure can cause impulse control problems, and at the same time, diminish a person's ability to respond to various social and environmental stimuli. In this regard, lead's asymmetric effects on nerve conduction might help explain the finding that lead levels are four times higher among convicted juvenile offenders than among a group

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[3]Lanphear et al. (2005, p. 894) conclude, "For a given increase in blood lead, the lead-associated intellectual decrement for children with a maximal blood lead level < 7.5 μg/dL was significantly greater than that observed for those with a maximal blood lead level ≥ 7.5 μg/dL ($p = 0.015$)."

of non-delinquent high school students (Needleman 2004; Simmons 1993).

Lead also interacts with Protein Kinase C (PKC), which regulates a broad range of metabolic functions, including cell growth, learning, and memory. PKC is activated by calcium, and at sufficiently high concentrations, lead competes successfully with calcium for binding sites on PKC (Newton 1995). Once lead has supplanted calcium on these sites it does not interact with the enzyme the same way that calcium would, and as a result, it disrupts PKC's ability to trigger cell growth and regulate the processes related to learning and memory. That lead is able to inhibit the release of neurotransmitters is related to PKC-associated proteins and processes. The connection between PKC and lead helps explain why lead exposure undermines mental development among children and young adults (Godwin 2001).

Lead neurotoxicity depends on its ability to penetrate the blood-brain barrier (BBB). The BBB is a construct that refers to the resistance most molecules confront when they spread out over the brain. Two factors inhibit molecular diffusion in the brain. First, the capillaries of the brain have tight cellular junctions. Second, the brain's capillaries are surrounded by a fatty sheath composed of astrocyte cells. At sufficiently high blood-lead levels (> 80 μg/dl), lead directly undermines the integrity of the BBB and alters vascular permeability in the brain. This explains historical cases where individuals consuming extraordinarily high lead levels in their tap water eventually died from hemorrhagic convulsions and brain edema. At low blood-lead levels, lead does not appear to gain entry into the brain by directly attacking the BBB. Instead at lower levels of exposure, lead gains entry into the brain through its ability to adhere to various proteins and enzymes which are necessary for proper functioning of the central nervous system. As suggested above, lead adheres to these proteins and enzymes as the direct result of its capacity to mimic calcium, as well as zinc and perhaps magnesium (Bradbury and Deane 1993; Needleman 2004).

2.B. Pathways From Exposure to Water-Born Lead to Diminished Intellectual Capacity

In the context of exposure to water-borne lead, we must consider the mechanisms by which lead will enter an individual's system at different stages in the life course: *in utero* (when the mother's exposure is a concern), in early life (when the child's feeding regime may shape exposure), and at later ages (when the direct ingestion of water as beverages and as a component of food preparation determine exposure levels). In terms of *in utero* exposure, it is important to be clear that nearly all lead in the human body is stored in the bones, and that much of this lead is mobilized during pregnancy (Dawson et al. 2000, and Dawson, Evans, Nosovitch, et al. 1999). Neurodevelopment, therefore, can be affected as early as the first trimester and throughout pregnancy (Manton et al. 2003).

Some evidence suggests that first pregnancies and lactations are at greater risk for lead exposure than subsequent pregnancies and closely spaced multiple pregnancies at the highest lead levels (Manton et. al. 2003). During lactation, lead can also be released from the nursing mother's bones. This release has been found to be greater than during pregnancy (Gulson et al. 1998). Formula prepared with lead contaminated water will elevate the blood lead levels (BLL) of infants. For example, infants who consume formula prepared with lead-contaminated water may be at higher risk because of the large volume of water they consume relative to their body size and the higher percentage of lead they absorb (Baum and Shannon 1997; CDC 2010).

Woodbury (1925) examined infant mortality and feeding practices in eight American cities for 22,967 live births and 813 still births in selected years between 1911 and 1916 for the Children's Bureau. Feeding practices were grouped into (1) exclusively breast-fed infants, (2) exclusively artificially fed infants, and (3) partially breast-fed infants. The formula fed to groups (2) and (3) would have been made with water. These rates varied by father's income, with higher income households using more artificial formula, and by nationality (Italian, Polish, and Jewish mothers used exclusively breast feeding longer than native mothers and all of these used it longer than Portuguese and French-Canadian mothers; Woodbury 1925, Table 71, p. 216) . By the end of the ninth month after birth, only 13 percent of infants were exclusively breastfed (Woodbury 1925, Table 67, p. 88), so even before the end of the first year of life, infants were at risk for exposure to water-borne lead. Other sources of lead exposure in children as they age include neonatal bone turnover (Gulson et al. 2001), because of bone growth and shaping and reshaping of bones, and hand to mouth activity (Manton et al. 2000).

2.C. How Enriched Environments Can Mitigate the Effects of Lead

Evidence from animal experiments shows how enriched environments can attenuate the effects of lead. These studies do not just show that animals from enriched, stimulative environments do better than those from not, but that the same amount of lead exposure adversely affected those from an enriched environment less than those from a deprived environment. For example, there are a series of laboratory experiments where rats from enriched environments and deprived environments were randomly assigned to lead exposure or no lead exposure.

In these experiments, lead was transmitted to the treated rats (in both enriched and deprived environments) through drinking water. Rats in enriched environments shared cages with other rats while deprived rats were isolated. Rats in enriched environments also had access to water mazes, exercise wheels, and other environmental stimuli. Strikingly, the neurological processing of lead-poisoned rats from enriched environments did not differ significantly (or differed relatively little) from that of non-lead-poisoned rats from enriched environments; large neurological disparities only emerged in rats from deprived environments.[4] Along the same lines, there are studies showing that rats impaired by lead poisoning can be made healthier and regain neurological capacity by environmental enrichment.[5] Finally, there is strong evidence that prenatal lead exposure in rats has long-term behavioral, physiological, and anatomical effects (McGivern 1991).

In addition, there are several avenues through which diet might lessen the neurotoxic effects of lead. For example, one way lead impairs neurological functioning is by altering the pro/antioxidant ratio in the brain and inducing oxidative stress (the biological equivalent of rust). Given this, foods rich in antioxidants are hypothesized to mitigate the effects of lead. Experiments with rats confirm this and show that ingesting green tea extract can reduce lead-related oxidative stress (Khalef et al. 2012). Animal experiments also suggest that selenium, which has the same molecular structure as lead, might protect against lead toxicity by binding

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[4]Probably the strongest evidence along these lines comes from Schneider et al. (2001). See also Guilart et al. (2003) and Petit and Alfano (1979).

[5]See Cao et al. (2008).

at cellular sites to which lead might otherwise migrate to (Han et al. 2013). Given its similarity to lead, and the importance of calcium in neurotransmission and neurogenesis, calcium has long been thought by at least some observers to confer protection against lead. There is animal evidence consistent with this hypothesis, but the evidence among human subjects is, at best, mixed. Iron too is sometimes hypothesized to protect against, and might even help undue some of the neurological damage caused by lead exposure (Wright et al. 2003).

Taken together, the evidence presented in the previous two paragraphs suggests that an enriched environment and dietary supplements do not just have a positive and independent impact on cognition. Diet and enriched environments might actually prevent and mitigate the biochemical changes induced by lead exposure (e.g., they lower the pro/antioxidant ratio, which would otherwise be too high in the presence of lead) and actually prevent or undue the physiological damage done by lead. There is, however, an important limitation to this evidence: it is based almost entirely on animal experiments.

Direct evidence on how social and dietary factors mediate the effects of lead on humans, particularly children, is hard to come by. The regression results below, while not definitive, are consistent with the hypothesis that children from enriched environments are less vulnerable to the neurotoxic effects of lead. More generally, the regression results suggest that environmental degradation undermines the long term economic performance of poor socioeconomic groups more so than advantaged groups, and that it does so, at least in part, through its effects on cognitive ability.

2.D. Water Acidity and Lead Water Pipes

During the early- and mid-twentieth century, lead was often used in the construction of water service lines. Service lines were the pipes that connected individual homes and apartment buildings to street mains. It is important to note that lead service pipes were not the only source of lead in public water systems. Other, relatively small, sources of lead included household solder, plumbing fixtures, and faucets.

Aside from lead, service lines were also made of plain iron or steel; galvanized iron or steel; and cement-lined iron. Relative to these other materials, lead had two features that made it attractive to the engineers who designed public water systems: it was both malleable and durable. Malleability reduced labor costs by making it easier to bend the service main around existing infrastructure and obstructions, and compared to iron, lead was a soft and pliable metal. As for durability, the life of the typical lead service pipe was thirty-five years. By contrast, plain iron or steel pipe lasted sixteen years; galvanized pipe twenty years; and cement lined pipe twenty-eight years. Based solely on engineering concerns, these characteristics made lead the ideal material for service lines. As one prominent trade journal wrote: "Lead is in many respects the most satisfactory material to use for service pipes. Its pliability and its comparative freedom from corrosive action make it almost ideal from a mechanical standpoint."[6]

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[6]Information and quotations in this paragraph come from the *Engineering News*, September 28, 1916, pp. 594-96 (hereafter cited as EN); and from the Committee on Service Pipes (1917), p. 328 (hereafter cited as CSP). The editors of the *Engineering News* were not alone in suggesting that lead, even with concerns about safety, was the best material for service lines. A survey of the superintendents of forty-one municipal water companies found that about half (20) preferred lead service lines to all other types of lines. This survey was conducted in 1884 by water industry expert from New London, Connecticut. The results were reported in the

The two problems with using lead were its high up-front cost and its potential toxicity. In terms of up-front cost of materials, a small iron or steel pipe that was neither galvanized nor lined was certainly cheaper than lead. But as stated above, untreated iron and steel pipes had expected life spans that were less than half that of lead pipes. Because replacing broken service mains often required digging up paved streets and working around other infrastructure such as gas and sewer mains, the costs of reduced main life overwhelmed whatever savings were generated from reduced materials costs.[7] As for concerns that lead service lines might poison the water they carried, most engineers appear to have believed that such concerns were overblown (EN, p. 595).

At the turn of the twentieth century, the use of lead service mains was common. This can be seen in two independent samples of cities. In 1916, the New England Water-Works Association surveyed 304 cities and towns, largely in New England, and found that 95 (31 percent) of these cities used lead or lead-lined services (CSP, pp. 326-30; and EN, p. 594). A second and independent sample is more geographically diverse and includes 797 cities and towns observed in 1900 from all over the United States. Of these cities, 209 (26 percent) used lead or lead-lined services exclusively; 137 (17 percent) used lead or lead-lined services in

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Journal of the New England Water Works Association, September, 1917, pp. 346-47.

[7]A prominent trade journal explained (EN, p. 595): "The cost of lead pipe of sufficient thickness to safely withstand the pressure is more than the cost of many other materials used for services, but in a paved street the greater duration of life probably more than compensates for the extra cost, and in places where the streets are occupied by other pipes and conduits the ease of getting over and under these obstructions with a flexible pipe is a great advantage."

conjunction with some other material type, such as galvanized iron or cement-lined iron; and 451 (57 percent) used no lead. Table 1, which breaks down lead use by city size, suggests a strong positive correlation between lead use and city size. For cities with populations less than 8,000, 33 percent used lead service pipes. In contrast, for cities with populations between 30,000 and 300,000, 72 percent used lead pipes; and for the largest cities, those with populations greater than 300,000, all but one (94 percent) used lead service pipes.[8]

Today, there exists a large literature in engineering estimating and documenting the connection between a given water supply's chemical characteristics and its ability to leach lead from service pipes and indoor plumbing. Figure 1 summarizes the relevant aspects of this literature. It is helpful to remember that a pH below 7 implies acidic, while a pH above 7 implies alkaline. As Figure 1 shows, for water supplies with a pH level below about 6.5, increases in pH levels (less acidity) are associated with reduced leaching and lower lead levels. For water supplies with pH levels between 6.5 and 8.5, variation in pH has a negligible effect on water lead levels. For water supplies with pH levels exceeding 8.5, increases in pH (more alkalinity) are associated with greater leaching and higher lead levels. We emphasize that the precise locations of the inflection points in Figure 1 are not entirely clear, but what matters is the U-shaped pattern: for very acidic water supplies, decreased acidity reduces lead uptake, while for highly alkaline water supplies, decreased acidity (increased alkalinity) increases lead uptake. Exactly where on the pH scale these relationships change is open to debate (Schock 1990).

[8]The construction of this sample is described in Troesken and Beeson (2003).

Changes in pH levels have a large impact on water lead levels. For example, moving from a pH of 6 to 7 reduces lead levels by 50 to 90 percent, depending on other chemical factors in the water supply (Schock, 1990). Historically, the impact of such differences was substantial given the amount of lead present in urban water systems. Troesken (2006, pp. 53-55) concludes that historical water lead levels were far in excess of those mandated by the EPA today (no more than 15 parts per billion). In Massachusetts in 1900, the typical city had water lead levels that were 20 to 100 times greater than the current EPA standard. There were a few cities and towns with particularly corrosive water supplies where lead levels exceeded the current EPA standard by factors of 300 to 700.

Though the exact points at which the lead take-up relationship changes in Figure 1 are unknown, we hypothesize that the U-shaped relationship between water pH and lead levels would manifest itself in an inverted U-shaped relationship between water pH and intelligence like that shown in Figure 1. As noted in the introduction, our analysis will exploit data on Army enlistees during World War II. Given the non-monotonic relationship plotted in Figure 1, we expect that for Army enlistees from areas with highly acidic water supplies, increased pH (alkalinity) would have generated higher scores on army intelligence tests as enlistees' blood lead levels would have fallen as water supplies became more alkaline and less acidic. For enlistees from areas with more neutral water supplies, places with pH levels between 6.5 and 8.5, variation in pH would not affect intelligence scores. For enlistees from areas with alkaline water supplies, places with pH levels greater than 8.5, increased pH would result in lower intelligence scores.

Central to our analysis is the claim that households were randomly assigned to water supplies with varying levels of pH. This claim is based on two observations. First, as explained in the following section, few individuals understood the chemistry behind water-related lead poisoning, and fewer still altered their locational choices because of it. Second, the threshold for what was considered a safe level of lead exposure during the early twentieth century was much higher than what is considered safe today, so that even individuals highly attuned to health issues and the dangers of lead considered water-related lead exposure a minor concern.

2.E. Did Historical Actors Understand the Chemistry of Water-Lead?

Large American cities first built their public water systems during the early nineteenth century; medium sized cities during the mid to late nineteenth century; and small cities during the late nineteenth and early twentieth century (Baker 1897). Throughout this time, even the most well-informed historical actors did not understand the chemical processes that made lead water pipes safe in some contexts but dangerous in others. Using what was referred to as the "Doctrine of Protective Power" (DPP), engineers in the United States and Europe argued that lead pipes were safe in all but a handful of special circumstances. Without delving into the reasoning behind the DPP, engineers argued that as pipes and plumbing aged, a protective coating quickly formed on the interior of pipes and plumbing fixtures, preventing consumers from drinking undue amounts of lead (Troesken 2006). While it is true that a protective coating does eventually form on most pipes, that process can take decades, and for some water supplies, it cannot be relied upon to protect consumers even after long periods of time. In its most extreme forms, the DPP was used to justify the use of lead pipes and plumbing even in the presence of highly corrosive water supplies.[9] If there was so little concern among engineers who ran public water systems about the likelihood of lead exposure, it seems unlikely that the general public was better informed.

But for the sake of argument, suppose for the moment that everyone had a rudimentary understanding of the relevant chemistry. It would be implausible to suggest that nineteenth-century households made locational decisions, even in part, using the chemical relationships defined in Figure 1.[10] To the extent that consumers thought about the characteristics of a given water supply, they thought about it in terms of how soft the water was, or in terms of its taste. Soft water, which also tended to be highly acidic, was more appealing aesthetically and also because many observers, including physicians, thought it healthier than hard water (Troesken 2006). It is true that consumers cared about bacterial pollution, but there was much less concern regarding inorganic pollutants such as lead. There was even a school of thought maintaining that lead and other inorganic materials were a good thing because they might destroy the organisms that caused typhoid and infantile diarrhea (Melosi 2002, p. 273). Moreover, if there was selection taking place, it would have had to have worked in a non-monotonic way, akin to the relationship observed in Figure 1. A more plausible objection to our estimating strategy is that pH was correlated with other

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[9]See, for example, Troesken (2006, pp. 184-189), discussing Glasgow's decision to distribute water from Loch Katrine (which was highly corrosive) through lead service pipes.

[10]The concept of pH and methods of measuring it were not introduced until 1909. See Sorenson (1909).

environmental and familial factors that influenced intelligence. The difficulty with this line of thought is that, as our controls for environment and family background improve, the results only get stronger (Ferrie, Rolf, and Troesken 2012).

Compounding the adverse effects of the Doctrine of Protective Power were misleading beliefs about the safe level of lead exposure. With the exception of perhaps one or two physicians writing in England, medical researchers and government authorities argued that lead was a pervasive and unavoidable part of the natural environment and that humans could withstand all but the most extreme levels of exposure (Needleman 1998, 2000, and 2004). There were, for example, studies documenting the horrendous health outcomes among children born to women who worked in the lead industry and this eventually prompted government officials in the United States and Europe to eventually ban women from work in lead refineries. But these studies focused on levels of lead exposure that far exceeded anything modern observers might consider acceptable (e.g., Hamilton 1919).

Around 1900, even those who should have been the most attuned to the dangers of lead exposure (water system engineers and physicians) routinely argued that water lead levels 50 to 100 times greater than the modern EPA threshold were perfectly safe; and for those who were skeptical of the idea that lead pipes had adverse net health effects (i.e. that the benefits from the DPP outweighed the risks at low and moderate exposure levels), the threshold was much higher. As late as 1916, the available evidence indicates that nearly all engineers believed that the already minimal concerns about lead service pipes were overblown (e.g., Committee on Service Pipes 1917). And even for the few engineers who conceded that lead might pose a problem for some water supplies, the threshold levels of lead exposure they believed were safe were two or three orders of magnitude greater than those considered safe by European and American authorities today (Troesken 2006). The same skepticism can also be found among physicians, who one might think were the professionals most sympathetic to health concerns. As late as the 1940s, articles appeared in the *Journal of the American Medical Association* arguing that lead water pipes were generally safe and that consumers had little to worry about (Troesken 2006, pp. 46-52).

3. Data and Sample Properties

We hypothesize that children from enriched environments would have been less vulnerable to water-related lead exposure than children from disadvantaged backgrounds. In out estimation, water-related lead exposure is measured indirectly by variation in water pH levels. As the discussion above suggests, as pH levels move away from neutrality (7), lead uptake would increase. This, in turn, would imply that water lead levels (and intelligence) would have been related to pH in a non-monotonic way. Moreover, to the extent that the adverse consequences of lead exposure would have been mitigated for children from wealthier, advantaged households, the strength of that relationship would have been weaker among individuals from advantaged homes than those from disadvantaged homes. As already mentioned, we use assignment to the Army Air Corps as a proxy for intelligence. Figure 2 illustrates our thinking. Notice that there is an inverted U-shaped relationship between water pH and air corps assignment, and our hypothesis suggests that this pattern should be stronger for individuals from disadvantaged (low-SES) backgrounds (bold dotted line), than for individuals from advantaged (high-SES) backgrounds (thin solid line). The regression results comport well with this prediction.

Based on the discussion in section 2.C, there are at least four mechanisms through which socioeconomic status might have mitigated the adverse effects of water-related lead exposure and flattened out the inverted U-shaped pattern in Figure 2. First, individuals from advantaged socioeconomic backgrounds likely received more stimulation from their parents as young children. Second, to the extent that higher status families had access to better schools and richer neighborhood environments, children from such families would have received more and better stimulation than those from lower status households. Third, those from wealthier and higher socioeconomic status homes would have had better diets, particularly in terms of calcium and iron intake, which as noted above might have some role in protecting against, and perhaps even un-doing, the adverse effects of lead. Fourth, for the simple reason that increased wealth and income leads to more consumer choices and options, it seems likely that higher socioeconomic status would have conferred greater stimulation directly through that avenue as well.

Assessing the link between early-life lead exposure and later-life cognitive functioning, requires data that follow individuals from the homes in which they resided as children to a later date at which intelligence tests were administered. For the first half of the twentieth century, we have constructed such data by taking advantage of (1) the availability of a new 5% public use sample (IPUMS) drawn from the 1930 U.S. Census of Population (Ruggles et al. 2010); and (2) the availability of data on assignment to the air corps among Army recruits during World War II—because only the most intelligent recruits were assigned to the air corps, air corp assignment is an excellent proxy for scores on the army intelligence exam at the time, the Army General Classification Test (AGCT) (Feyrer et al. 2013).

Our data begin with the nine million males who enlisted in the U.S. Army during World War II. Their enlistment records are in the National Archives and Records Administration (2002), Record Group 64, and are available on-line.[11] These records provide information on the recruit's full name, year of birth, and state of birth. This information is sufficient to link individuals from this source to the 1930 5% IPUMS (Ruggles et al. 2010). The IPUMS data are a nationally-representative one-in-twenty sample of the U.S. population drawn from the manuscript schedules of the 1930 U.S. Census of Population. We have linked more than 148,000 enlistees to the IPUMS sample.[12] However, in the analysis that follows, we restrict our attention to the 44,040 enlistees who, as of 1930, resided in places with 30,000 or more inhabitants. We limit ourselves to larger places because we only know the chemistry of local water supplies for cities above this population threshold. For the 44,040 urban enlistees in our sample, we exploit data on the following variables as of 1930: enlistee's race (41,450 of the

[11] See http://aad.archives.gov/aad/fielded-search.jsp?dt=893.

[12] Failure to link is accounted for by mis-spellings on the original documents (the census or the enlistee's punch card), faulty transcription of the original information, mis-reporting of age in either source, and the commonness of particular combinations of surname and given name within cells defined by year and state of birth. We are using only those individuals uniquely linked (with a small tolerance allowed for spelling and year of birth). The linked population is not substantially different from the population of U.S. Army enlistees in World War II.

enlistees were white; 2,590 were black[13]); value of housing, whether owned or rented; enlistee's state of residence; enlistee's father's labor market status (employed, unemployed, out of labor market); enlistee's state of birth; the occupational status (blue collar or white collar) of the enlistee's father; and enlistee's year of birth. These Census data are combined with information about the pH level of water used by the public water company in the enlistee's city of residence and with the enlistee's air corps status. As explained above, only the most intelligent enlistees were assigned to the air corps.

Our data on pH levels for any given enlistee's water supply is based on measures of the chemical characteristics of water supplies during the late twentieth century. The pH is measured at the point where water enters the city's system, so it is pH before any treatment has occurred.[14] In using these data we are assuming that the pH readings for urban water systems made in the late twentieth century accurately reflect pH levels in the second and third decades of the twentieth century. To the extent that modern pH is a [non-systemayically] noisy measure of 1900 pH, the effect of pH on an outcome like air corps assignment will be attenuated. If we observe an effect, it is likely a lower bound on the true effect.

There are two concerns in using such recent data as a proxy for the prevailing pH levels in the 1930s. First there might have been changes in water treatment practices—such as the introduction of lime to control water hardness—may have occurred that resulted in changes in

[13]For the regressions in this paper, we restrict our sample to white recruits.

[14] These data come from Baker (1897) and were generously provided by Karen Clay. The data on the pH of each city's water intake list one entry per city. If there were several cities served by the same water system, they would each have the same reported pH level.

pH. Second "acid rain," which increased from the 1930s through 1950s (Schindler 1988, pp. 149-150), could have reduced pH levels in affected watersheds, so current pH levels would understate historic levels.

If the modern and historical (circa 1930) measures of pH levels diverge significantly it will generate attenuation bias in the estimated coefficients. One possibility in this regard is that cities undertook water softening techniques to make their water more palatable. This would have been through the addition of lime. If lime addition raised pH across the whole range of pH in the sample, this would result in a rightward shift in the pH-intelligence relationship in Figure 1: inferences drawn from a regression coefficient ∂(intelligence)/∂pH would still be valid along the linear, upward-sloping section of the figure, along the flat section, or along the linear downward-sloping section. If instead pH rose after the 1930s in places where pH was lowest to begin with (as cities actively attempted to raise their pH and reduce pipe corrosion), the result would be a downward bend in the pH-intelligence relationship in Figure 1 along the upward-sloping linear section. Inference based on a regression coefficient ∂(intelligence)/∂pH would understate the true magnitude of the relationship. The acid rain problem is specific to the Midwest and Northeast. The use of state dummies will address this concern (allowing the pH-intelligence relationship to have a different vertical position in different states to reflect the extent to which the gap between modern and historical pH levels differs by state).[15]

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[15]For a justification of using of modern pH levels as a proxy for historical pH levels, see Clay et al. (2014, pp. 13-15). Paleolimnological evidence (Davis et al. 1994) reveals that the acidity of surface water changes very slowly: over 300 years, the acidity of New England lakes

We describe the characteristics of the resulting sample in three tables. Table 2 provides descriptive statistics on a few key variables. In particular, 18 percent of the enlistees in our sample were assigned to the air corps. The typical recruit came from a city with a slightly alkaline water supply; for the mean recruit, pH was 7.5. Thirty-nine percent of the recruits came from cities using lead pipes. Sixty percent of the recruits had blue collar fathers and 63 percent of the recruits had fathers who were unemployed at the time of the 1930 census.

Table 3 describes the geographic distribution of our sample. It highlights how water pH varied sharply across the states and how recruits were concentrated in five states. In particular, 22 percent of the enlistees were from New York State, with the majority of those coming from New York City. Nine percent of the sample resided in Ohio, while ten percent came from Pennsylvania. Nearly eight percent of the enlistees came from Illinois, and 5.6 percent come from Massachusetts. While these numbers suggest the sample draws heavily from a few states, these states are not limited to a specific region, and even states with relatively small sample shares contain a significant number of enlistees in absolute numbers. For example, just over 4 percent of the sample was from California which translates into 1,959 enlistees. Similarly, just under 1 percent of the sample, or 379 enlistees, came from Florida; 1 percent of the sample, or 422 enlistees, came from Tennessee; and 2 percent, or 1,024 enlistees, came from Washington state. As for water pH levels, they vary from a low of 5.8 in Delaware to a high of 8.2 in California and Missouri.

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changed by only 0.03 pH units. As late as 1962, only 26 of the largest water systems in the U.S. were using lime to soften their water (Durfour and Becker 1964, p. 47).

If one looks at the spatial distribution of enlistees across cities rather than states, the patterns are not altered in any meaningful way. In particular, the sample includes enlistees from 293 cities. The median city contains 68 enlistees; the mean city contains 150. As Table 4 shows, the cities from which the greatest number of enlistees came are: New York City (7,230 or 16 percent of the sample); Chicago (2,590 or 5.8 percent of the sample); and Philadelphia (1,781 or 4 percent of the sample). There were several cities with around 200 enlistees, representing about 2 percent of the sample. These cities include: Baltimore, Boston, Cleveland, Detroit, Los Angeles, and St. Louis. The cities in the sample with highest and lowest drinking water pH are as follows. Baton Rouge, Louisiana had a pH level of 8.7 and twenty enlistees. Berkeley, Oakland, and San Francisco all had a pH level of 8.9 and had 52, 210, and 320 enlistees respectively. Similarly, Fall and New Bedford, Massachusetts had pH levels of 5.7 and 165 and 127 enlistees, respectively. Warwick Town, Rhode Island and Wilmington, Delaware had pH levels of 5.8 and 60 and 70 enlistees, respectively.

Figure 3 provides a visual depiction of the geographic distribution of two key sample properties: the use of lead water pipes; and the alkalinity of public water supplies. The figure shows that most of the sample cities are concentrated in the Northeast. The figure also shows that highly alkaline waters were located in the West and Midwest, while soft waters were, by and large, found in the Northeast. The use of lead service lines, by contrast, was geographically dispersed, with cities throughout the country using lead pipes.

4. Regression Analysis

To explore how early life lead exposure interacts with socioeconomic status to shape later life intelligence, we estimate variants of a simple probit model:

$$(1)\ \Pr(y_i = 1 \mid \boldsymbol{X}_i) = \Phi(\boldsymbol{X}_i'\beta),$$

where y_i assumes a value of one if enlistee i is assigned to the air corps and zero otherwise; Φ is the cumulative standard normal distribution; and $\boldsymbol{X}_i$ is a vector of regressors hypothesized to influence probability of assignment to the air corps. In each of the following regressions, the vector **X** consists of dummies for year of birth and state of birth (with the latter also controlling for state of residence in regressions where we limit the sample to non-movers, i.e. those for whom birth state=state of residence in 1930). We then introduce a dummy for SES and an interaction between that dummy and both pH and pH-squared, with three different dummies used in four different specifications: an indicator variable indicating whether the recruit's father held a blue-collar job (=1 if blue collar; 0 otherwise); an indicator variable indicating if the recruit lived in a home with rent less than $30 per month; and an indicator variable indicating if the recruit's father was unemployed at the time of the 1930 Census.

For the reader's convenience, when we use interactions, we report the full pH and pH-squared effects for both SES groups (i.e. we have already added the interaction coefficient to the main effect for the group in which the dummy is 1). Tests of the null hypotheses that the pH or pH-squared effect is zero for a particular SES group can then be read directly from the table. As the discussion above suggests, the motivation for including both pH and pH-squared is that water-lead levels and pH are related in non-monotonically. Specifically, the relationship is U-shaped, where lead levels are minimized at neutrality and rise as water becomes more acidic or more alkaline.

Table 5 reports the results for a baseline regression We restrict our sample only to non-movers, that is, individuals who stayed in the same city between the 1930 Census and enlistment. We restrict the sample to non-movers because these are the individuals who had the greatest probability of accumulating large amounts of lead over the long term.   The first column reports how the probability of air corps assignment is affected by pH and pH-squared for recruits growing up in cities without lead water pipes. As we expect, for recruits growing up in non-lead cities, there is no relationship between water pH and the probability of assignment to the air corp. The second column indicates that for recruits from cities using a mixture of lead and non-lead pipes, there is an attenuated and statistically insignificant relationship between pH and the probability of air corps assignment; as explained below, the relationship follows an inverted-U. By contrast, for recruits from cities with lead water pipes, the correlation between pH levels and air corps assignment is strong and statistically significant, with increases in pH in acidic water supplies leading to an increase in the probability of an air corps assignment and increases in pH in alkaline water supplies leading to a decrease in the probability of an air corps assignment.

Figure 4 provides a visual depiction of the results presented in Table 5. It plots the predicted probability of air corps assignment for different classes of workers. Notice that for recruits from cities with non-lead water pipes, there is no inverted U-shaped relationship or an attenuated one at best. For recruits from cities using some but not all lead, there is a modest inverted-U shaped relationship between pH and the probability of air corps assignment. By contrast, for recruits from cities with lead pipes there exists a strong inverted U-shaped pattern so that for pH levels below 7.5 increases in pH result in an increased probability of air corps assignment; while for recruits from cities with alkaline water supplies (i.e., those with pH levels above 7.5) increases in pH result in decreases in the probability of air corps assignment.

Having estimated these baseline models, we now turn to identifying and measuring interaction effects; that is, how pH interacts with socioeconomic status to affect the probability of air corps assignment. Given the discussion in the previous sections, it seems reasonable to hypothesize that variation in water pH would have affected recruits from relatively low economic socioeconomic backgrounds more so than recruits from high socioeconomic backgrounds. As explained in the context of Figure 2, we expect the relationship between intelligence (as proxied by assignment to the air corps) to have been related to drinking water pH in an inverted U-shaped pattern, and that this inverted U would have been flatter for high socioeconomic groups. To test this hypothesis, we consider three indicators of low socioeconomic status: father's occupational status in 1930 (blue collar/white collar); father's employment status in 1930 (unemployed/employed); and whether the enlistee was from a home where the rent was below the 50th percentile in terms of rental rates.[16]

[16]One obvious marker of socioeconomic status we are not considering is race. We do not consider race because once we restrict our sample to stayers (enlistees who did not move between 1930 and 1940) and enlistees growing up in places with lead pipes, we do not have common support over the pH levels that drive our estimation strategy. For example, while there are more than 200 whites coming from towns with a pH level less than 6, there are no blacks with pH levels less than 6. (In earlier versions of this paper, we had enough black observations to estimate a relationship because in those samples we were not restricting the sample based on the usage of lead pipes; we lumped all cities together, regardless of the type of water pipes they used.) The same logic holds true for parental literacy. Once we restrict the sample to enlistees from places with lead pipes, there are so few observations with one or more illiterate parents that we cannot cleanly identify the effects of pH on the probability of air corps

Specifically, letting β_l and β_s be the coefficients on pH and pH-squared, respectively, we expect the following:

β_l(low socioeconomic status group) > β_l(high socioeconomic status group) > 0

and

β_s(low socioeconomic status group) < β_s(high socioeconomic status group) < 0

Coefficients with these relative magnitudes would generate the patterns highlighted in figure 2, where low socioeconomic groups exhibit a stronger and steep inverted-U shaped pattern than high socioeconomic groups.

Tables 6a and 6b report regression results for the interaction effects between pH and socioeconomic status. Henceforth, all reported regression results are for recruits from cities that used lead water pipes exclusively. Marginal effects are shown graphically in the accompanying figures. Probit regression coefficients (rather than marginal effects) are reported and (city-clustered) standard errors appear in parentheses. The results for single binary regressions are reported in two pairwise columns, with the high socioeconomic status coefficients reported first, and the low socioeconomic status reported second.

The first two columns of Table 6a report the results for recruits with white-collar and blue collar fathers interacted with pH and pH-squared. Recruits with white collar fathers have high socioeconomic status; those with blue collar fathers are assumed to have low socioeconomic status. For recruits with white collar fathers, the magnitudes of the coefficients and standard errors suggest a relationship between pH and the probability of assignment to

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assignment.

the air corps but that relationship is not statistically significant. By contrast, in the second column of Table 6a, the coefficients on pH and pH-squared for recruits with blue-collar fathers are larger (in absolute value) than for those with white collar fathers and they are statistically significant at the 5 percent level.

Figure 5 plots the predicted probability of air corps assignment against pH for recruits with blue collar fathers and for those white collar fathers. Notice that those recruits with blue collar fathers and from cities with relatively acidic water supplies are predicted to have a 7 percent probability of assignment to the air corps, while those from cities with water supplies near neutrality, or just above, are predicted to have been assigned to the air corps over 22 percent of the time. By contrast, for recruits with white collar fathers a slightly less steep (and again statistically insignificant) relationship emerges. In particular, for recruits with white collar fathers, the probability of air corps assignment rises from around 14 percent for highly acidic water supplies to just under 26 percent for recruits from areas with neutral water supplies. For recruits from cities with highly alkaline water supplies, the probability of air corps assignment is around 21 percent.

The second set of results reported in Table 6a are for regression comparing recruits with employed and unemployed fathers. For recruits with fathers who were employed in 1930 (high-SES), the coefficients on pH and pH-squared are statistically insignificant and have the wrong sign. By contrast, the results for recruits with unemployed fathers (low-SES) are statistically significant at the 1 percent level and have the correct sign, so that at low levels of pH increases in pH are associated with an increased probability of air corps assignment while at high levels of pH increases in pH are associated with reductions in the probability of assignment. The results are depicted in Figure 6. From the figure, for recruits with unemployed fathers, the predicted probability of air corps assignment rises from around 10 percent for highly acidic water supples to just over 20 percent for neutral water supplies. For recruits with unemployed fathers from places with alkaline water supplies the probability of air corps assignment falls to around 10 percent. Although there is a steep U-shaped relationship for recruits with employed fathers, that relationship is not statistically significant.

Table 6b explores how water pH interacts with low-rent status. In particular, the regression for this table uses home ownership and low-value renters as proxies for socioeconomic status. For recruits from households where their parents owned their homes, the coefficients on pH and pH-squared have the predicted signs but are statistically insignificant. By contrast, for recruits from households paying less than $30/month, there is a relatively strong and statistically significant relationship between the probability of air corp assignment and pH levels. This can be seen in Figure 7, which plots the predicted probability of air corps assignment for recruits from households belonging to the low rent category against those in the home ownership category. For recruits with parents who owned their home or paid more than $30 a month in rent, the probability of air corp assignment rises from 12 percent for acidic water supplies to a high of around 24 percent for more neutral supplies to a low of 15 percent for alkaline supplies. But again, this relationship is not statistically significant. By contrast, recruits from households that paid less than $30 a month appear to have been more sensitive to variation in pH, with the probability of air corps assignment hovering around 5 percent for highly acidic and alkaline water supplies, and a probability of nearly 20 percent for more neutral water supplies.

We began this empirical section by showing that in cities without lead pipes the U-shaped relationship between the probability of air corps assignment and pH does not exist. This suggests that unobservable characteristics are not driving the relationship we do observe in cities with lead pipes. Another straightforward test involves obtaining an index of unobservable characteristics and regressing that index against pH and pH squared. If our estimation strategy is sound, pH and pH-squared should have coefficients that are close to zero and statistically insignificant. Toward this end, we regress AAC (air corps assignment) against state and birth year fixed effects using a probit for enlistees with blue collar fathers, unemployed fathers, and from households that paid less than $30 per month in rent. We then take the predicted values from these regressions and use them as an index for unobservables. In doing so, we assume that unobservables are correlated with observable characteristics.

Regressing these predicted values against pH and pH-squared yields results that generally suggest that pH and pH-squared are not systematically correlated with unobservable characteristics. The results are reported in table 7. Note that for blue collar fathers, unemployed fathers, and low-rent households the coefficients on pH and pH-squared are close to zero and highly insignificant. Figures 8, 9, and 10, plot the observed predicted values and trend lines for quadratic fits with 95 percent confidence intervals.

5. Concluding Remarks

This paper has explored the extent to which disadvantaged groups exhibited greater longer-term vulnerability to early-life exposure to lead than better placed groups. In pursuing this line of research, it is among the first papers to consider the hypothesis that environmental pollution plays an important role in propagating and sustaining socioeconomic disadvantages in education and labor market outcomes. The paper is based on the idea that early life water-related lead exposure is randomly assigned through the acidity of local drinking water supplies: as pH deviates from neutrality (7), more lead is corroded from the inside of lead pipes and lead exposure rises. As long as people are not choosing their locations because of the pH of their drinking water, or with factors associated with pH, this is a viable approach. Given all this, we hypothesize that later life economic outcomes will be related to pH in a non-monotonic fashion so that positive outcomes are maximized at neutrality and fall off as water deviates from neutrality and becomes more acidic or more alkaline.

Looking at World War II draftees, our proxy for economic outcomes is assignment to the air corps: the most intelligent and disciplined recruits were assigned to the Army Air Corps. Given this, we assume that assignment to the air corps while in the army is a signal of future economic success. There is moreover strong evidence to support our hypothesis. Specifically, for all recruits there is an inverted U-shaped relationship between the probability of assignment to the air corps and the pH of drinking water in youth, but this relationship is much stronger for recruits from disadvantaged backgrounds (e.g., recruits with blue collar fathers) than for recruits from more advantaged backgrounds (e.g., recruits with white collar fathers). These results can help explain the origins and maintenance of socioeconomic disadvantage. As a placebo test, we compare our results across cities with lead water pipes and those with non-lead pipes. Consistent with our predictions, the non-monotonic relationship is only observed for recruits from cities with lead water pipes. In addition, using the predicted value of air corps assignment as an indicator of unobserverable characteristics, we find little evidence that unobservables are systematically correlated with pH and pH-squared.

City size in 1900	no. of cities	Cities using only lead	Cities using lead & other	Cities using no lead
Population > 300,000	16	8 (50%)	7 (44%)	1 (16%)
30,000 < Pop < 300,000	107	55 (51%)	22 (21%)	30 (28%)
8,000 < Pop < 30,000	156	46 (29%)	36 (23%)	74 (47%)
Population < 8,000	518	100 (19%)	72 (14%)	346 (67%)
All towns and cities	797	209 (26%)	137 (17%)	451 (57%)

Table 1. Lead Use and City Size

Variables	N (1)	Mean (2)	S.D. (3)	Min. (4)	Max. (5)
pH	18,986	7.520	0.542	5.7	8.9
Home Rented for Under $30/Month 1930	18,986	0.438	0.496	0	1
Lead Service Mains	18,986	0.391	0.488	0	1
Blue Collar Father 1930	18,986	0.601	0.490	0	1
Army Air Corps Assignment	18,986	0.181	0.385	0	1
Father Unemployed 1930	18,986	0.632	0.482	0	1
Birth State=Residence State 1930	18,986	0.893	0.309	0	1

Table 2. Descriptive Statistics

State	*n*	*%N*	*% Air*	pH	*State*	*n*	*%N*	*% Air*	pH
Ala.	47	.001	.277	7.7	Neb.	215	.005	.307	8.1
Ariz.	38	.001	.132	8.0	Nev.	16	.000	.188	7.7
Ark.	78	.002	.179	6.7	NH	187	.004	.144	6.3
Cal.	1959	.044	.228	8.2	NJ	2157	.049	.108	7.4
Col.	232	.005	.198	7.9	NM	25	.001	.36	7.3
Conn.	1124	.026	.080	6.7	NY	9750	.221	.111	7.4
Del.	70	.002	.186	5.8	NC.	383	.009	.146	7.0
DC	358	.008	.092	8.0	ND.	34	.001	.324	8.1
Fla.	379	.009	.150	7.4	Ohio	3952	.090	.117	7.8
Geo.	378	.009	.138	6.8	Okla.	274	.006	.252	8.1
Ill.	3392	.077	.221	7.8	Ore.	273	.006	.238	7.1
Ind.	1126	.026	.120	8.0	Penn.	4424	.100	.111	7.6
Iowa	440	.010	.205	7.8	RI.	474	.011	.141	6.4
Kan.	175	.004	.166	8.1	SC	115	.003	.122	6.8
Kent.	527	.012	.125	7.5	Tenn.	422	.010	.161	7.0
Lou.	289	.007	.131	8.0	Texas	963	.022	.266	7.6
Maine	254	.006	.091	6.9	Utah	186	.004	.140	7.4
Mary.	929	.021	.080	7.3	Ver.	10	.000	.300	7.6
Mass.	2480	.056	.115	6.4	Vir.	516	.012	.110	7.3
Mich.	1840	.042	.211	8.0	Wash.	475	.011	.194	7.1
Minn.	640	.015	.253	8.1	WV.	246	.006	.138	7.3
Miss.	71	.002	.239	6.5	Wisc.	1024	.023	.214	7.7
Mo.	1109	.025	.158	8.2					

Table 3. Sample Properties Across States

City	*N*	*% of total sample*	*% Air*	pH
Baltimore	887	0.0201	0.0767	7.3
Boston	865	0.0196	0.1156	6.5
Buffalo	685	0.0155	0.1037	8.2
Chicago	2590	0.0588	0.2135	7.7
Cincinnati	467	0.0106	0.1049	7.6
Cleveland	1183	0.0269	0.0938	8.0
Detroit	1048	0.0238	0.2204	8.0
Indianapolis	357	0.0081	0.1232	8.1
Jersey City	367	0.0083	0.1144	7.1
Los Angeles	712	0.0162	0.2472	7.9
Louisville	340	0.0077	0.1176	7.5
Milwaukee	580	0.0132	0.1983	7.7
New York City	7230	0.1641	0.1122	7.3
Newark	506	0.0115	0.0870	7.7
Philadelphia	1781	0.0404	0.1016	7.6
Pittsburgh	820	0.0186	0.1317	7.3
Rochester	378	0.0086	0.1243	7.8
St. Louis	675	0.0153	0.1096	8.3
Toledo	345	0.0078	0.1217	8.1
Washington DC	358	0.0081	0.0922	8.0

Table 4. Sample Properties Across the Cities with the Most Enlistees

Table 5. Impact of pH on Probability of Assignment to the Army Air Corps

	No Lead	Some Lead	Lead Only
pH	-0.240	0.569	3.814
	(0.966)	(1.080)	(1.052)***
pH^2	0.015	-0.045	-0.261
	(0.064)	(0.069)	(0.072)***
Constant	-0.326	-2.665	-14.720
	(3.619)	(5.175)	(4.725)***

Note: Coefficients are from a single binary probit regression (1=AAC assignment, 0=other), including controls for birth year and birth state, white non-movers (birth state=residence state) only; standard errors (clustered at the city level) in parentheses; N=10,415; Pseudo-R^2=0.0342;
* $p<0.1$; ** $p<0.05$; *** $p<0.01$

Table 6a. Impact of pH on Probability of Assignment to the Army Air Corps By Parental Characteristics

	Father's Occupation		Father's Labor Market Status	
	White Collar	Blue Collar	Employed	Unemployed
pH	1.941	4.065	-6.621	3.501
	(2.019)	(1.679)**	(9.733)	(1.251)***
pH^2	-0.127	-0.276	0.449	-0.236
	(0.135)	(0.115)**	(0.658)	(0.086)***
Constant	-7.531	-7.695	23.980	-37.056
	(7.535)	(8.477)	(35.771)	(34.695)
N	3,206		4,374	
Pseudo-R^2	0.0427		0.0365	

Note: Coefficients for each characteristic are from a single binary probit regression (1=AAC assignment, 0=other), including controls for birth year and birth state, white non-movers (birth state=residence state) only; standard errors (clustered at the city level) in parentheses;
* p<0.1; ** p<0.05; *** p<0.01

Table 6b. Impact of pH on Probability of Assignment to the Army Air Corps By Parental Characteristics

	Parents' Home Ownership	
	Owners	Renters <$30 Month
pH	2.465	4.765
	(1.660)	(1.277)***
pH^2	-0.168	-0.319
	(0.113)	(0.087)***
Constant	-9.111	-8.858
	(6.069)	(5.389)
N	4,374	
Pseudo-R^2	.0404	

Note: Coefficients for each characteristic are from a single binary probit regression (1=AAC assignment, 0=other), including controls for birth year and birth state, white non-movers (birth state=residence state) only; standard errors (clustered at the city level) in parentheses;
* $p<0.1$; ** $p<0.05$; *** $p<0.01$

Table 7. Is pH Correlated with Unobservable Characteristics?

	Predicted p(AAC) based on state and birth year fixed effects		
Variable	Blue collar fathers	Unemployed fathers	Rent less than $30/month
pH	.0019	-.0883	-.0727
	(.061)	(.124)	(.201)
pH-squared	.0005	.0074	.0055
	(.004)	(.009)	(.014)
Constant	.1377	.3842	.3844
	(.221)	(.452)	(.789)
N	2,041	478	1,152
Adjusted-R^2	.003	.016	.005

Note: Standard errors (clustered at the city level) in parentheses; * p<0.1; ** p<0.05; *** p<0.01

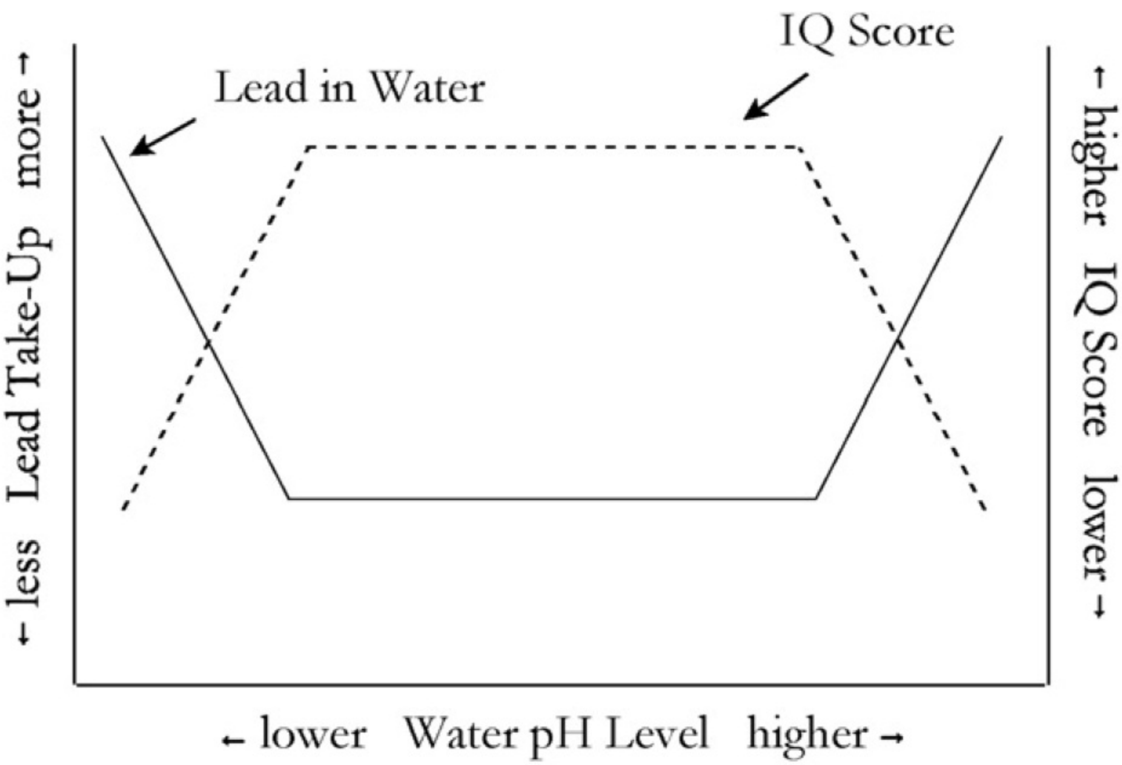

Fig. 1. pH, water-lead levels, and IQ.
Source: The U-shaped pH–plumbosolvency relationship is shown in Moore (1973, Fig. 1, p. 222), Schock (1990, Fig. 4, p. 66), and Cardew (2002, Figs. 3 and 4, pp. 200–201). The assumed underlying negative lead–IQ relationship is shown in Canfield et al. (2003, Fig. 2, p. 1525).

Figure 1. Relationship Between pH, Plumbosolvency, and Intelligence

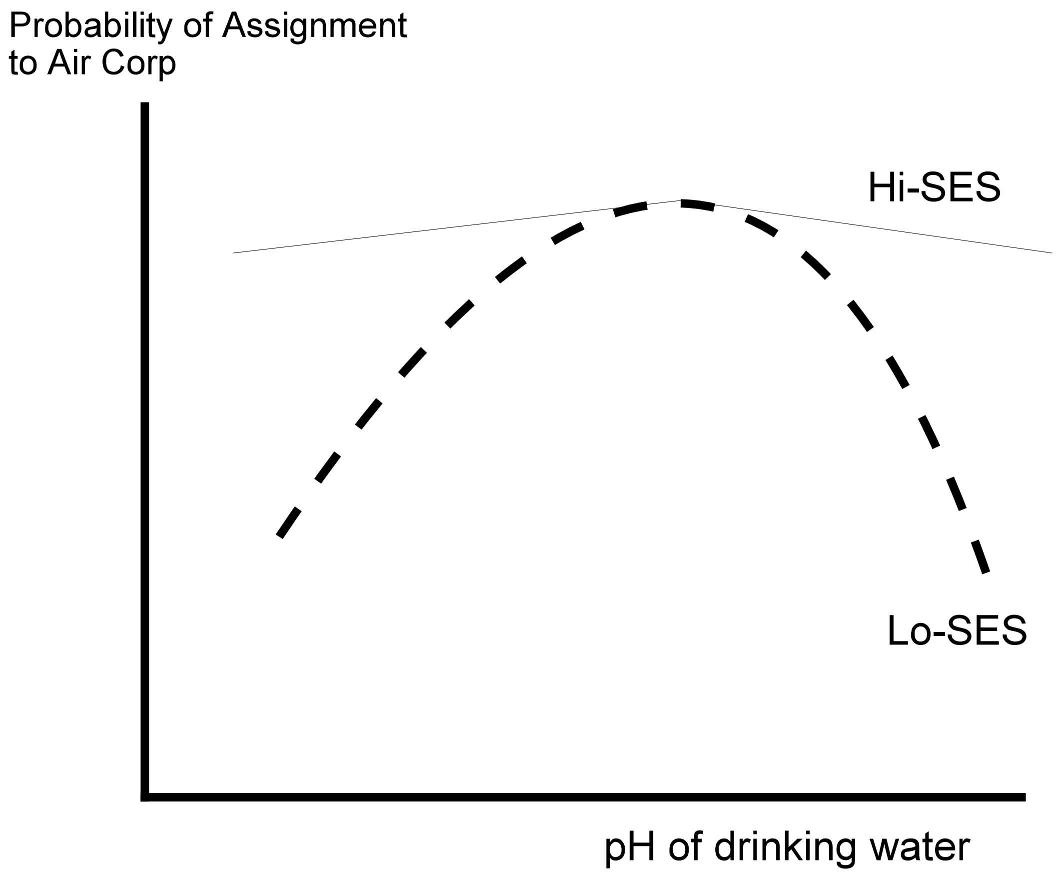

Figure 2. pH, Socioeconomic Status, and Probability of Assignment to the Air Corps

Source: see text

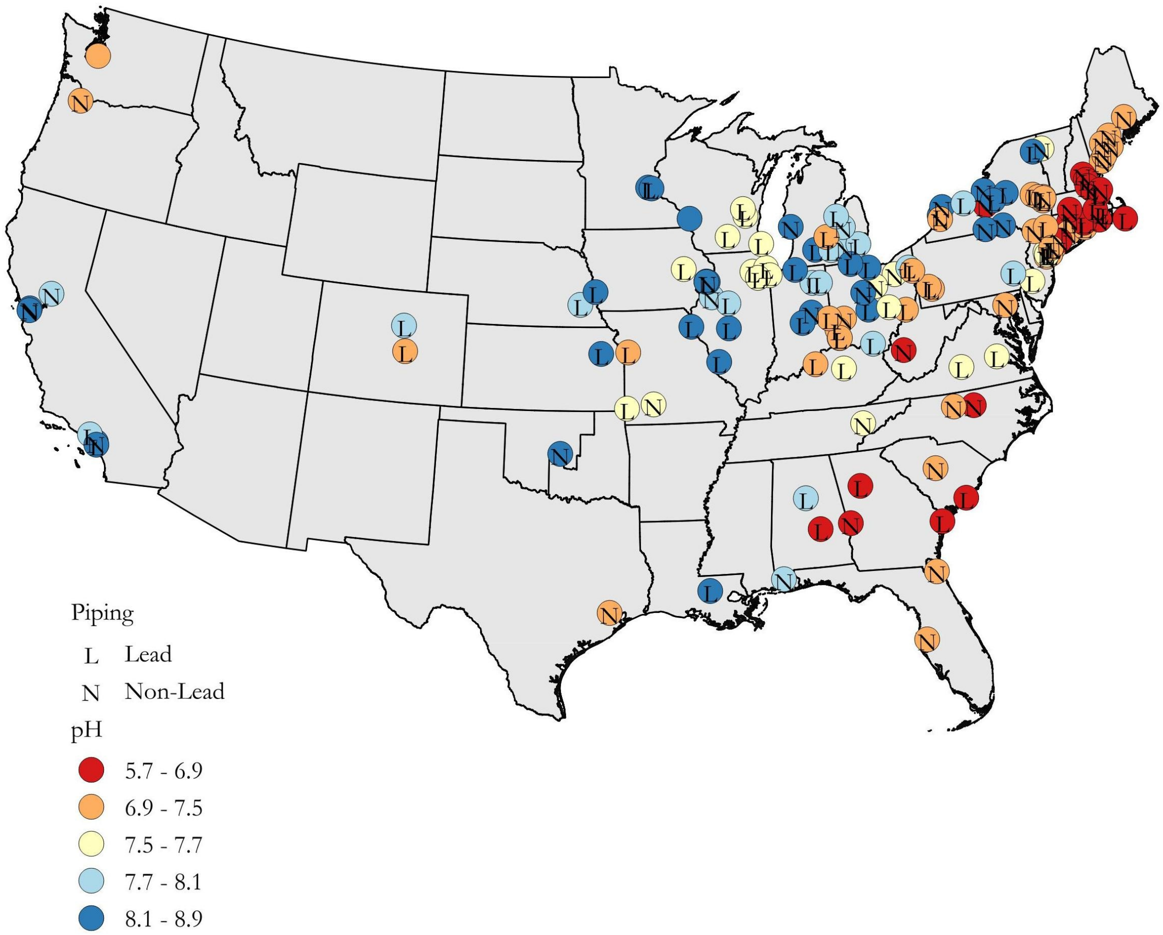

Figure 3. pH and Piping for Cities Used in the Analysis.

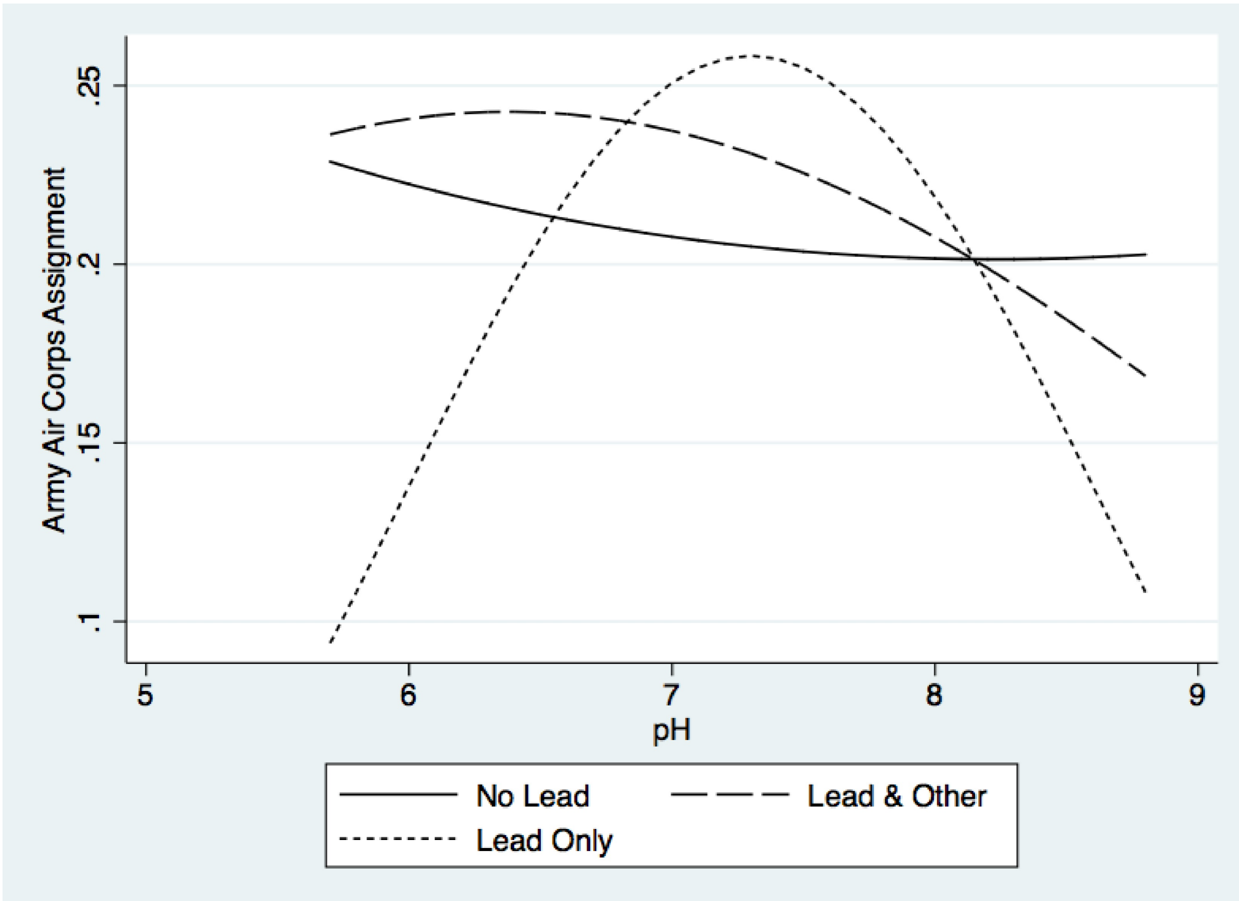

Figure 4. Water pH, Lead Pipes, and the Probability of Assignment to the Air Corps

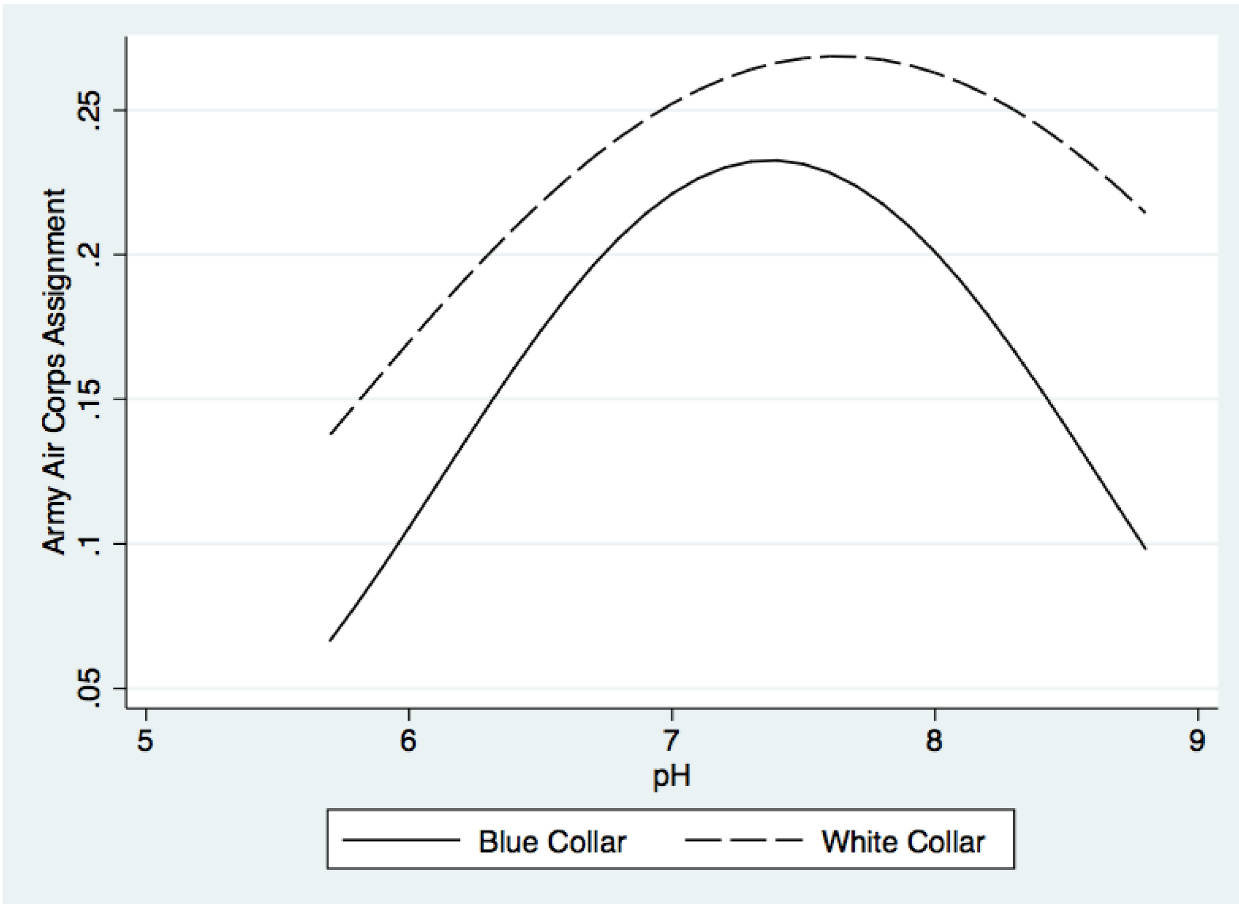

Figure 5. Water pH and the Probability of Assignment to the Air Corps: Blue vs. White Collar Fathers

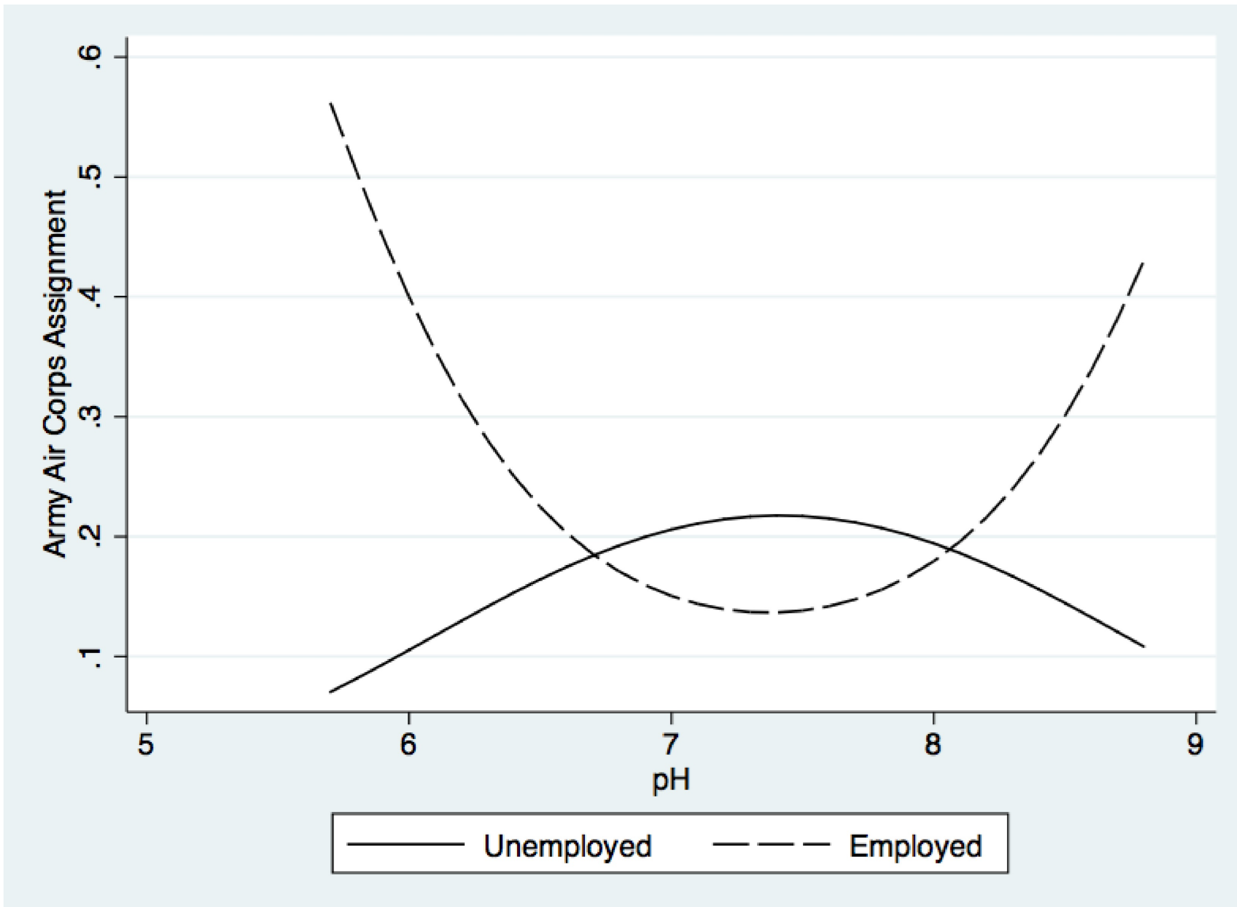

Figure 6. Water pH and the Probability of Assignment to the Air Corps: Unemployed vs. Employed Fathers

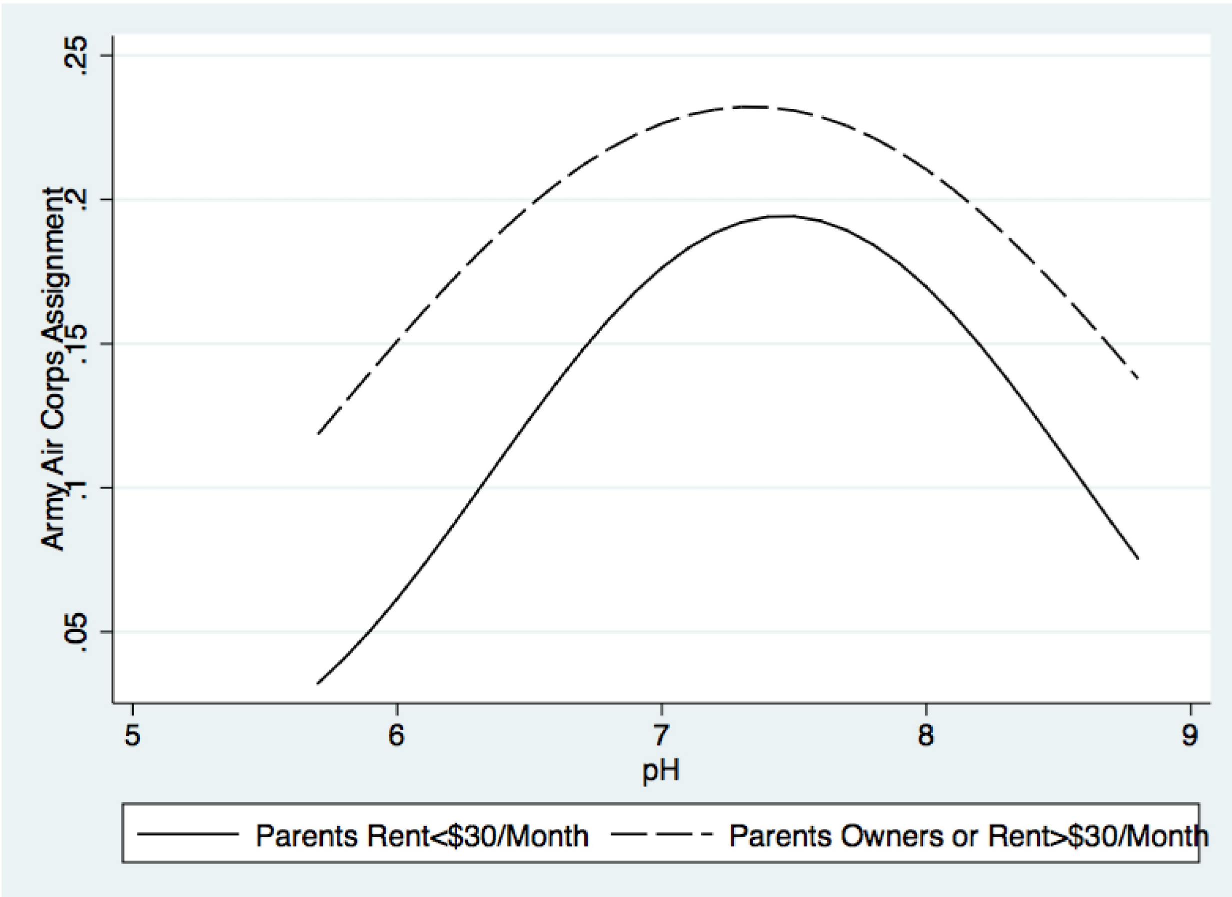

Figure 7. Water pH and the Probability of Assignment to the Air Corps: Low Rent Parents vs. Parents Who Own Their Home

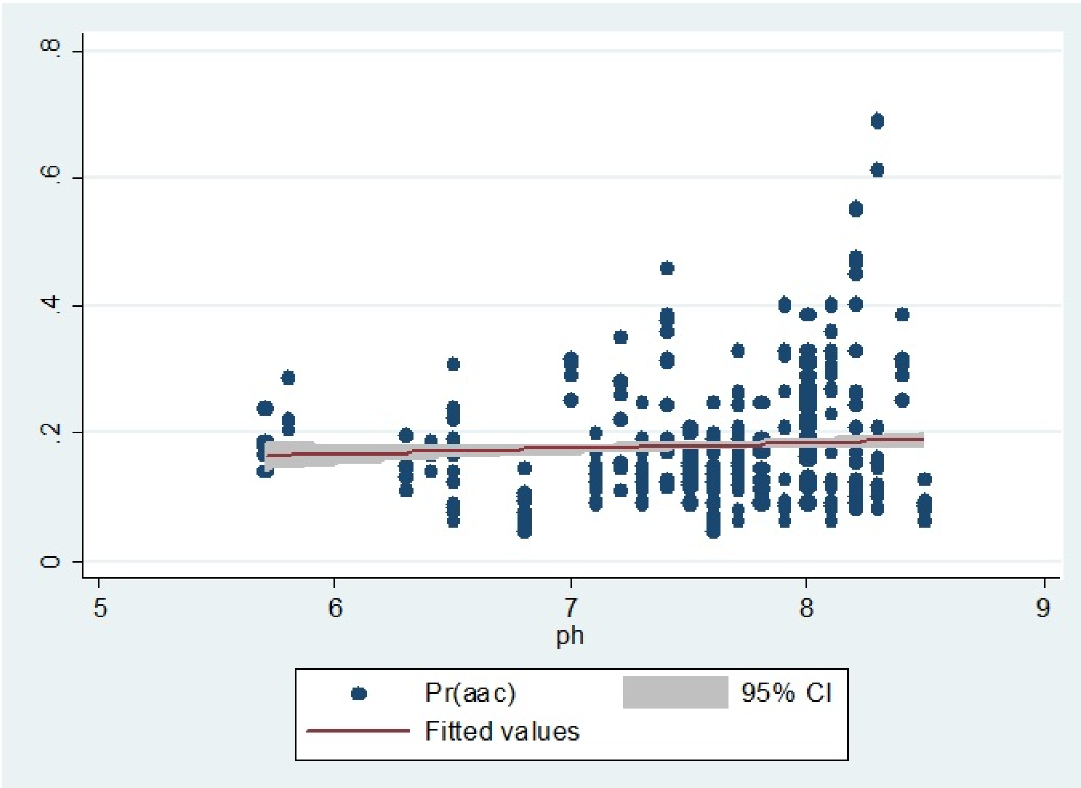

Figure 8. Predicted Air Corps Assignment and pH for Recruits with Unemployed Fathers

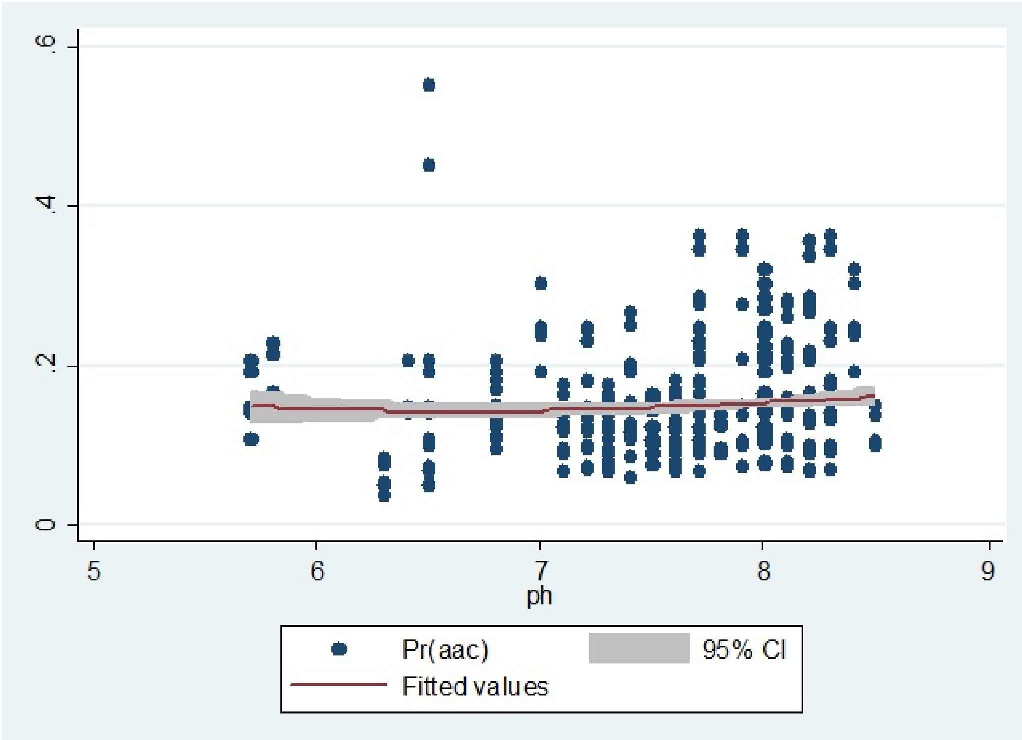

Figure9. Predicted Air Corps Assignment and pH for Recruits with Unemployed Fathers

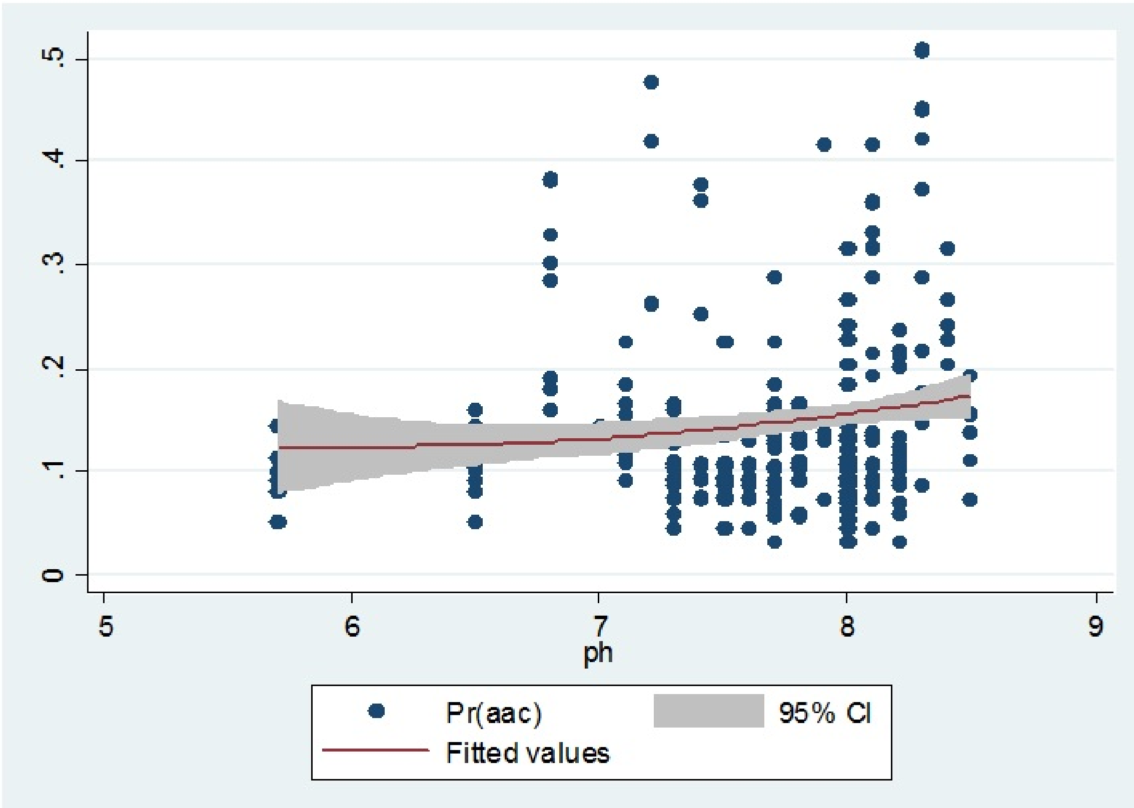

Figure 10. Predicted Air Corps Assignment and pH for Recruits From Low-Rent Households

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