Demography (2022)
DOI 10.1215/00703370-9774819

ADVANCE PUBLICATION

Death by Robots? Automation and Working-Age Mortality in the United States

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ABSTRACT The decline of manufacturing employment is frequently invoked as a key cause of worsening U.S. population health trends, including rising mortality due to "deaths of despair." Increasing automation—the use of industrial robots to perform tasks previously done by human workers—is one structural force driving the decline of manufacturing jobs and wages. In this study, we examine the impact of automation on age- and sex-specific mortality. Using exogenous variation in automation to support causal inference, we find that increases in automation over the period 1993–2007 led to substantive increases in all-cause mortality for both men and women aged 45–54. Disaggregating by cause, we find evidence that automation is associated with increases in drug overdose deaths, suicide, homicide, and cardiovascular mortality, although patterns differ by age and sex. We further examine heterogeneity in effects by safety net program generosity, labor market policies, and the supply of prescription opioids.

KEYWORDS Mortality • Deindustrialization • Labor Demand • Automation • Social Policy

Introduction

Today, a person born in the United States is expected to die an average of three years sooner than persons born in other high-income countries (Ho and Hendi 2018). This was not always the case: U.S. life expectancy diverged from that in peer countries starting around 1980, relative stagnation that recently culminated in a decline in expected longevity for the first time on record (Woolf and Schoomaker 2019). Demographic evidence reveals that this deterioration in U.S. population health is driven primarily by rising mortality among less educated, working-age adults. Increasing premature death in this subgroup—from suicide, drug overdose, and other so-called "deaths of despair"—has received widespread attention in both academic and popular discourse (Case and Deaton 2017).

The most common explanations attribute this troubling trend to structural changes in the U.S. economy, which reduced opportunity and increased precarity for working-age adults without a four-year college degree. A growing body of empirical research supports this contention (Coile and Duggan 2019; Naik et al. 2019; Seltzer 2020;

ELECTRONIC SUPPLEMENTARY MATERIAL The online version of this article (https://doi.org/10.1215/00703370-9774819) contains supplementary material.

Venkataramani, O'Brien et al. 2020). Much of this work examines the impact of the decline in domestic manufacturing, a sector that historically served as a path to the middle class for those without a college degree (Cherlin 2014). For example, Venkataramani, Bair et al. (2020) found that sharp reductions in local manufacturing jobs following automobile assembly plant closures led to an acute increase in opioid overdose mortality. Other studies have linked exposure to competition from foreign manufacturing—which reduces wages and employment opportunities for domestic manufacturing workers—to increases in mortality among working-age men with less education (Adda and Fawaz 2020; Autor et al. 2019; Pierce and Schott 2020).

This article examines the mortality impact of another structural force behind the decline of manufacturing: automation. Since the 1980s, technological improvements, coupled with the pressures of an increasingly competitive global marketplace, have fueled the adoption of industrial robots on plant floors (Acemoglu and Restrepo 2020; Autor and Salomons 2018). Although automation in some sectors may augment opportunities and raise wages by increasing the productivity of human workers (Autor 2015; Eggleston et al. 2021), this specific class of industrial robots displaced workers. According to work by Acemoglu and Restrepo (2020), adoption of industrial robots led to the loss of an estimated 420,000–750,000 jobs over the 1990s and 2000s, the majority of which were in manufacturing; workers fortunate enough to keep their jobs still experienced meaningful declines in wages (Acemoglu and Restrepo 2020).

The decline in economic opportunities due to automation has been borne primarily by less educated workers, the same group that has faced rising mortality rates. This suggests a causal link between automation and mortality, which we argue may operate through "material" pathways by impacting current employment, wages, and access to health care, as well as through "despair" pathways by reducing future economic opportunities. Although a recent consensus study report from the National Academies of Sciences, Engineering, and Medicine (2021:6) identifies "technological advances that replace workers" as one potential driver of increasing working-age mortality, this association has not been examined in the literature. With the adoption of industrial robots projected to increase twofold to fourfold in the coming decade (Acemoglu and Restrepo 2020)—a trend that may be further exacerbated by responses to the COVID-19 pandemic (Chernoff and Warman 2020)—understanding the potential consequences of automation on mortality outcomes is critical for policymakers. It is also instructive to examine heterogeneity in these relationships to identify policies that may mitigate any adverse consequences of continued automation on population health.

We use newly available measures of the adoption of industrial robots across U.S. commuting zones between 1993 and 2007 to examine the impacts of one key form of automation on mortality. Specifically, we apply the instrumental variable strategy used by Acemoglu and Restrepo (2020), who created a plausibly exogenous measure of robot penetration by combining information on preexisting employment shares in different industries in each commuting zone with the trajectory of robot adoption in each of those industries from a set of European countries. This method addresses confounding from omitted factors that may affect both automation and mortality. For example, health may have been worsening among workers even prior to automation, which may induce firms to replace sicker workers with robots. In the absence of the instrumental variable, such a process may lead us to erroneously draw a relationship between automation and population health. Combining this instrument with restricted-access U.S. death certificate data from 1993–2007, we estimate the causal effect of commuting zone–level automation on cause-specific, county-level mortality among working-age adults by age and sex in a series of first-differences models.

We find that increases in automation led to substantive increases in mortality, with positive and statistically significant effects on all-cause mortality for both men and women aged 45–54, the same age-group that has seen mortality increase in recent years. Point estimates indicate that each additional robot per 1,000 workers led to just over eight additional deaths per 100,000 males aged 45–54 and just under four additional deaths per 100,000 females in the same age-group. Automation, therefore, contributed to the slowdown in mortality improvements over this study period, portending the absolute increase observed for some subgroups in recent years (Case and Deaton 2017). Disaggregating by cause, we find that automation led to increases in drug overdose mortality for men of all age-groups and for younger (20–29) women; our estimates indicate that automation explains 12% of the overall increase in drug overdose mortality among all working-age adults over the study period. Automation also led to a substantial increase in suicide mortality for males aged 45–54, contributing to the secular rise in suicide mortality for middle-aged males observed in recent decades (Hedegaard et al. 2020). We also see evidence that automation was associated with increased homicide, cancer, and cardiovascular mortality in specific age–sex groups. Our findings are robust to accounting for preexisting trends in mortality and removing "outlier" commuting zones with exceptionally high penetration of industrial robots during the study period.

This study is among the first to demonstrate a causal association between long-run secular trends of automation-induced deindustrialization and working-age mortality.[1] Our findings are consistent with a large body of work correlating declines in manufacturing with worsening individual and population health, including mortality (e.g., Seltzer 2020). They are also in line with research identifying the causal effect of long-run manufacturing decline on mortality in specific communities (e.g., Sullivan and von Wachter 2009), in response to increased exposure to foreign trade (Adda and Fawaz 2020; Autor et al. 2019; Pierce and Schott 2020), or from acute shocks, such as plant closures (e.g., Browning and Heinesen 2012; Venkataramani, Bair et al. 2020).

We go on to examine three contextual features of places that both theory and prior work suggest could moderate the relationship between automation and mortality: social safety net policies, labor market policies, and prescription opioid supply. Sev-

[1] Closest to the present paper is a recent working paper (Gihleb et al. 2020) examining the causal impact of industrial robot adoption in the United States and Germany on a range of outcomes; it found that automation was associated with an overall increase in alcohol and suicide mortality. However, their analysis pooled all ages (including non-working-age adults) and genders, and included data from a more limited time frame and more limited set of counties. Moreover, they did not consider other causes of death. Our study also relates to work by Patel and colleagues (2018), who found that county-level measures of automation were associated with worse self-reported health, though this analysis is descriptive and precludes causal interpretations. Finally, Gunadi and Ryu (2021) assessed causal relationships between automation and self-reported health specifically among low-skill workers, finding improvements in health as a result of reallocation of workers to less physically intensive tasks.

eral recent studies emphasized the role of state policy variation in explaining levels and trends in health disparities, including mortality (see Montez 2017; Montez et al. 2020; Montez et al. 2019). Similarly, we find evidence that the generosity of state safety net programs—Medicaid and Unemployment Insurance (UI)—mitigated the effect of automation on mortality among middle-aged males, specifically deaths due to suicide and drug overdose. We also find evidence that state labor market policies moderated the effect of automation on mortality for middle-aged males: the effect of automation on drug overdose mortality and suicide mortality was more pronounced in states with "right-to-work" (RTW) laws and in states with lower minimum wage rates. Taken together, these findings demonstrate the central importance of public policies in moderating the effects of deindustrialization on deaths of despair.

We also examine effect heterogeneity as a function of the supply of prescription opioids in a local area, constructing estimates from national prescription drug surveillance data. We find suggestive—but imprecisely estimated—evidence that the effect of automation on drug overdose mortality may be higher in areas with higher per capita supply of prescription opioids. This evidence may inform ongoing debates over the relative roles of supply versus demand factors in driving the opioid overdose epidemic (Currie et al. 2018; Currie and Schwandt 2020; Hollingsworth et al. 2017; Seltzer 2020).

In the following sections, we describe the mechanisms through which automation may impact working-age mortality, drawing on a growing body of research demonstrating the impact of the economy on individual and population health. We then describe our three potential contextual moderators before turning to our data, methods, and results.

Theoretical Pathways

Theory and empirical research suggest two pathways through which the rise of industrial automation may impact working-age mortality: what we term the "material" pathway and the "despair" pathway. These pathways are not mutually exclusive, but rather complementary, inviting us to consider how the same structural economic trends may yield increases in mortality from causes as distinct as suicide and cardiovascular disease.

Material Pathway

The first pathway through which automation may impact working-age mortality is by shaping material outcomes known to impact individual and population health, including employment and wages. Acemoglu and Restrepo (2020) found that the rise of industrial robots had substantial negative effects on employment both directly through displacement of manufacturing workers and indirectly by depressing local economic demand, thereby reducing jobs in other industries, such as the service sector. In addition to lower employment rates, they found a substantial negative effect on average wages in the commuting zone, experienced even by those who remain employed. These direct and indirect effects of automation on employment and wages, in turn, are likely to impact health outcomes. Previous research has established a link between manufacturing decline and working-age mortality, examining both long-term secular trends (e.g., Seltzer 2020) and acute declines in employment opportunities due to plant closures (e.g., Venkataramani, Bair et al. 2020). Moreover, a large body of work across the social sciences has found income and employment to be key determinants of health; individuals with higher incomes live longer (Chetty et al. 2016), and areas with higher average income have higher average life expectancy (Dwyer-Lindgren et al. 2017).

Employment and wages are not the only mechanisms through which automation may impact material outcomes with consequences for health. For example, most working-age persons in the United States rely on employer-provided health insurance benefits; manufacturing is one sector in which less educated workers were historically provided such nonwage benefits. To the extent that automation decreases the total number of jobs that provide health insurance coverage, it may decrease health care access and utilization, particularly for preventative and diagnostic visits (see Freeman et al. 2008 for a review). This, in turn, could drive increased mortality for conditions such as cancer and heart disease. At the community level, increasing automation and worker displacement may lead to lower tax revenues, thus reducing public-sector spending on everything from health to education.[2] To the extent automation reduces public-sector investment in health care services, we would expect that to increase mortality on the margins.

It is possible that automation may also improve health for some subsets of the population, particularly if tasks done by industrial robots allow existing workers to focus on less dangerous or taxing tasks. For example, recent work suggests that adoption of industrial robots may improve self-reported health among some types of workers, likely owing to reductions in physical tasks (Gihleb et al. 2020; Gunadi and Ryu 2021). However, given the substantial negative estimated effect of automation on the material economic outcomes of affected workers and their communities, we expect to find an association between the changing intensity of robot penetration and working-age mortality across U.S. counties.

Despair Pathway

The second pathway through which automation may impact working-age mortality is by shaping the real and perceived economic opportunity of residents in affected areas. Analyzing the social and economic correlates of recent trends in mortality for different subpopulations, Siddiqi and colleagues (2019) found that the material pathways described here cannot entirely account for worsening mortality among middle-aged White individuals, given that the same adverse trends also impacted Black Americans who, in contrast, did not experience the same increases in mortality until more recently. The authors attributed increasing mortality among the former group to perceived status loss due to declining relative group position, specifically vis-à-vis

[2] Feler and Senses (2017) found exactly that in their analysis of the impact of foreign trade exposure on the local provision of public goods.

racial and ethnic minorities. In addition, recent work demonstrates that occupational *expectations* are stronger predictors of death from drug overdose and suicide than actual occupational attainment (Muller et al. 2020). These findings are consistent with emerging work showing that area-level prospects for social mobility are strongly associated with a range of individual- and area-level measures of health behaviors and physical and mental health outcomes, even after adjusting for socioeconomic status (Venkataramani, Daza, and Emanuel 2020; Venkataramani et al. 2016), as well as with evidence that mortality among middle-aged White individuals increased more in areas characterized by low economic mobility (O'Brien et al. 2017). How people understand and conceive of their position in the social hierarchy, and the opportunities and possibilities available to them, can impact health outcomes regardless of the material reality.

We argue that the decline of manufacturing employment is likely to have a negative impact on perceived economic opportunity and future expectations, particularly for residents of the industrial heartland. Historically, regions of the United States with high levels of manufacturing employment have been characterized by high rates of intergenerational economic mobility—the likelihood that children will achieve the American dream of doing better than their parents in adulthood (Berger and Engzell 2020). Indeed, recent work finds that the decline in manufacturing is a key driver of declining rates of economic mobility in many parts of the industrial Midwest and Northeast (Connor and Storper 2020). To the extent that automation reduces local area economic opportunity, or the perception thereof, we might expect increased mortality from drug overdose, suicide, and other so-called "deaths of despair" (Case and Deaton 2017). Compounding these forces is the fact that areas facing deindustrialization also experience shifts in key social factors—for example, changes in marriage markets and destruction of social capital—that may further worsen health outcomes (Cherlin 2014; Wilson 1996).

The material and despair pathways through which automation may impact mortality are complementary and mutually reinforcing; they also reveal how the determinants of health and mortality cannot be neatly categorized as processes occurring at either the individual or the ecological levels. Automation is a technological shock that has implications for both individuals and their communities. Whether and to what extent the material hit to an individual—say, in the form of job loss or lower wages—translates into heightened mortality risk are likely to vary as a function of the overall economic health of the local area. At the same time, residing in an area hit hard by automation-driven deindustrialization may heighten mortality risk even among those whose own immediate material reality is unchanged by dimming prospects for economic mobility and weakening of the public sector. In the following analysis, we estimate change in mortality at the county level, capturing the net effect of these distinct but related pathways.

Potential Contextual Moderators

The United States is a large and heterogeneous country. Therefore, we expect the effect of technological adoption on population health to vary systematically across places. We consider three aspects of local context that may moderate the relationship between automation and working-age mortality: social safety net policies, labor market policies, and prescription opioid supply.

Social Safety Net Policies

Evidence suggests that cross-state variation in the generosity of social safety net programs is an important determinant of spatial patterns in population health (Montez 2017; Montez et al. 2020). In the context of this analysis, we might expect social safety net program generosity to moderate the relationship between automation and mortality by blunting the social and economic hit to workers, families, and their communities. Our measures of program generosity are taken from Fox et al. (2020), who created summary indices for each social program that are based on program generosity, eligibility requirements, and administrative burdens to accessing benefits.[3] In addition to a composite measure capturing the overall generosity of state social safety net policies, we consider two specific programs that exhibit substantial variation across state lines: Medicaid and UI. We use measures from the earliest year available (2000) in their data.

Our prior is that the generosity of state Medicaid programs is the most likely element to moderate the relationship between automation and mortality; during our study period, there was considerable cross-state variation in Medicaid income eligibility thresholds for working-age adults. Research has found that variation in Medicaid policy impacted spatial patterns in both all-cause and drug overdose mortality (Miller et al. 2021; Sommers et al. 2012; Venkataramani and Chatterjee 2019). Although generosity of (and eligibility for) UI varies across state lines, it is a time-limited social benefit. Even so, work by Kuka (2020) found a causal association between UI generosity and health insurance coverage and utilization, particularly during periods of high unemployment. She also found that UI generosity was associated with higher self-rated health. Similarly, Cylus et al. (2014) showed that more generous UI benefits at the state level were associated with lower suicide rates, particularly during periods of high unemployment. Moreover, other evidence suggests that UI program generosity is associated with improved job matching for unemployed workers (Farooq et al. 2020), which may both reduce despair and improve material outcomes for workers in ways that benefit health.

Labor Market Policies

Beyond the social safety net, there is substantial variation in state labor market policies. We consider two: minimum wage rates and RTW laws. Evidence on the effect of state minimum wage rates on health outcomes of the working-age population is mixed, with most studies finding no discernible effects (see Leigh et al. 2019 for a

[3] For example, the Medicaid generosity index combines multiple measures of generosity (based on coverage of optional benefits, e.g., dental, vision, psychologists), eligibility requirements (i.e., income eligibility thresholds for children, pregnant women, parents, and nonparents), and administrative burdens (e.g., presence of asset tests, face-to-face interviews, presumptive eligibility, continuous enrollment). This index ranges from 0 to 100; see Fox et al. (2020) for details. Fox et al. also constructed indices for the Temporary Assistance for Needy Families (TANF) and Supplemental Nutrition Assistance Program (SNAP). However, we did not consider these programs in our analysis given either the limited scope of the program (TANF) or the relative lack of cross-state variation in generosity during the study period (SNAP).

review). There is, however, growing evidence linking higher minimum wage rates to reductions in mortality from suicide among working-age adults (Dow et al. 2020; Gertner et al. 2019). Moreover, correlational analyses have found that reports of unmet medical needs among low-skilled workers were lower in states with higher minimum wages, net of individual and contextual covariates (McCarrier et al. 2011). In our conceptual framework, higher minimum wages may moderate the effect of automation on mortality by mitigating the wage loss associated with a decline in manufacturing employment. Our analysis tests for effect heterogeneity as a function of the state minimum wage rate in nominal dollars in the year 2000 (obtained from University of Kentucky Center for Poverty Research 2021).

We also consider the potential moderating effect of state RTW laws. Such laws are state-level prohibitions on unions that require nonmembers who benefit from union-negotiated benefits to contribute to the cost of union representation. The empirical evidence on the effects of RTW laws on labor market indicators such as aggregate employment and wages is mixed and inconclusive (see Collins 2012 for a review), although there is evidence that they reduce labor organizing (Ellwood and Fine 1987) and private-sector unionization rates (Eren and Ozbeklik 2016). To the extent that these laws shape the quality and/or quantity of jobs available to displaced workers, they may moderate the association between automation and working-age mortality. We explore this using a binary indicator for whether the state had a RTW law as of 2000 with data taken from Caughey and Warshaw (2016).

Prescription Opioid Supply

Several studies have found a positive association between local-area, prescription opioid supply and drug overdose rates (see, e.g., Alpert et al. 2019; Currie and Schwandt 2020; Monnat 2019; Ruhm 2019). Therefore, we also consider the possibility that the local opioid supply may moderate the effect of automation on mortality. Specifically, we hypothesize that any effect of robot adoption on drug overdose mortality is likely to be higher in local areas with a greater supply of prescription opioids. To examine this, we amassed data on the prevalence of oxycodone prescriptions across counties in the United States, as reported to the Automated Reports and Consolidated Ordering System (ARCOS), which is maintained by the U.S. Department of Justice and collects information on controlled substance transactions from manufacturers and distributors. We used these data to calculate the (logged) milligram equivalent of morphine of oxycodone prescribed per working-age adult between ages 20–64 in each U.S. county in 2000.

Methods

Data

For our main exposure—commuting zone–level exposure to automation—data were obtained from Acemoglu and Restrepo (2020). This measure captures the *predicted* increase in industrial robots per 1,000 workers over the period 1993–2007. The

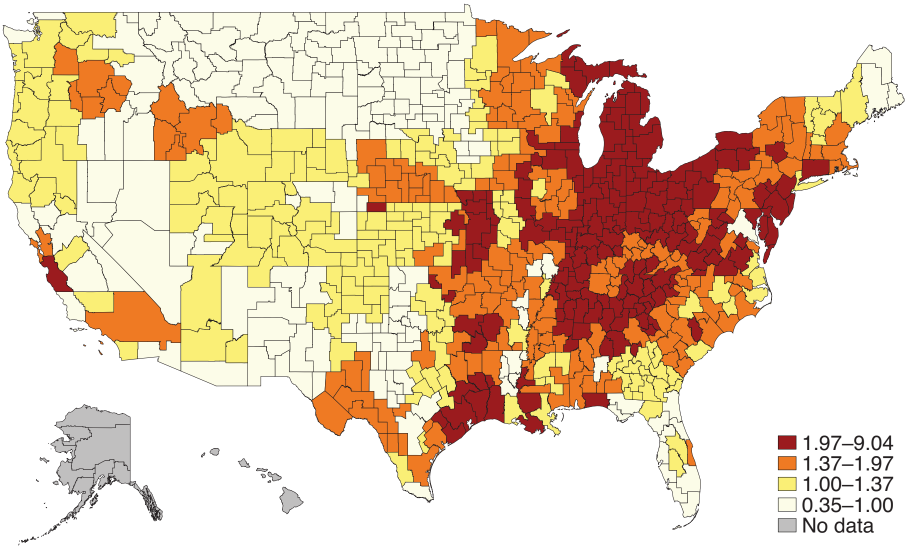

Fig. 1 Exposure to automation, 1993–2007. The figure maps quartiles of commuting zone–level exposure to automation, as measured by change in the number of industrial robots per 1,000 workers, by county. Data were obtained from Acemoglu and Restrepo (2020).

measure is constructed using 1970 U.S. commuting zone–level data[4] on employment shares across 19 different industries, as well as data on the growth in industrial robots in each of these industries for five European countries (Denmark, Finland, France, Italy, and Sweden). The use of data from these countries—which adopted industrial robots sooner than the United States did—allowed Acemoglu and Restrepo (2020) to limit bias from endogenous, commuting zone, labor demand factors that may have jointly influenced automation and our outcomes of interest (e.g., worsening health leading both to firms adopting automation technologies and to increased working-age mortality; see Currie et al. 2018; Krueger 2017). This type of measure is known as a “shift-share instrument” in the econometrics literature (Goldsmith-Pinkham et al. 2020). Figure 1 maps the predicted change in automation across commuting zones between 1993 and 2007 as estimated by Acemoglu and Restrepo (2020).

We constructed county-specific, age-adjusted mortality rates by age-group, sex, and cause using restricted-access, death certificate data obtained from the U.S. National Center for Health Statistics and annual age- and sex-specific population estimates from the U.S. Census Bureau. We examine sex-specific mortality rates for the 20–29, 30–44, 45–54, and 55–64 age-groups, given evidence of heterogeneous impacts by age and sex in other work. For each group, we compute mortality rates from all causes, as well as from drug overdoses, suicides, homicides, cardiovascular diseases, respiratory illnesses, cancers, and unintentional injuries (excluding drug overdoses; see Table A1 of the online appendix for relevant ICD-9 and ICD-10 codes,

[4] Acemoglu and Restrepo (2020) used 1970 values to address potential bias from mean reversion in industrial employment shares in the 1980s.

and Table A2 for mortality rates by age and sex in 1993). To best match the automation data, we compute changes in mortality rates for each demographic group and cause (per 100,000) between 1993 and 2007. For each baseline and endline year, we use the surrounding three-year average for mortality rates to improve the precision of measurement (Woolf and Schoomaker 2019).

Analytic Strategy

To estimate the impact of automation on working-age mortality, we estimate versions of the following first-differences model:

$$\Delta Y_{i,j,r,t1-t0} = \alpha_1 \times \Delta Automation_{j,r,t1-t0} + \boldsymbol{\beta} \times \mathbf{BaselineChar}_{j,r,t0} + \boldsymbol{\theta}_r + e_{i,j,r,t}, \quad (1)$$

where i indexes the county, j indexes the commuting zone, and $t1$ and $t0$ index 2007 and 1993, respectively. $\Delta Y_{i,j,r,t1-t0}$ represents the change in mortality at the county level and $\Delta Automation_{j,r,t1-t0}$ represents the change in the number of industrial robots per 1,000 workers at the commuting zone level. This specification corresponds to the "long-difference" model used by Acemoglu and Restrepo (2020).

α_1 , which captures the association between exposure to automation and mortality, is our parameter of interest. This parameter captures health impacts accruing from both the material and despair pathways—that is, the effects of automation-led job and benefit loss, diminished wages among still-employed workers (Elser et al. 2019), reduced physical exertion and injury risk among still employed workers (Gihleb et al. 2020; Gunadi and Ryu 2021), reduced economic opportunities and future expectations, and the effects of shifting social factors (e.g., changes to marriage markets, destruction of social capital) (Cherlin 2014; Wilson 1996). Our research design and data limitations do not allow us to assess the specific contribution of each of these pathways, and we flag this as an important area for future research.

Shift-share instrumental variables may be susceptible to bias if the baseline characteristics (here, commuting zone industrial shares in 1970) used to create the instrument are correlated with other baseline characteristics, the subsequent trends of which may also affect the outcomes of interest (e.g., educational attainment) (Goldsmith-Pinkham et al. 2020). To address this concern, we follow Acemoglu and Restrepo (2020)'s preferred specification and adjust a rich set of baseline characteristics (denoted by the vector $\mathbf{BaselineChar}_{j,r,t0}$) measured in 1990, including commuting zone demographic (age distribution, race/ethnicity population shares) and socioeconomic characteristics (shares completing high school and college education, share employed in manufacturing, share employed in routine occupations, and exposure to foreign trade). We also include a vector of fixed effects for the nine census divisions (denoted by $\boldsymbol{\theta}_r$), given regional patterns in the evolution of automation and our main outcomes (see Figure 1). We estimate the foregoing model for mortality outcomes separately by age–sex groups and cause. In all analyses, we cluster standard errors at the state level to account for potential geographic correlation in the exposure and outcomes, and weight by appropriate (age–sex group) population size. Clustering at the commuting zone level produces substantively identical results (see Table A3 in the online appendix).

We test for potential contextual moderators by estimating models that include an interaction term between our contextual measure (e.g., state minimum wage rate) and the automation measure. We also include in our models all interactions between the focal contextual measure and the full set of covariates, to reduce the possibility that the interaction effects of interest are confounded by other interactions between the contextual measure and observable characteristics potentially correlated with our automation measure. Specifically, we estimate versions of the following equation:

$$\begin{aligned}\Delta Y_{i,j,r,t1-t0} = {} & \gamma_1 \times \Delta Automation_{j,r,t1-t0} + \gamma_2 \times \Delta Automation_{j,r,t1-t0} \times StateContext_{j,r} \\ & + \gamma_3 \times StateContext_{j,r} + \boldsymbol{\delta} \times \mathbf{BaselineChar}_{j,r,t0} \\ & + \boldsymbol{\vartheta} \times \mathbf{BaselineChar}_{j,r,t0} \times StateContext_{j,r} \\ & + \boldsymbol{\theta}_r + \boldsymbol{\theta}_r \times StateContext_{j,r} + u_{i,j,r,t}. \end{aligned} \tag{2}$$

The key parameter of interest here is γ_2, which captures the interaction between the focal contextual measure ($StateContext_{j,r}$) and our automation instrument. We estimate this model specifically for men and women aged 45–54, for whom increases in midlife mortality have been most prominent and for whom we find large impacts of automation on all-cause mortality in our main analyses. For the ease of interpretation, we report marginal effects of automation on mortality evaluated at high and low values of the contextual measure $StateContext_{j,r}$ (we report estimated coefficients on the interaction term in Tables A9–A14 in the online appendix).

Results

Impacts of Automation on Mortality

Main Findings

Figure 2 plots estimated coefficients of the effects of automation on mortality by cause for males of four age-groups (Table A3 of the online appendix reports the coefficients and standard errors). Across all age-groups, the estimated effect of automation on all-cause mortality was positive and substantial in magnitude; however, only for males aged 45–54 was the point estimate statistically distinguishable from zero at conventional alpha levels ($p < .05$). Among this group, an increase of one robot per 1,000 workers was associated with a statistically significant eight additional deaths per 100,000 persons (relative to a scenario in which there was no increase in industrial robots). This is a sizable relative increase in mortality, notably among the exact demographic subgroup identified by Case and Deaton (2017) as suffering from increased deaths of despair. The average increase in automation over the study period (two robots per 1,000 workers) was thus associated with 16 additional deaths per 100,000 persons, equivalent to roughly 25% of the overall secular decline seen in this age-group between 1993 and 2007 (64 deaths per 100,000).

Disaggregating by cause, we find evidence that increases in robot penetration led to significant increases in drug overdose mortality across all four age-groups. The average increase in automation across commuting zones of two robots per 1,000 workers can account for 13.5% of the overall increase (14 deaths per 100,000) in drug overdose

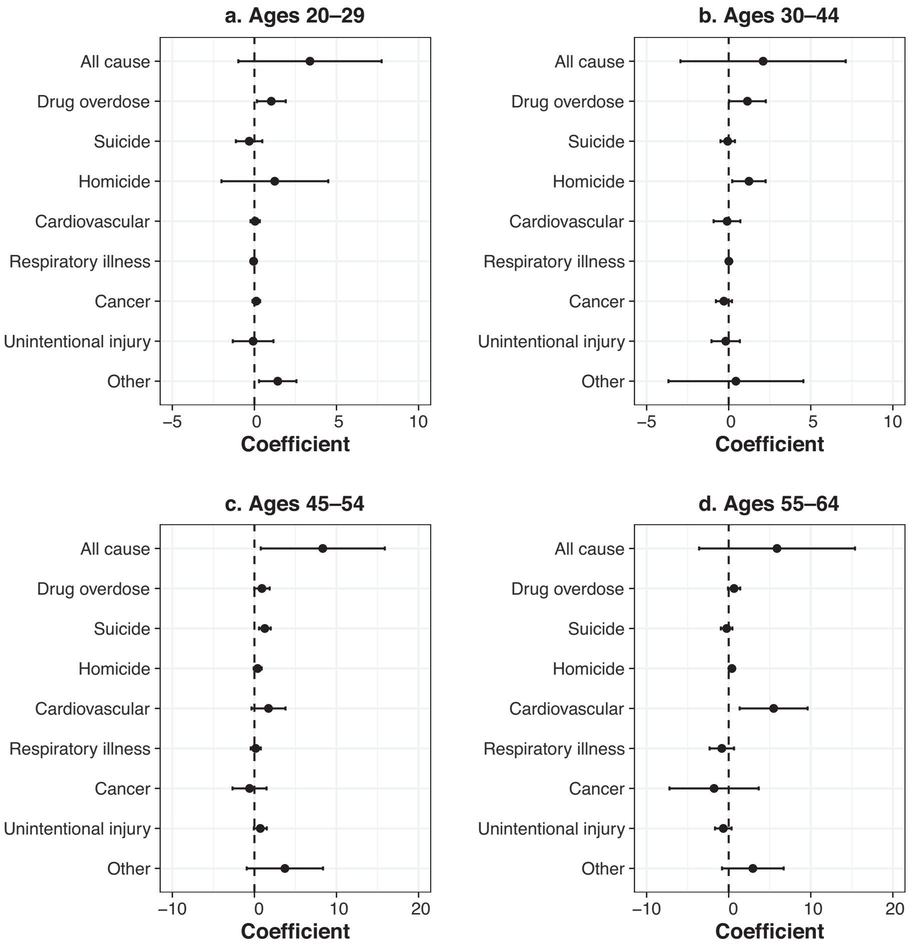

Fig. 2 Impacts of automation on mortality of males by age-group. Estimates are from a first-differences model regressing changes in mortality rates (per 100,000) for each listed age–sex group on automation over the period 1993–2007, expressed as the change in the number of industrial robots per 1,000 workers between 1993 and 2007. Each point (and 95% CI) represents estimates from a separate regression ($N=3{,}108$). All models adjust for the characteristics and fixed effects described in Table 1. Standard errors are clustered at the state level.

deaths between 1993 and 2007 among men aged 20–29 ($p<.05$), 20.1% of the overall increase (11 per 100,000) among those aged 30–44 ($p<.05$), 8.2% of the overall increase (22 per 100,000) among those aged 45–54 ($p<.10$), and 12.0% of the overall increase (11 per 100,000) among those aged 55–65 ($p<.10$). To place these findings in context, we note that the relative share of drug overdose deaths explained by automation was somewhat smaller than the share explained by local exposure to international trade. For example, Pierce and Schott (2020) noted that local economic shocks resulting from the United States granting permanent trade relations with China could account for approximately 40% of the growth in drug overdose mortality in the early 2000s.

Estimates for other causes of death varied by age-group. Among men aged 30–44, we find evidence that automation led to increases in homicide deaths. Among those aged 45–54, we see evidence of impacts on suicide mortality rates, with the average increase in robot penetration of two per 1,000 workers, accounting for 51% of the overall increase in suicide deaths (five deaths per 100,000) in this age-group over the study period. In addition to increasing deaths of despair, we also find evidence that automation was associated with elevated risk of cardiovascular mortality, particularly among males aged 55–64, for whom each additional robot per 1,000 workers was associated with an additional five deaths per 100,000.[5] This finding is consistent with an emerging literature linking area-level economic prosperity with cardiovascular disease outcomes (Khatana et al. 2021).

Figure 3 presents the corresponding analysis for females. Here the estimated effect sizes were generally smaller but follow a similar pattern: automation was associated with an increase in all-cause mortality among working-age females, with statistically significant effects among those aged 20–29 ($p < .05$) and 45–54 ($p < .01$). In the latter group, the average increase in automation led to a relative increase in mortality equal to about 59% of the overall decline in all-cause mortality observed over the study period (13 deaths per 100,000). As with men, drug overdose mortality among women aged 20–29 increased with automation. Among women aged 30–44, we find that automation was associated with higher cancer mortality rates.[6] The largest absolute impact was on cardiovascular mortality for women aged 55–64, with each additional robot per 1,000 workers associated with an increase of just under four deaths per 100,000.

Taken together, our findings reveal a direct link between the rise of automation and the mortality among adults aged 45–54, operating largely through increasing deaths from drug overdose and suicide. We also see that automation led to a relative increase in overall mortality among younger females and, for certain age–sex groups, increased mortality from causes as varied as cancer and cardiovascular disease.

Robustness Checks

Following Acemoglu and Restrepo (2020), we checked that our findings were not being driven by a subset of commuting zones where adoption of industrial robots distinctly outpaced the rest of the United States. We reestimated our models after removing these "outlier" commuting zones and found similar substantive effects (Table A4, column 1, in the online appendix).[7] We also examined the effect of automation in areas with high levels of manufacturing employment, defined as counties in the top quartile of the share

[5] In absolute terms, this is the largest effect for a specific cause of death across all age–sex groups. However, given that the baseline rates for cardiovascular disease mortality are an order of magnitude larger than for other disease (except for cancer), these effects are in fact smaller in relative (e.g., percentage increase) terms than, for example, the automation-driven increase in drug overdose deaths among men in any age-group.

[6] Given small sample sizes, we follow standard practice and aggregate cancers from all causes into a single statistic for the purposes of this analysis.

[7] We also note that Acemoglu and Restrepo (2020) found that the bulk of the effects of automation on labor market outcomes were unlikely to be explained by migration, and that migration in general appeared to play a minor role in other studies examining the link between economic opportunity and health (Autor et al. 2019; Ganong and Shoag 2017; Sullivan and von Wachter 2020).

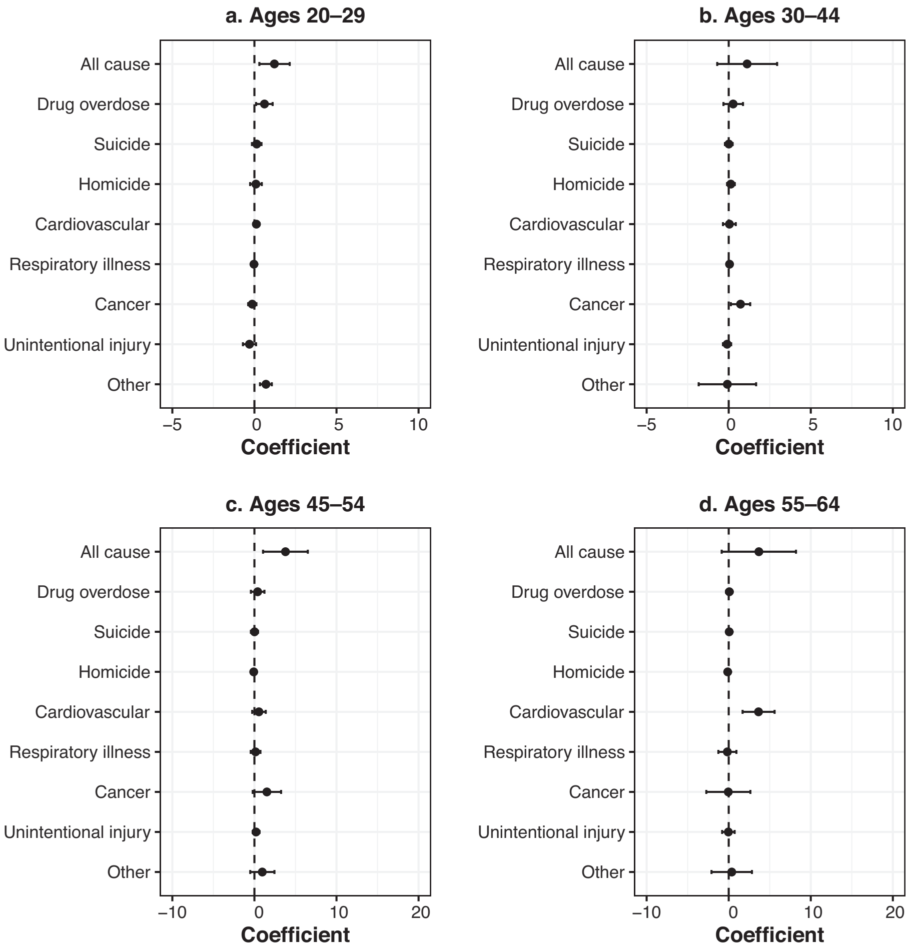

Fig. 3 Impacts of automation on mortality among females by age-group. Estimates are from a first-differences model regressing changes in mortality rates (per 100,000) for each listed age–sex group on automation over the period 1993–2007, expressed as the change in the number of industrial robots per 1,000 workers between 1993 and 2007. Each point (and 95% CI) represents estimates from a separate regression (N=3,108). All models adjust for the characteristics and fixed effects described in Table 1. Standard errors are clustered at the state level.

of residents employed in manufacturing in 1980 (Table A4, column 2). Notably, we find the estimated effect of automation on drug overdose mortality and suicide mortality to be substantially larger (and statistically different) when we restrict our sample to communities in which manufacturing workers tended to live, consistent with the fact that automation affected these workers the most (Acemoglu and Restrepo 2020).

A key threat to inference in our research design is preexisting trends in the outcome of interest. Namely, areas with greater adoption of industrial robots over the study period may have already experienced worsening mortality. We address this possibility by estimating models regressing changes in cause-specific mortality rates between 1981 and 1992 on automation between 1993 and 2007 (conditional on the same covariates in our main specification). Large, positive estimates on automation in these models would be consistent with upward-biasing preexisting trends. As seen in column 3 of Table A4 (online appendix), we find no evidence of preexisting trends of increasing mortality rates. If anything, some of the estimates suggest pretrends in the opposite direction. To correct for this, we estimate versions of our main model for each cause of death while adjusting for the 1981–1992 pretrends; our results are substantively unchanged by inclusion of this covariate (Table A4, column 4).

Contextual Moderators

To test for potential contextual moderators of the effect of automation on mortality, we estimate versions of our core model that additionally include interaction terms between the contextual measure and automation (as well as interactions between the contextual measure and each of the covariates; see Eq. (2)). For safety net and labor market policies, we focus on outcomes for males aged 45–54, for whom the effect of robots on mortality was largest (for corresponding analysis for females aged 45–54, see Table A8 in the online appendix). For opioid supply, we examine all-cause and drug overdose mortality for all working-age males and females.

Safety Net Programs

We examine effect heterogeneity using a composite index of the overall generosity of state social safety net programs, as well as indices of the generosity of two specific programs that vary across state lines: Medicaid and UI. Note that our policy generosity variables are measured in 2000, and because this time point falls in the middle of the study period, estimates on interaction terms cannot be interpreted causally if program generosity was responsive to economic shocks. Even if they were not, program generosity may be correlated with other policy choices or state-level factors. Consequently, we consider this exercise to be descriptive.

Table 1 presents estimates from our safety net policy heterogeneity models. Each set of rows shows the marginal effects (and standard errors) obtained from a separate regression model, with margins evaluated at the 25th and 75th percentile of the national distribution of overall safety net program generosity, as well as specifically for Medicaid and UI program generosity. Estimates of the interaction term between automation and safety net programs—which effectively test whether the differences between effects in low versus high program generosity areas are statistically significant—are presented in Tables A9–A11 of the online appendix. Focusing on coefficient magnitudes, UI generosity appeared to moderate the effect of automation on all-cause mortality for men aged 45–54. Point estimates indicated that in states with relatively less generous UI benefits, an additional robot per 1,000 workers was associated with an increase in all-cause mortality of about 16 deaths per 100,000, compared with about 10 deaths per 100,000 in states with relatively more generous UI programs; however, these differences were not statistically significant (Table A11 in the online appendix).

Turning to cause-specific mortality, we find strong evidence that state safety net generosity—overall, and for both UI and Medicaid in particular—moderated the

Table 1 Heterogeneity in the impacts of automation on mortality rates among males aged 45–54

	State Safety Net Generosity						State Labor Market Policies			
	Overall Generosity Index		Medicaid Generosity Index		UI Generosity Index		Right to Work Law		State Minimum Wage	
Mortality	Low	High	Low	High	Low	High	Low	High	Low	High
All-Cause	9.62	5.66†	3.23	3.20	15.87*	10.45**	8.86**	28.36*	13.54	6.83*
	(7.69)	(3.10)	(6.52)	(3.47)	(7.07)	(3.60)	(3.17)	(10.72)	(10.69)	(3.33)
Drug	1.75	0.47	2.48**	0.17	–0.43	–0.19	0.88	1.09	0.74	1.01*
	(1.30)	(0.41)	(0.84)	(0.59)	(1.54)	(0.62)	(0.60)	(1.58)	(1.70)	(0.41)
Suicide	3.69***	1.18**	2.82***	1.06*	3.29**	1.54**	0.68†	4.56**	2.97**	1.16**
	(0.98)	(0.35)	(0.71)	(0.47)	(1.17)	(0.50)	(0.36)	(1.54)	(0.83)	(0.38)
Homicide	–1.06*	0.13	–0.67	0.03	–0.07	0.13	0.45	0.11	–0.57	0.33
	(0.49)	(0.19)	(0.42)	(0.23)	(0.42)	(0.25)	(0.31)	(0.54)	(1.08)	(0.26)
Cardiovascular	1.73	0.51	0.77	0.08	5.59	2.61	–0.27	7.90	–0.40	1.38
	(3.45)	(0.87)	(1.96)	(0.90)	(3.86)	(1.63)	(0.81)	(6.98)	(2.58)	(1.08)
Respiratory Illness	–0.52	0.12	–0.53	–0.10	–0.09	0.13	0.12	0.12	–0.05	0.17
	(0.67)	(0.30)	(0.46)	(0.31)	(0.98)	(0.41)	(0.37)	(0.66)	(0.94)	(0.30)
Cancer	1.60	–0.61	0.82	–0.98	1.82	0.06	–0.26	6.09†	4.24	–0.38
	(2.47)	(0.97)	(1.82)	(1.17)	(3.08)	(1.49)	(0.99)	(3.61)	(3.27)	(0.79)
Unintentional Injury (without drug)	0.36	0.64	0.89	0.20	0.59	0.93†	1.28**	0.85	–0.18	0.47
	(1.19)	(0.39)	(0.67)	(0.41)	(1.16)	(0.53)	(0.41)	(1.34)	(1.36)	(0.36)
Other	2.19	3.16*	–2.91	2.60†	4.82	5.02*	5.88**	7.65*	6.90	2.68
	(3.60)	(1.20)	(3.37)	(1.39)	(3.54)	(1.91)	(1.96)	(3.64)	(6.13)	(2.28)
N (clusters)	3,108 (48)		3,108 (48)		3,108 (48)		3,108 (48)		3,108 (48)	

Notes: Estimates are from a first-differences model regressing changes in mortality rates for males aged 45–54 (per 100,000) on automation over the period 1993–2007, expressed as the change in the number of industrial robots per 1,000 workers between 1993 and 2007. Each set of rows shows the marginal effects (and standard errors) obtained from a separate regression model, with margins for Overall, Medicaid, and Unemployment Insurance (UI) Generosity Indices evaluated at the 25th (low) and 75th (high) percentile of the national distribution of the heterogeneity variable, and margins for state minimum wage evaluated at the 10th (low) and 90th (high) percentiles. Margins for right to work are evaluated at discrete levels—not having a right-to-work (RTW) law (low) and having a RTW law (high). All models adjust for a rich set of commuting zone demographic (age distribution, race/ethnicity population shares) and socioeconomic characteristics (shares completing high school and college education, share employed in manufacturing, share employed in routine occupations, and exposure to foreign trade) for the year 2000, census division fixed effects, and interactions between all of these covariates and the heterogeneity variables of interest. For RTW and state minimum wage analyses, we use census region instead of census division fixed effects given the lack of variation in these outcomes within certain census divisions. Standard errors are clustered at the state level.

†$p<.10$; *$p<.05$; **$p<.01$; ***$p<.001$

effect of automation on suicide mortality (with estimates on the key interaction term between automation and program generosity being statistically significant; see Tables A9–A11 in the online appendix). We also find evidence that state Medicaid program generosity substantially mitigates the effect of automation on drug overdose mortality, an interaction effect that was precisely estimated (Table A10 in the online appendix) and consistent with prior work. Notably, we find no evidence that these programs moderated the effect of automation on other causes of death. Taken together, these findings suggest that social safety policies may play a uniquely important role in blunting the effect of automation on drug overdose and suicide deaths.

Labor Market Policies

We next examine state labor market policy, specifically RTW laws and minimum wage rates. Estimates presented in the right panel of Table 1 reveal that the effect of automation on middle-aged male all-cause mortality is higher in states with a RTW law than in those without (with the interaction between automation and RTW being statistically significant for all-cause mortality at the 10% level; see Table A12 in the online appendix). Point estimates suggest that every additional robot per 1,000 workers was associated with an increase of 28 deaths per 100,000 in RTW states, compared with about nine deaths per 100,000 in the rest of the country. This appears to be driven in part by higher rates of suicide mortality in RTW states in response to automation. We see a similar pattern when we examine state minimum wage rates: the effect of automation on suicide mortality was higher in states with relatively lower minimum wage rates (Table A13, online appendix). This again provides suggestive evidence that public policy—specifically state labor market policies—may play an important role in blunting the effect of automation on suicide deaths.

Local Supply of Prescription Opioids

Finally, Table 2 examines heterogeneity in the effect of automation on all-cause and drug overdose mortality as a function of the county-level supply of prescription opioids (logged milligram equivalents of morphine per capita) for the year 2000. Here, we find that for both males and females of working age, the effect of automation on drug overdose mortality was higher in areas with a relatively greater supply of prescription opioids. However, this interaction effect was not statistically significant (see Table A14, online appendix). The direction of this finding suggests that opioid supply and economic demand may have worked interactively to produce the opioid crisis, a finding that warrants further exploration in contexts where there may be greater statistical power to detect true differences.

Discussion and Conclusion

Technological change has led to increasing automation of routine tasks, a trend that is expected to continue in the coming decades. Since the 1990s, adoption of labor-displacing automation technologies in U.S. labor markets has coincided with rising

Table 2 Impact of automation on mortality by sex, given the county-level oxycodone supply

	All-Cause		Drug	
Sex and Age	p25	p75	p25	p75
Male, Ages 20–64	–0.40	–1.76	1.27*	2.08†
	(2.88)	(6.70)	(0.53)	(1.05)
Female, Ages 20–64	1.75	2.62	0.60†	1.07†
	(1.16)	(1.94)	(0.32)	(0.60)
N (clusters)	3,058 (48)		3,058 (48)	

Notes: Estimates are from a first-differences model regressing changes in mortality rates for males and females aged 20–64 (per 100,000) on automation over the period 1993–2007, expressed as the change in the number of industrial robots per 1,000 workers between 1993 and 2007. Each set of rows shows the marginal effects (and standard errors) obtained from a separate regression model, with margins evaluated at the 25th and 75th percentile of county-level log milligram equivalents of morphine supplied per capita in 2000. All models adjust for the characteristics, fixed effects, and interactions described in Table 1. Fifty counties did not have outcome data. Standard errors are clustered at the state level.

†$p<.10$; *$p<.05$

rates of mortality, particularly among individuals with lower levels of education. Our study suggests a causal link between these trends, with (average) increases in automation accounting for a slowdown in mortality improvements equivalent to 25% of the overall decline in mortality among males aged 45–54 and 59% of the decline for females aged 45–54 observed during the study period, portending the stagnation and reversal in longevity seen in more recent years. We find that this increase is driven in large part by increased mortality from so-called deaths of despair, including drug overdose and suicide. The effect of automation on despair mortality, in turn, appears to vary as a function of state safety net generosity, prevailing minimum wage rates and right to work laws, and the local level of prescription opioid supply.

Our findings have implications for policymakers and researchers. First, they add causal evidence in support of the theory that declining economic opportunity—whether through automation or increased exposure to foreign trade—is a major driver of worsening population health and declines in expected longevity among working-age persons without a college degree (Monnat 2019; Seltzer 2020). Second, the mortality consequences of fading opportunity are heterogeneous by sex, age, and cause of death. For example, while the largest impacts were for men aged 45–54, we also find important impacts on drug overdose, cancer, and all-cause mortality for younger women. This reveals that the impact of automation on mortality extends well beyond its direct effect on displaced workers to shape the population health of entire communities. This, in turn, motivates future research to identify and decompose potential indirect or ecological effects: for example, areas hit hard by the forces of deindustrialization face the double whammy of fewer high-quality jobs and the resulting deterioration in the wealth of tax bases used to fund the public sector.

Third, our findings also reveal that public policy plays an important role in mitigating the effect of deindustrialization on population health. Efforts to blunt the economic impacts of automation on workers through enhanced social safety net programs can make a difference—as can policies that improve local labor market opportunities and the quality of jobs available to workers (and "would-be workers") displaced by automation, such as higher minimum wage laws or rules that make it easier for workers to unionize. At the same time, constraining the supply of prescription opioids is critical to reducing the likelihood that the economic punch to individuals and communities from the arrival of industrial robots and reduction in manufacturing employment translates into higher rates of drug overdose mortality.

Deindustrialization driven by foreign competition and automation is expected to continue—perhaps even accelerate—in coming years. Counteracting these forces will require significant public-sector investment in displaced workers. It will also require national investments in these distressed communities. To mitigate the negative health effects of this structural change to the economy, policymakers should consider targeting income support to this population, either by expanding eligibility and/or generosity of existing programs or by introducing new transfer programs. At the same time, our findings suggest there may be real health gains to investing in industrial policies that increase the number of quality jobs as well as programs to help workers develop new skills and transition to new sectors (Katz et al. 2020). Efforts to improve the economic well-being of workers displaced by structural shifts to the economy—from automation or foreign trade—will have substantial benefits for population health. ■

Acknowledgments The authors thank David Asch, J. Michael Collins, Kosali Simon, Justin Sydnor, and seminar participants at the Social Security Administration, University of Wisconsin–Madison, and University of Pennsylvania for helpful comments and suggestions. They also thank Ashley Fox for providing access to her database on state welfare program generosity and administrative burdens. The research reported here was performed pursuant to a grant from the U.S. Social Security Administration (SSA) funded as part of the Retirement and Disability Consortium. The opinions and conclusions expressed are solely those of the authors and do not represent the opinions or policy of SSA or any agency of the federal government. Neither the U.S. Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of the contents of this report. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply endorsement, recommendation, or favoring by the U.S. Government or any agency thereof.

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