Temperature Extremes, Health, and Human Capital

Joshua Graff Zivin and Jeffrey Shrader

Summary

The extreme temperatures expected under climate change may be especially harmful to children. Children are more vulnerable to heat partly because of their physiological features, but, perhaps more important, because they behave and respond differently than adults do. Children are less likely to manage their own heat risk and may have fewer ways to avoid heat; for example, because they don't plan their own schedules, they typically can't avoid activity during hot portions of the day. And very young children may not be able to tell adults that they're feeling heat's effects.

Joshua Graff Zivin and Jeffrey Shrader zero in on how rising temperatures from global warming can be expected to affect children. They review evidence that high temperatures would mean more deaths, especially among fetuses and young children (as well as the elderly). When combined with other conditions—such as high humidity, diseases, or pollution—heat can be even deadlier. Even when it doesn't kill, high heat directly causes heat-related illnesses such as heat exhaustion; worsens other conditions, such as asthma, by increasing smog and ozone pollution; and harms fetuses in the womb, often with long-term consequences. High temperatures can also make learning more difficult, affecting children's adult job prospects.

What can we do to protect children from a hotter climate? Graff Zivin and Shrader discuss a range of policies that could help. Such policies include requiring air conditioning in schools; heat wave warning systems coupled with public infrastructure that helps people stay indoors and stay cool; and readjusting schedules so that, for example, children are mostly indoors during the hottest time of day or the hottest season of the year.

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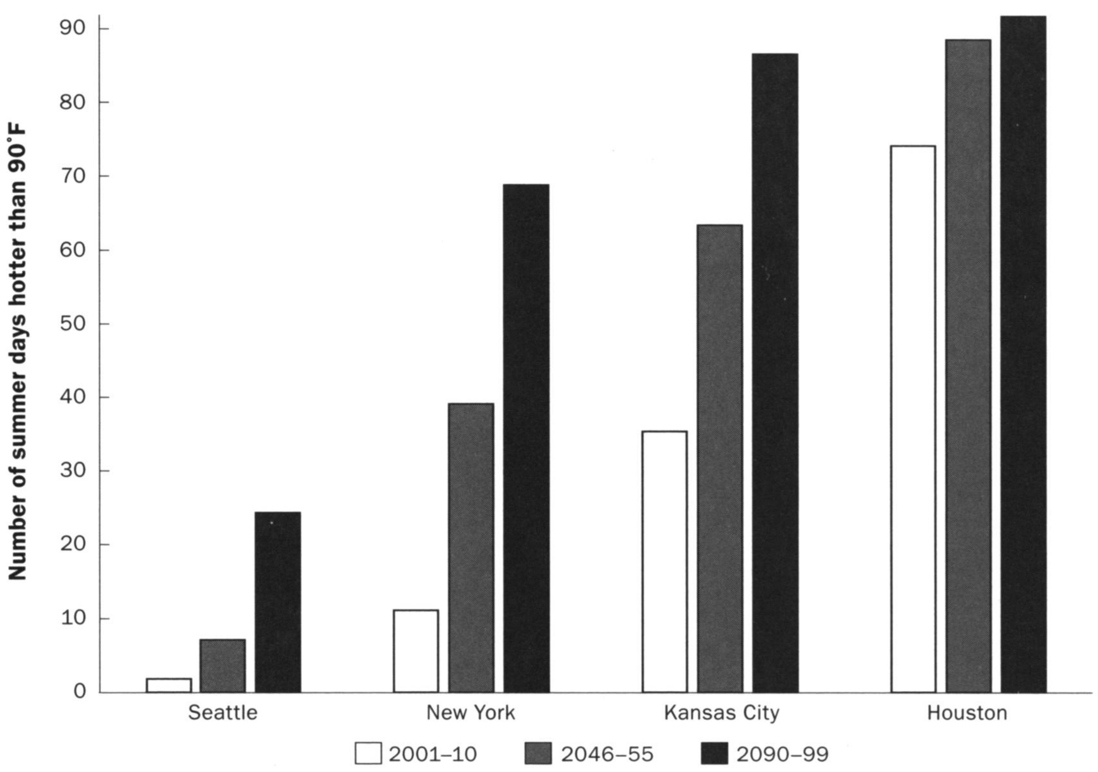
By burning fossil fuels and thereby releasing carbon dioxide and other gases, we are reshaping the global climate.[1] The changes we expect globally will both increase average temperatures and shift the climate toward greater and more frequent extreme temperatures. Already, average Americans experience more hot days per year than they did 60 years ago, and the number is expected to rise dramatically in the coming decades (see figure 1).

Rising temperatures and the increasing frequency of extremely high temperatures are likely to cause more death and illness and to diminish children's ability to learn and adults' ability to perform mental tasks.[2] Children, including fetuses in the womb, will likely suffer especially severe effects from climate change because they are more sensitive to temperature and rely on others to adapt. For a variety of reasons, the negative effects of more heat will outweigh the benefits of reduced exposure to cold, and heat is thus the focus of this article.

In this article, we assess a warming climate's likely effects on child wellbeing, limiting our attention to temperature's direct effects

Figure 1. Projected number of summer days above 90˚F in four US cities



Note: Each projection is the ensemble average of business-as-usual scenario forecasts for the continental United States.

Sources: Katherine Hayhoe et al., "Development and Dissemination of a High-Resolution National Climate Change Dataset," *Final Report for United States Geological Survey,* USGS G10AC00248 (2013); Anne M. K. Stoner et al., "An Asynchronous Regional Regression Model for Statistical Downscaling of Daily Climate Variables," *International Journal of Climatology* 33 (2013): 2473–94; Melinda S. Dalton and Sonya A. Jones, comps., *Southeast Regional Assessment Project for the National Climate Change and Wildlife Science Center, U.S. Geological Survey* (Reston, VA: U.S. Geological Survey, 2010).

on health. Direct effects include physical or mental impairment from heat stress on the body. Examples include death caused by heat stroke, cardiovascular disease, respiratory impairment, or malformed fetal brains, but we also consider more general bodily stress caused by heat. We largely ignore indirect health effects that could arise from a hotter climate due to food insecurity, natural disasters, or increased global conflict; those matters are covered by other authors in this issue.[4] When possible, we rely on studies of the temperature–health relationship that have focused explicitly on children. But such studies leave substantial gaps in the evidence, so we also make use of studies about the general population to help complete the picture. To ensure that our conclusions are relevant for policy, we concentrate on studies that focus on the causal relationships between temperature and human wellbeing (see box 1).

We've organized our discussion around three broad impacts on health: death, illness, and human capital. Human capital involves the skills, knowledge, and abilities that an individual can use to create economic value. Most of heat's effects on wellbeing are acute; heat-related deaths, for example, happen within hours of a heat wave. Heat's effects aren't limited to acute events, however. Research increasingly shows that exposure to warmer days in the womb or during infancy can cause long-lasting, often lifelong harm.[5]

We have compelling evidence that short-lived temperature shocks can damage a child's health, but the key policy issue regarding the health effects of climate change is how a permanent shift in the overall distribution of weather would play out. A sustained shift toward more extreme temperatures could have even more profound impacts than current estimates indicate. On the other hand, if the effects of climate change move slowly, we have a better chance to limit their impact through adaptation. Some recent evidence suggests that we may indeed be able to adapt, calling into question the generalized conclusions often drawn from studies that rely only on short-term variations in weather to predict the long-term effects of heat. Laboratory studies have particular

What is Causal Analysis?

Imagine that you're a parent trying to decide whether to enroll your child in a charter school, or that you're a doctor deciding whether to prescribe a certain medicine for a patient, or that you're a senator deciding whether to lower the tax rate. In each case, you want an answer to the question: Would my action actually cause an improvement in outcomes? If my child goes to a charter school, would she have a better chance of attending a good college? Would the medicine make my patient healthier? Would lowering taxes make the economy grow faster? In each case, it's not enough just to know that there's an association or a correlation between an action being considering and the outcome of the action. Two events may be likely to occur at the same time or place, but if we don't know how one influences the other, then the fact that they're associated doesn't tell us whether our action would do some good.

Causal analysis sheds light on questions like those by determining when an action is simply *associated* with an outcome versus when the action indeed *causes* the outcome. A simple example serves to illustrate the difference between correlation and causation: Death often occurs after a hospital stay. Therefore, a hospital stay is correlated or associated with dying. But, in general, hospital stays don't cause death. Rather, some very sick people seek care at hospitals and then die. It's the fact that sick people seek care at hospitals that creates the relationship, and a policy maker would be making a grave misjudgment by closing all hospitals in an effort to reduce the number of citizen deaths. Numerous statistical and scientific techniques have been developed to distinguish causality from correlation, and applying and refining those techniques is a major component of empirical research in the social sciences.

limitations, because they don't consider how adaptive actions could limit negative effects over the long run.

It's clear that public policy can and must help minimize the damage to children's health caused by climate change. The immediate and compounding impacts of harm to children should carry great weight when it comes to encouraging action to cut greenhouse gas emissions. Public information campaigns and alert systems will also become increasingly important in helping us minimize exposure and take action to avoid exposure in the first place. Investing more in emergency response can also help us minimize the damage when we do experience extreme temperatures. Children are vulnerable, and they have little choice about how and where they spend their time, so policies expressly designed to protect them and the adults who care for them may be especially important.

Extreme Temperatures Kill

Although humans are very well adapted to high temperatures, heat can and does kill. It does so through direct effects such as heat stroke, cardiovascular failure, or other physical disease and through indirect effects such as starvation after crop loss or the spread of infectious disease.[6] Research indicates that children are especially vulnerable to heat-related death—partly because of their physiological features, but, perhaps more important, because they behave and respond differently than adults do.

How Heat Kills

Generally, heat directly causes death through cardiovascular failure—often made worse by respiratory disease—or by overheating the body and causing a heat stroke. Studies that examine specific causes of death often focus on cardiovascular impairment, which is generally more relevant for the elderly than it is for children.[7] Among infants, evidence from heat waves suggests that in addition to cardiovascular illness, blood disorders and failures of the digestive system are leading causes of death.[8] As temperatures rise in developing countries, so does the prevalence of gastrointestinal illnesses.[9] Heat-related deaths among children are also increased by many of the indirect impacts of rising temperatures, including disease transmission by insects like mosquitoes.

One of the main ways heat kills is by limiting the body's ability to regulate its own temperature. When body temperature rises as a result of ambient heat, physical exertion, or fever, more blood flows to the skin and we sweat to dissipate body heat. If the ambient temperature is too high, those mechanisms can't cool the body efficiently and may even work to warm the body further. Adverse weather conditions like high humidity magnify that effect by reducing cardiovascular efficiency.[10]

Children are a special case. Infants' and children's vulnerability to cold temperatures is well established, and humans have evolved physical features to combat that susceptibility, including extra fatty tissue in infancy and reduced sweating during childhood. Children may also be physiologically more vulnerable to high temperature because they regulate their body temperature less efficiently, although the evidence here is less conclusive.[11]

At least one mechanism by which heat kills is unique to the very young. In a series of studies starting in the early 1990s, high heat has been linked to sudden infant death syndrome (SIDS).[12] Because the infant body is relatively more vulnerable to heat loss, it compensates with higher fat and reduced sweating. An infant who is wrapped or covered heavily might be unable to shed excess heat, producing brain trauma. Brain trauma can also occur when infants sleep in the same bed as a warm adult, or when they suffer from fever, or when they're exposed to high ambient air temperature.

Behavior, too, may contribute to the disproportionate number of heat-related deaths among children. Children are less likely to manage their own heat risk and may have fewer ways to avoid heat than adults do. For instance, children playing sports often don't hydrate sufficiently.[13] Also, because children don't usually choose their daily schedule, they typically can't avoid activity during hot portions of the day. We'll return to that issue in more detail when we discuss adaptation.

Estimating the Relationship between Heat and Death

Much of the research on heat's direct health impacts has focused on death, partly because death is an important topic and partly because it's easy to measure. The abundant research documenting the relationship between temperature and death provides good estimates of the overall effect of the relationship and explores in detail the mechanisms by which heat kills. Moreover, in contrast to studies of most other temperature effects on health, many studies of heat deaths explicitly examine impacts on children, which lets us clearly compare them with adults.

Studies that classify their results by age group tend to find that death rates are highest among the elderly and second highest among children. A recent review of public health studies concluded that children younger than 15 years have a higher risk of dying from heat than adults do; infants and children younger than five years are particularly at risk.[14] The review estimates that in developed countries, adults experience a 2 to 3 percent increase in mortality with every 1°C (1.8°F) rise in temperature above a threshold of 27°C (80.6°F) to 29°C (84.2°F). For children, the mortality rate is estimated to be 50 to 100 percent higher than for adults.[15]

Economists Olivier Deschênes (one of the editors of this issue) and Michael Greenstone show that death rates increase dramatically at temperatures above 32°C (89.6°F): a day above 32°C sees triple the death rate of a day at 26°C (78.8°F) to 32°C. As in the review of public health studies, they found that infants suffer the second-highest heat mortality rate among all age groups, after the elderly. Deschênes and Greenstone predict that, given the current understanding of how climate change will unfold, infants constitute the age group likely to experience the greatest increase in mortality rates.[16]

Very few studies examine how heat interacts with other climatic and atmospheric conditions, and therefore we know little about those potentially important relationships. One exception is Tulane University economist Alan Barreca's work on the interaction of heat with humidity.[17] Barreca shows that high humidity independently leads to more deaths and that humidity interacts with heat, making high heat even deadlier. Barreca also shows that humidity levels are associated with increases in infant deaths: three additional days of high humidity increase the average monthly infant mortality rate by 1.1 percent.

High heat can also harm health when it interacts with air pollution. Such interaction isn't generally that important, but the formation of ozone pollution depends on high temperatures, and high ozone levels have been proposed as one explanation for the particularly deadly European heat wave of 2003.[18] Ozone is also a significant predictor of childhood asthma.[19]

In contrast to records of the deaths of infants and children, fetal mortality isn't well recorded, so the extent of heat-related deaths in the womb is not clear. The fact that exposing unborn children to extreme temperatures has measurable impacts on their health after birth, which we discuss in the next section, lends credence to the idea that heat can also kill the unborn.

Heat and Death in Developing Countries

Outside the United States and Europe, estimates of deaths caused by heat are sparse. In a review of 36 epidemiological studies, only eight contained any data from countries outside the Organisation for Economic Co-operation and Development, and of those eight studies, most were from a single country: Brazil.[20] Developing-country studies can shed light on how income and infrastructure help mitigate damage from heat. A recent study of weather-related infant mortality in a group of African countries showed that in poorer countries, temperature can kill through many channels. In particular, malaria infection as a result of increased mosquito activity was one of the main sources of temperature-based infant deaths.[21]

A study of temperature-related deaths in India found that heat's average effect on mortality there is more than 10 times greater than in the United States, largely because crop failure arising from excessive heat leads to losses of real income. Urban residents in India experience temperature-related mortality rates similar to rates among residents of the United States, suggesting, first, that deaths caused directly by heat may be relatively few in number compared with those caused by heat's effects on productivity and, second, that the possibilities for adaptation are extensive across the globe.[22]

In developed countries, infant and child mortality from heat is higher among low-income groups, suggesting that wealthier households can make investments that offset at least some of the damage from high heat.[23] Death rates associated with high temperatures are also higher in the northern United States than in the southern United States—likely because of the adoption of air conditioning in areas that routinely experience high heat.[24] This gap has narrowed, however, because over time, heat-related mortality rates have fallen faster in the northern states relative to those in the South.[25] We return to that issue later, when we discuss adaptation and avoidance.

In summary, high temperatures are strongly associated with increases in death rates among all age groups, and the very young are particularly at risk. Heat kills in many ways, varying with location, level of development, and degree of acclimatization. Without investment in infrastructure to protect people from heat, we can expect child mortality associated with high temperatures to rise as the globe warms. Also, because the majority of developing countries already have warmer climates than the United States and Europe do, we should expect to see fewer gains from reduced low temperatures in those countries, making the net effect of climate change there even more severe. To learn more about heat's effects on children in developing countries, see the article by Rema Hanna and Paulina Oliva elsewhere in this issue.

Illness

Even when it doesn't kill, high temperature can cause illnesses or worsen existing medical conditions to the point that sufferers must be hospitalized. Compared with studies of heat-related deaths, however, we've seen fewer studies of how temperature affects illness—partly because of data limitations. For example, detailed hospitalization data can be difficult to obtain, and data on physician and pharmacy visits are even scarcer.[26] Moreover, many heat-related illnesses may be socially costly without producing doctor or emergency room visits, because the symptoms are treatable at home—for instance, through rest and hydration. Access to health insurance coverage (in places like the United States, where coverage is not universal) may also limit doctor and pharmacy visits, making it hard to infer how income shapes the relationship.

How Heat Impairs Health

Heat exhaustion and heat stroke are the most serious illnesses caused directly by heat. They generally result from dehydration associated with exposure to or physical activity during periods of high heat. As it regulates heat, the body loses water and salt in the form of sweat. If the water and salt don't get replaced over time, the body can overheat, leading to the dizziness, muscle cramps, and fever that characterize heat exhaustion. At the extreme, heat exhaustion becomes heat stroke, which, even when it doesn't kill, generally leads to permanent neurological damage.[27]

High heat also strains the heart and can make breathing difficult. Combined with high humidity and behaviors like exercise or wearing inappropriately heavy clothing, high temperatures can cause heart attack, stroke, and respiratory failure.[28] Medical conditions that impede the circulatory or respiratory system—such as asthma, heart disease, or a previous stroke—increase the likelihood of those acute episodes.[29]

Pregnant women and their fetuses are especially vulnerable to high temperatures for several reasons, including higher core temperature because of the pregnant woman's increased fat deposition, her diminished capacity to sweat, and the additional thermal stress associated with fetal maintenance.[30] Warmer temperatures increase both the proportion of preterm births and the incidence of low-birth-weight babies.[31] Shocks to the fetus often have lifelong consequences.[32] And the negative relationship between fetal health and temperature may mean that early life exposure to extreme temperatures can have long-lasting effects, discussed next.

Linking Heat and Illness

The vast majority of evidence on heat and ill health focuses on adults. For example, for each 1°C above 29°C (84.2°F), adult hospitalizations for respiratory disease rise by about 3 percent. Cardiovascular illness rates also rise in many cases, with effects concentrated among older people.[33] Recent research from Germany showed that hospital admissions rise by up to 20 percent on hot days, although, again, the effects occur predominantly among people older than 60 years.[34]

The evidence on how heat affects children's health is more nuanced. A study from Spain found that hospital admissions in general rose dramatically above 34°C–36°C

(93.2°F–96.8°F) and that children younger than nine years were slightly more likely to be admitted than were adults aged 18 to 44 years. Moreover, admissions of children appeared to be higher during periods when high heat was combined with elevated levels of particulate matter, although that finding is not universal.[35] In contrast, a recent study in New York about how hot weather affects hospital admissions due to cardiovascular and respiratory diseases found no significant link between high temperatures and either cardiovascular or respiratory diseases for people from birth to 19 years old. In fact, in the New York study, the estimated magnitude of temperature effects for that age group was the lowest among all groups.[36] But the wide age range in the study could be masking larger effects on the very young by averaging them in with older children and adolescents.

In contrast to heat's effect on fetal mortality, its health effects on fetuses have been better studied. A study that summarized several investigations into how temperature affects mammalian fetuses found that a wide range of less than fatal outcomes could occur. The study's authors cautioned that even though healthy thermal ranges vary among other mammalian species and are not always reliable models for human biology, we can learn some general lessons from them. For example, elevating fetal temperature by 2°C–2.5°C for as little as one hour can cause moderate to severe damage to the nervous system and impede neural development. Physical exertion combined with elevated ambient temperature could trigger potentially dangerous internal temperature spikes, although a stationary, healthy woman would likely be able to avoid them.[37]

Research on humans has focused on preterm births and birth weight. A recent study concluded that the adverse effects of high temperature were consistently stronger for birth weight than for early birth.[38] Another study compared infants' birth weights with the temperatures their mothers were exposed to during each trimester of pregnancy. It found that in all trimesters, high temperatures were associated with reduced birth weight but that the effect was slightly larger during the third trimester.[39] Birth weight is a proxy measure of fetal health that can be linked to illness in childhood and later in life.[40]

The evidence for heat effects on children's ill health is less conclusive than in the case of childhood mortality, but the impacts on fetal health appear to be unambiguously negative. Children appear to be less susceptible than adults or the elderly to some of the more dramatic heat-induced illnesses, perhaps because they tend not to suffer from the combinations of conditions that can lead to adult hospitalizations. On the other hand, children may be more at risk for heat exhaustion and related illnesses because they are less able to monitor and respond to signs of their own dehydration. But because parents or caregivers can treat children's dehydration fairly easily, we may be less likely to see those effects in the data. Studies of heat-related illness thus likely understate the true rate among children.

Heat and Human Capital

In addition to causing illness and death, extreme temperatures may also make it harder to learn and thus may limit children's educational attainment and economic prospects in the long run. Though we have little direct evidence of such a relationship, studies of the fetal period establish the linkage indirectly—through impacts on birth outcomes that prove important for education and work later in life.

How Heat Hinders Human Capital Formation

Excess heat in the womb can produce physical defects, delay brain development, and lead to a host of central nervous system problems that make it harder to accumulate human capital in the long run.[41] As we've seen, low birth weight is a common proxy measure for fetal setbacks and has been shown to significantly affect education and work outcomes later in life. Reduced fetal nutrition may be one important mechanism behind that relationship.[42]

In addition to how temperature affects birth weight and central nervous system functioning, it may also play an important role in gene expression. We now know that environmental stress can affect how genetic code gets translated into observable human traits and that gestation is a particularly susceptible period for such effects.[43] Exposure to high temperatures has been implicated as a source of environmental stress in a wide range of plants and animals.[44] Vertebrates' brains and other central nervous system structures are particularly sensitive to such sources of environmental stress, suggesting that cognitive development may be vulnerable to such exposures.[45]

Once outside the womb, the developing brain is still sensitive to heat on chemical and electrical levels.[46] Rapid brain development, which can be disrupted by extreme heat, continues through early childhood.[47] In more mature children, ambient temperature, as well as the heat generated by the brain itself, can impede mental processes, thereby creating the potential for heat to hinder learning. Although it represents only 2 percent of the mass of a typical body, the brain generates 20 percent of the body's heat.[48] The body is generally able to efficiently discard heat created by the brain, but when the weather is warm and humid or when we engage in heavy physical activity, our bodies can struggle to regulate temperature, leading to spikes in brain temperature of up to 2.5°C.[49]

Evidence on the Heat–Human Capital Relationship

Experimental evidence supports the notion that heat can directly impair cognitive function. For example, soldiers exposed to hot environments perform worse on complex cognitive tasks, are more prone to error, and are less able to carry out physical tasks.[50] Other studies show that heat exposure reduces performance on multitracked tasks that mimic real-world school and office duties, impairs working memory, and lowers test scores.[51] A review of a number of studies of office workers' productivity estimated that performance declines rapidly when temperatures go above or below 21°C–22°C (69.8°C–71.6°F). For instance, at 27°C (80.6°F), office workers' performance declines by 5 percent relative to their performance at 21°C.[52]

Though heat appears important to human capital formation and productivity, its real-world effects on those areas have been poorly documented, likely because it's hard to observe the relevant outcomes. But the gains from such studies would be immense. The effects are likely to be substantially important, and low-level temperature impacts are, by definition, much more widespread than the extreme temperatures that lead to the majority of hospitalizations and deaths. Thus, from the standpoint of total welfare, human capital effects might be more important than the relatively well-understood, direct temperature effects we discussed in previous sections.

Studies of pollution's impacts have analyzed school attendance, and we could do the same for temperature.[53] Researchers have documented a link between school attendance and indoor air pollution, outdoor air pollution, and ventilation rates.[54] We aren't aware of any studies by economists that show a similar link between temperature and school attendance, although the data needed to do so are relatively available. We know that high temperatures reduce the adult labor supply, so it's certainly plausible that heat also increases school absenteeism.[55]

Student test scores offer a more direct way to assess the human capital effects of temperature. Economists Joshua Graff Zivin (one of the authors of this article), Solomon Hsiang, and Matthew Neidell have shown that a temperature above 26°C (78.8°F) on the day of a math test can diminish students' performance.[56]

Heat and Human Capital in the Long Run

The studies and hypotheses we've discussed focus largely on acute responses to temperature. Temporarily impaired brain function that leads to absenteeism or reductions in test scores, however, doesn't necessarily affect either cognition or human capital attainment in the long term. Do the acute effects we've identified translate into poorer outcomes in school or work later in life? When it comes to estimating the impact of climate change, the question of long-term effects becomes even more important. Simple aggregation of short-lived, acute-impact estimates might overstate the true damage associated with long-run temperature changes. On the other hand, multiple acute responses could have substantial long-term impacts by hampering children's acquisition of skills, an issue we discuss later in the context of adaptation.[57]

The study that found a link between temperature and test scores also offers evidence of climate's long-term effects on human capital formation. In particular, the authors found that longer-term weather averages are not strongly associated with student performance. The authors suggest that compensatory adaptive behaviors—particularly, additional investments in learning that are made after heat events—might be mitigating the short-term effects.[58] But we have evidence that temperature can have long-term effects on national wealth. We don't know whether that result is driven by changes in human capital or by something else, but the big differences in aggregate output that are associated with differences in climate suggest that high heat may cause at least some loss of human capital or some decline in productivity.[59]

Short-run shocks can also be linked to long-run outcomes through fetal exposures that reduce birth weight. For example, low-birth-weight children in Britain were significantly less likely to pass standardized tests as teenagers.[60] A sample of Californians found similar effects on school attainment and adult poverty.[61] Studies of twins, which let researchers control for genetic endowments and other family characteristics, have also consistently found that low birth weight diminishes educational attainment, IQ, and even earnings.[62]

Put simply, it seems that temperature extremes can impair cognitive functioning in children. The evidence for long-run effects from those impairments is inconclusive, however. One study that directly examined the relationship found no effect, but another that focused on wages—an implicit measure of cognitive attainment—found that extreme heat has a negative effect.[63] The long-run effect of temperature exposure in the womb has not been well studied, but evidence from studies of pollution and other fetal health shocks suggest that in utero heat exposure might have long-run impacts from reductions in fetal nutrition, genetic damage, or other causes.[64] Such impacts may represent climate change's greatest threat to children's long-term prosperity and wellbeing.

Adaptation

How will the magnitude of the effects we've talked about change in the future? As figure 1 shows, under business-as-usual emissions scenarios, current climate models predict that the average number of summer days above 90°F (32°C) will increase dramatically. Across the United States, the average person currently experiences 1.4 such days per year, but by the end of this century, he or she is expected to experience more than 40.[65] If heat's short-run effects can be generalized to a setting wherein extreme heat is routine and commonplace, then simply extrapolating from those effects, the change would dramatically increase the number of deaths, the number of hospitalizations, and the loss of productivity associated with high heat. We believe, however, that such simple extrapolation doesn't accurately predict the future. On one hand, adaptation and technological development could lessen many of those impacts. On the other, if the impacts of heat are nonlinear—such that damage is much more severe at greater temperature extremes—then the impacts may be even worse than current estimates suggest.

Adaptation to climate change will likely mitigate some of the damage from high heat. The extent to which adaptation can offset harm from anticipated temperature extremes under climate change—and at what cost—is a crucial issue. Moreover, the difference in adaptation to the total level of heat versus relative change in heat becomes important. Figure 1 shows that cities in the southern United States will experience many more hot days than will cities in the north, but those cities already experience some hot days now. Will people who live in places where many hot days already occur suffer more? Or will the effects be worse in places where hot days are expected to be less frequent but where extreme heat is currently not a problem?

One technological development—air conditioning—has already greatly reduced temperature-related deaths in the United States, especially among children and older people.[66] Indeed, air conditioning may also help explain differences in the relationship between heat and death in developing countries and developed countries.

Unfortunately, air conditioning makes climate change worse. First, air conditioning is a major consumer of energy in developed countries, which will likely be the case around the world in coming decades. Given our current reliance on fossil fuels to produce energy, air conditioning contributes to greenhouse gas emissions and therefore to warming the planet.[67] Air conditioning also directly raises urban air temperatures. A high level of air conditioner use in cities is associated with warming of up to 0.5°C during the day and 1.5°C at night.[68] Because of the potentially greater health impacts of nighttime temperature, that fact is particularly worrisome. It may also exacerbate inequality in urban areas because the poorest people can't shield themselves from the increased heat generated by their wealthier neighbors.

Choosing where to live is another adaptation strategy that can influence exposure to climate extremes.[69] Most climate-related migration in the past four decades has seen population shifts from colder, northern areas to warmer, southern areas.[70] That migration has resulted in much lower cold-related mortality, but it could exacerbate future damage from a warming climate. The same areas that have experienced increased migration are also those with the fastest-growing populations of children. Whether the same pattern holds for other countries is an open question.

Shifting the timing of activities during the day—a less drastic strategy than migration—can also help reduce exposure to climatic extremes. Many cities worldwide warn citizens to limit outdoor activities during periods of excessive heat. Some countries systematize that avoidance through cultural norms that dictate the timing of the school year and through siestas, which suspend the workday during the hottest part of the day.[71] Those strategies can be quite effective, but they're usually limited in scope and potentially costly because, for instance, keeping children from exposure to high ambient temperature might reduce their physical activity. Perhaps compensating investments in children's health and human capital to limit heat-related impacts after exposure rather than preventing it in the first place may prove to be a more useful adaptation.[72] For such actions to be successful, however, timing is crucial. Small losses in attainment during early childhood can become compounded over time, making early intervention important.

Evidence for acclimatization points to biological adaptation's limited role in both the short and the long run.[73] Small-scale medical studies of performance of physical tasks have shown that adults can partially acclimatize to even very high heat (above 40°C [104°F]). But studies on how acclimatization affects cognitive performance have been inconclusive.[74]

Adaptation is especially complicated when it comes to children, who generally can't choose their own adaptation strategies. Children don't purchase air conditioners, decide where to live, or even set their own schedules. Instead, children must communicate their temperature-related discomfort to caregivers, who must then take action on children's behalf. Effectively communicating that information is challenging for very young children, but even those able to clearly convey their discomfort may not have their needs met if adult caregivers don't perceive heat or experience temperature-related physical impairment in the same way children do.

The appallingly routine incidents of children being left in hot cars illustrate the problem viscerally. Each year in the United States, about 40 children die from being locked inside a hot vehicle. According to a recent study, in 43 percent of cases the caregivers simply forgot they were transporting children; being aware of the presence of children is obviously a clear prerequisite for thinking through the steps required to manage children's exposure to extremes.[75]

Conclusions

The extreme temperatures expected under climate change will affect human health, and they may have especially harmful impacts on children. But public policy can help. First, we have many tools that encourage reducing greenhouse gas emissions with a view to averting the worst of the warming scenarios. The immediacy of the health impacts we've discussed—in contrast to effects that depend on slow-moving climate changes rather than weather extremes—could energize international climate negotiations. Threats to human capital, which is generally viewed as an engine of economic growth, should offer additional motivation.

Public policy can also do more to encourage adaptation. Government policies could encourage many of the private responses we detailed in the previous section. Currently, national policy doesn't require schools to maintain specific temperatures for students, although the Centers for Disease Control and Prevention has issued nonbinding recommendations.[76] Many states have their own regulations regarding temperature and humidity in schools.[77]

Lack of air conditioning has forced schools to close. For instance, in 2014, heat forced the San Diego school system to close or alter the operating schedules of 120 schools; many schools in the district that lacked air conditioning saw temperatures in excess of 90°F (32.2°C).[78] In Des Moines, Iowa, the public schools have kept records of school closures since 1972; not until 2000 did they begin closing because of excessive heat.[79]

As the planet warms, it will become increasingly beneficial to require universal air conditioning for schools. Such a policy would also let schools stay in session during summer and move breaks to cooler seasons, thereby keeping children indoors in a climate-controlled environment during the most dangerous part of the year. Those benefits may be especially important for children of poorer families, who are less likely to have air conditioning at home.

Many places in the United States have heat wave warning systems. When weather forecasts predict extremely high heat, the systems inform the population about the risks.[80] Such warning systems can be effective in places like the United States, where many people have air conditioners or where public infrastructure lets people avoid the heat. In places like Europe, however, where fewer people have air conditioners, disseminating information might not be sufficient.

When the 2003 heat wave hit Europe, causing up to 40,000 deaths, only Lisbon and Rome had effective early warning systems. Lisbon and Rome still experienced very high numbers of excess deaths during the heat wave (although Lisbon fared relatively better than other cities), underscoring the need to combine information about heat risks with public infrastructure to mitigate the effects of heat.[81] As an example, in some cities, public buildings with air conditioning stay open longer during heat waves to let people take refuge.[82] Incentives to buy cooling systems might also help, but they should encourage investment in energy-efficient technologies that limit additional contributions to climate change.

Sociocultural institutions shape adaptive responses by dictating norms about the timing of workdays and school days. Restructuring schedules to avoid the hottest parts of the day requires a huge amount of social coordination that we may be able to achieve only with government assistance. Even with such policies, though, eliminating exposure to climate extremes seems unlikely. So we'll also need public investment in emergency preparedness and medical infrastructure.

Individuals and policy makers must consider the constraints that children face. In particular, it may be harder for children to mitigate their own heat exposure.[83] Children may also be at greater physiological risk of overheating, which makes it harder for their caregivers to assess when they're in danger of suffering from heat-related illnesses. Medical professionals such as emergency room doctors—who are likely to treat acute heat-related illness in children—need proper pediatric training. Even when the general care recommendations for adults and children don't differ, as they do in the treatment of heat exhaustion, the doctor's actions should be tailored to children. For instance, for heat stroke, the American Heart Association provides a series of child-specific recommendations, including alternative cardiopulmonary resuscitation procedures as well as warnings against common drugs used for treating adults.[84] In addition to caregivers' possible difficulty in recognizing heat's effects on children, the children themselves might have trouble communicating their needs. When combined with children's reduced ability to take personal action, this is a thorny problem in developed countries and a potential disaster in less developed ones with low levels of literacy and poor infrastructure.

Although we've relied on the best evidence available, research on nonlethal impacts from high heat exposure is surprisingly thin. Evidence of how heat's impacts on children are different from its impacts on adults is particularly sparse, and many basic relationships remain poorly understood. To what extent do temperature extremes affect children's health? How much of children's heat-related illness is treated outside the health-care system? What explains heat's potential impacts on school performance and human capital formation more generally? The evidence on adaptation is also incomplete, especially with regard to our options for limiting heat's impacts through avoidance and compensatory behaviors. We must assess the costs of those impacts and of all of the efforts undertaken to minimize them. Together, they compose an important future research agenda.

ENDNOTES

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