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Global warming, pollution and cognitive developments: The effects of high pollution and temperature levels on cognitive ability throughout the life course

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Global warming, pollution and cognitive developments : The effects of high pollution and temperature levels on cognitive ability throughout the life course

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The following paper examines the effects of high pollution and temperature levels on cognitive development and skill accumulation, as part of the broader framework for the topic Skills and the Environment in the Skills Outlook 2023.

This paper is authorised for publication by Stefano Scarpetta, Director, Directorate for Employment, Labour and Social Affairs.

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Global warming, pollution and cognitive developments : The effects of high pollution and temperature levels on cognitive ability throughout the life course

Abstract

Global warming and air pollution threaten human health, economic prosperity and human capital accumulation. The current review presents empirical findings on the effect of adverse environmental conditions on cognition, with a focus on pollution and high temperatures. The review takes a life-course perspective and quantifies both the direct and indirect effects of cumulative and transitory exposure to adverse conditions on cognition starting in-utero all the way to exposure in old age. The review makes clear that exposure to pollutants and high temperatures has economically meaningful costs for both individuals and societies, stemming from lower human capital accumulation. Furthermore, the evidence presented indicates that adverse environmental conditions have large distributional consequences, leading to widening disparities in educational opportunities both across countries and across socio-economic groups within-countries. The review discusses the mechanisms underpinning these effects and explores policies that have the potential to mitigate the negative impact of adverse conditions on cognition.

Résumé

Le réchauffement climatique et la pollution de l'air sont une menace pour notre santé, pour la prospérité économique et pour l'accumulation de capital humain. On trouvera dans le présent document des éléments empiriques qui renseignent sur les effets cognitifs des conditions environnementales défavorables, plus particulièrement la pollution et les fortes températures. L'examen s'étend sur toute l'existence et cherche à quantifier les effets directs et indirects d'une exposition cumulée et temporaire à ces conditions défavorables, depuis la vie utérine jusqu'à la vieillesse. Il en ressort clairement que l'exposition aux polluants et aux fortes températures a un coût économique significatif, tant pour les individus que pour les sociétés, qui résulte d'une moindre accumulation de capital humain. Les éléments produits montrent en outre qu'elle a de vastes conséquences sur le plan de la redistribution, à l'origine d'un creusement des disparités en ce qui concerne les perspectives éducatives, aussi bien entre pays qu'entre catégories socioéconomiques au sein d'un même pays. Le présent examen s'étend aux mécanismes dont ces effets procèdent et aux mesures susceptibles d'atténuer les répercussions des conditions environnementales défavorables sur la cognition.

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1 Introduction

1. Increases in global surface air temperatures have intensified population exposure to at least one extreme heat day per year with levels above thresholds set for human safety.[1] Given current population numbers, an increase in 1 degree Celsius from pre-industrial levels has led to an increase of people exposed from 97 million to 275 million. And should temperatures increase further, for example to 3 degrees Celsius, this number is set to increase to 1.22 billion (Li, Yuan and Kopp, 2020[1]). Increases in global temperatures and heat extremes also threaten to offset the progress made in lowering pollution emissions in developed countries, as high temperatures incur chemical reactions with gaseous pollutants and can trap surface level ozone, the primary source of "smog." The health burden of increasing temperatures and air pollution is large, as air pollution and high temperatures increase the incidence and severity of respiratory and cardiovascular diseases, including asthma, bronchitis, lung cancer and heart disease (Kampa and Castanas, 2008[2]). But beyond their impact on health, environmental conditions also have an impact on the developing brain, affecting people's capacity to acquire information and use it to achieve their goals (Graff Zivin et al., 2020[3]; Graff Zivin and Neidell, 2013[4]; Heyes and Saberian, 2019[5]; Ebenstein, Lavy and Roth, 2016[6]; Zhang, Chen and Zhang, 2018[7]; Archsmith, Heyes and Saberian, 2018[8]).

2. The aim of this paper is to review the literature on the cognitive effects of two environmental conditions: air pollution and ambient temperatures. [2] Air pollution was the key focus of research and policy actions in the past several decades, actions that led to marked decreases in levels of pollution in developed countries, although pockets of extreme pollution levels remain. Rising global temperatures are the focus of current efforts by the global community to halt climate change. Figure 1 shows the average levels of particulate matter (PM2.5), an extremely harmful air pollutant that populations in OECD countries are exposed to at the turn of the new millennium. Figure 2 highlights the increased number of extreme temperature events from 1980 until 2020. As the world considers how best to develop effective solutions and mobilise skills to promote a green and sustainable future, it is equally important to consider how environmental factors shape skill development and acquisition. First, this allows to fully account for the costs associated with environmental degradation since human capital development is an important source of economic growth. Second, it allows to develop and tailor policy solutions aimed at reducing the damage of current and foreseen environmental changes. Identifying the mechanisms underpinning negative effects of environmental conditions on skills development can reveal how such effects can be reduced.

3. Air pollution is a catch-all term that describes deterioration in air quality due to toxic compounds and gasses. Disasters alongside natural processes such as forest fires and desert dust can also contribute substantially to the air pollution burden in some regions (WHO, 2021[9]). Most national air quality guidelines define targets to consider how harmful for human health using six criteria defined on the basis of concentrations of the following pollutants: fine particulate matter (PM2.5), coarse particulate matter

[1] Extreme heat days refer to days with wet bulb globe temperature, an indicator that estimates the effects of heat stress on humans by combining temperature and other weather variables such as wind speed, above 33 degrees Celsius.

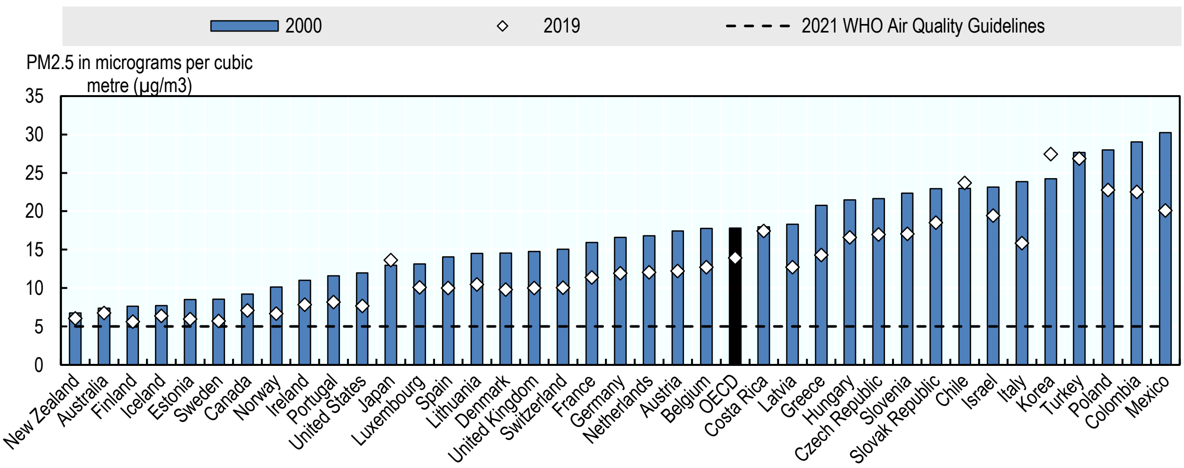
[2] Throughout this paper, the term ''environmental conditions'' is used to refer to air pollution and high temperatures.

(PM10), ozone (O3), nitrogen dioxide (NO2), sulphur dioxide (SO2) and carbon monoxide (CO), with additional standards for less ubiquitous pollutants.[3] These pollutants interact chemically with each other as well as temperature, climate conditions and economic factors, with resulting interactions determining their respective concentrations and air quality at ground level, where people breathe (Orru, Ebi and Forsberg, 2017[10]; Lanzi and Dellink, 2019[11]).

4. Figure 1 shows that on average across OECD countries, mean population exposure to PM2.5 pollution decreased from 17.8 micrograms per cubic meter (µg/m3) in 2000 to 13.93 µg/m3 in 2019, a decrease of about 22%. Although this decline marks an important success for population health, exposure remained above levels recommended by the World Health Organization (WHO). For example, in 2019 all OECD countries had levels of exposure higher than the updated air quality guidelines by the WHO in 2021 based on improved understanding of the adverse effects of PM on health. Outside of OECD countries and particularly in Asia, the Middle East and Africa, PM2.5 levels remain at critically high levels (OECD, 2021[12]). Additionally, rapidly urbanising areas and large cities typically have higher levels of PM2.5 pollution which can spill over into the surrounding regions (Han, Zhou and Li, 2015[13]).

5. Unlike air pollution, average temperatures have been rising consistently around the world at an unprecedented rate since 1970 (IPCC, 2021[14]). In 2020, global mean surface air temperature over land had risen 1.7 degrees Celsius above the climate normal, which references the period between 1951 and 1980, with the largest increases found in Europe (UNFAO, 2021[15]). In addition to higher average temperatures, hot temperature extremes have risen in frequency and intensity. Figure 2 shows that in 2020, the number of extreme temperature events classified as natural disasters around the world in the past 20 years averaged at about 22 per year, compared to an average of about seven extreme temperature events per year recorded from 1980 to 1999. Extreme temperature events are expected to continue increasing, with scientists estimating that very extreme heat events that occurred only once in a 50-year period will likely occur about 14 times more under a 2 degrees Celsius warming scenario (IPCC, 2021[14]).[4]

Figure 1. Mean population exposure to PM2.5, in 2000 and 2019



Note: Mean population exposure to particulate matter (PM2.5) is shown in units of micrograms per cubic metre (µg/m^3). The horizontal black dashed line indicates the WHO global air quality guidelines updated and published in 2021 for PM2.5 at 5 µg/m^3.
Source: OECD Environment Statistics (OECD, 2021[16]) *Exposure to PM2.5 in countries*, https://doi.org/10.1787/env-data-en

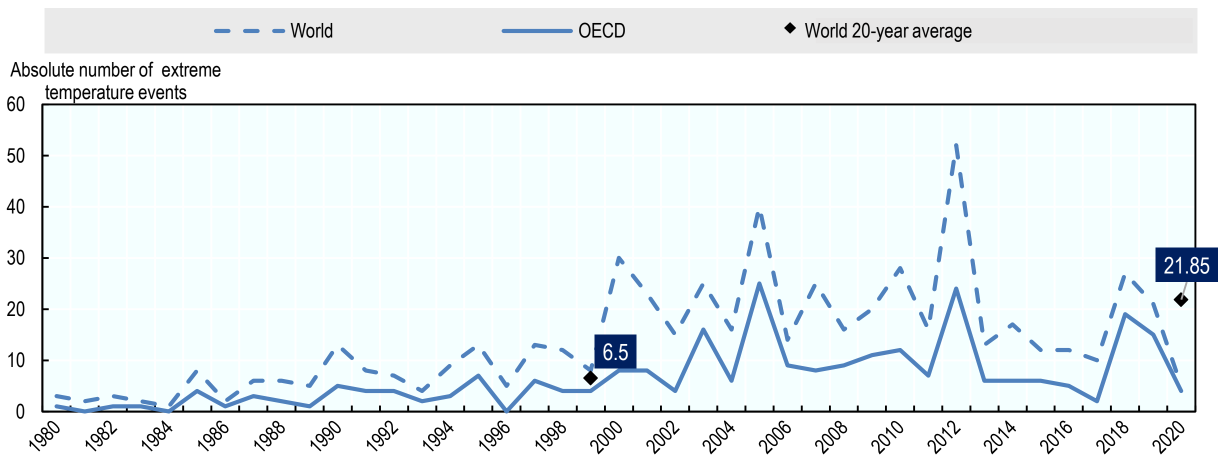
[3] See Table A.1 in the Annex for a reference list of common air pollutants, their sources, and potential effects on human health.

[4] Relative to the base period of between 1850 and 1900.

6. Recent evidence from the Intergovernmental Panel on Climate Change (IPCC) indicates that at least 50% of the rise in extreme temperature events is due to human-induced climate change, with carbon dioxide (CO2) recognized as the main driver (IPCC, 2021[14]). Other pollutants such as black carbon, a product of particulate matter and the result of incomplete fossil fuel combustion and biomass burning, also play a large role in accelerating warming by absorbing large amounts of solar radiation and turning it into heat (Bond et al., 2013[17]; Matthews and Paunu, 2019[18]). High latitude regions in the northern hemisphere and throughout the Arctic are expected to experience the greatest warming in coming decades, with North-Eastern Europe, Northern Russia, North-Eastern and Western North America, Western and Central South America, Northern and Southern Africa, the Arabian Peninsula, Central Asia and Central Australia also projected to experience large temperature increases (Gutiérrez et al., 2021[19]), with important consequences for health, societies and economies (OECD, 2021[20]).

7. Within individual regions, temperatures reach their highest levels in urban areas (i.e., ''urban island heat effect''), where 56.2% of the world population currently lives (UN, 2021[21]). Depending on location, the urban island effect creates an additional health exposure in cities, which has been estimated to be of between 1 and 11 additional degrees Celsius compared to current temperatures in non-urban settings. The urban island effect occurs because of, among other reasons, reduced green space, high urban density, and the widespread use of dark and impervious building materials such as cement, which absorb large amounts of heat from the sun (Deilami, Kamruzzaman and Liu, 2018[22]; Chapman et al., 2017[23]; Santamouris, 2020[24]). Climate change and increasing urbanisation are projected to exacerbate the urban island heat effect, particularly in low-income countries were residents have a lower ability to protect themselves and their communities against high temperatures (Chapman et al., 2017[23]). Additionally, urban overheating is likely to result in increased energy generation and rising levels of ozone, when protective behaviours such as the use of air conditioning are adopted, worsening air pollution at the ground level (Santamouris, 2020[24]).

Figure 2. Absolute number of natural disasters due to extreme temperature events per year, between 1980 and 2020



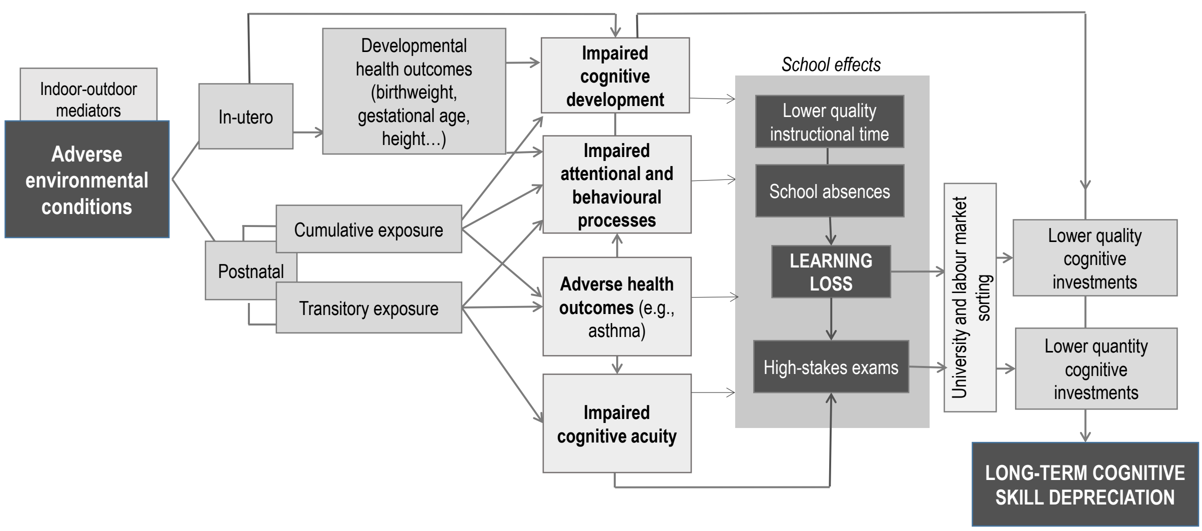
Note: A natural disaster event is included in this data if it fulfils at least one out of the following four criteria: (a) ten or more people were reported killed, (b) a hundred or more people were reported affected, (c) a declaration of a state of emergency was issued, or (d) a country called for international assistance. Extreme temperature events consist of either (a) a cold wave, (b) a heat wave or (c) severe winter conditions. Countries included in the OECD country-group are those that were OECD members in 2021.
Source: EM-DAT, CRED / UCLouvain (EM-DAT, 2021[25]), *International Disasters Database 2021*, www.emdat.be

8. The changes described will have important consequences for the health and human capital of societies. Figure 3 summarises the mechanisms through which adverse environmental conditions such as air pollution and extreme temperatures shape cognitive skills.

9. First, during gestation, exposure to air pollution and high temperatures can have a direct effect on later life cognitive ability by impairing natural developmental processes that occur in the central nervous system throughout early childhood (Harris et al., 2016[26]; Jedrychowski et al., 2014[27]; Perera et al., 2006[28]; Perera et al., 2009[29]; Tang et al., 2008[30]; Tang et al., 2014[31]; Volk et al., 2021[32]). Indirectly, children whose mothers experience adverse environmental conditions during pregnancy may also be born with low-birth weight or grow up to be shorter than their peers (Stieb et al., 2012[33]) or experience impaired lung development (Hehua et al., 2017[34]). In turn, these development outcomes can affect academic performance when children reach school age (Irani et al., 2017[35]; Bharadwaj et al., 2017[36]; Persico, Figlio and Roth, 2020[37]).

10. Second, postnatal environmental conditions can also have direct and indirect effects on short and long-term cognition, amplifying any previous cognitive losses. In the short-term, adverse exposure can impair cognitive acuity and attentional and behavioural processes which can result in lower academic achievement in schools (Sunyer et al., 2017[38]; Persico and Venator, 2019[39]). In addition, the exacerbation of respiratory and other illnesses may lead to increased school absences for students (Chen, Guo and Huang, 2018[40]; Currie et al., 2009[41]; Garg, Jagnani and Taraz, 2020[42]). These negative effects on health, behavioural and attentional processes may accumulate overtime to decrease the overall quality of cognitive investments during childhood such as instructional and studying time (Park et al., 2020[43]; Cho, 2017[44]).

Figure 3. Mechanisms of the effects of averse environmental conditions on cognition throughout the life course



Note: This figure traces the mechanisms through which adverse environmental conditions can affect cognitive acuity and development.

11. Third, towards the end of secondary school, high levels of transitory pollution and extreme temperatures can lower students' performance on high stakes exams used to select students for tertiary level education, influencing the ability of those most affected by adverse environmental conditions to attend higher education as well as the quality of that education (Graff Zivin et al., 2020[3]; Graff Zivin et al., 2020[45]; Ebenstein, Lavy and Roth, 2016[6]; Park, 2020[46]). Because levels of air pollution and temperatures have a geographical variation, individuals living in areas most exposed to negative conditions just prior to or during selective examinations that select applicants on the basis of exam ranking may suffer a penalty and fail to gain entrance into tertiary educational institutions or fail to enter the most prestigious institutions. Similarly, socio-economic condition could determine the possibility that individuals and families will mitigate the negative effects of environmental conditions and therefore acquire an edge during selection processes with potentially long-lasting consequences for income inequality. The resulting suboptimal educational and labour market sorting may alter long-term skill acquisition and earnings (Kyndt et al., 2012[47]). Once in the labour market, transitory exposure to adverse environmental conditions may further affect the willingness and ability of adults to engage in cognitively demanding activities (Meyer and Pagel, 2017[48]). In the long term, an increase in pollution exposure is associated with the development of neurodegenerative diseases such as Alzheimer's and related dementia (Chen et al., 2017[49]).

12. Importantly, the effects of air pollution on cognitive development have been found to occur below current international air quality standards (Chen, Guo and Huang, 2018[40]), in both indoor and outdoor settings (Roth, 2018[50]) and across various regions around the world. Similarly, these effects have been observed when the duration, intensity and spread of extreme temperature spells was well below current projections. In many cases, the largest effects are felt by socioeconomically disadvantaged children and adults who experience greater levels of pollution exposure and a lower ability for making protective investments (Hajat, Hsia and O'Neill, 2015[51]; Ebenstein, Lavy and Roth, 2016[6]). What Figure 3 does not show are the range of adaptations and protective measures individuals and societies can take to reduce the impact of environmental conditions on cognitive development. These include installing air filtration, air purifying systems and air conditioning units in schools, homes and the workplace, re-organising school curriculums and pedagogical formats to avoid exposure, and ensuring equal access to environmental information, which can help induce protective behaviours (Burns and Gottschalk, 2020[52]). Some of the adaptations indicated have the potential to reduce the impact of environmental conditions in both the short and the long term while others, most notably those that reduce exposure to harmful conditions through energy use – such as air conditioning – can reduce exposure in the short term but worsen the burden of harmful environmental conditions in the long term. Given recent projections for increased global surface warming in the next several decades, it is worth examining the empirical literature on adverse environmental exposures and their consequences on cognitive skill development throughout the life-course to better understand the magnitude of these effects, their underlying mechanisms and distributional consequences, and the potential for mitigating them.

2 The effects of environmental conditions on cognition over the life course

13. The intrauterine environment that a foetus receives, such as the nutrition, thermal conditions, toxins and drugs that a mother is exposed to, has the potential to influence future disease and developmental outcomes (Almond and Currie, 2011[53]; Currie et al., 2014[54]). Exposure to adverse environmental conditions while in-utero can thus have a series of long-term negative consequences, including reduced cognitive abilities, adversely influencing academic achievement and attainment. In the United States, children conceived within 2 miles of a Superfund site, i.e. a site containing a high concentrations of hazardous pollutants, experienced a 6.8% and 11% standard deviation (SD) reduction in math and reading scores respectively, during primary school compared to their siblings born following the clean-up of the pollution sites (Persico, Figlio and Roth, 2020[37]). These estimates are slightly higher than the approximate declines of between 3.4% and 7% SDs on math and language scores found for primary school-aged Chilean and Filipino students due to one-unit SD increases in CO and O3 prenatal exposures, respectively (Bharadwaj et al., 2017[36]; Peet, 2021[55]).[5]

14. In-utero and early life environmental conditions continue to affect students as they advance through school (Bharadwaj, Eberhard and Neilson, 2018[56]). For example, in the United States, a one-unit SD increase in particulate matter during the year of birth results in declines in math scores of between 2% and 6% of a SD by the time students reach secondary school (Sanders, 2012[57]). In Mexico, a one-unit SD increase in thermal inversions, a proxy for CO and PM10 pollution, during the second trimester of pregnancy can result in declines of 11% of a SD on Raven's fluid intelligence scores at around age 17 (Molina, 2021[58]).

15. This link continues into adulthood. Data from China indicate that experiencing ten additional days above 29.5 degrees Celsius in-utero results in 4.8% of a SD lower standardised test scores of middle-age adults (around 37-year-olds) (Hu and Li, 2019[59]). This means that compared to an adult whose mother did not experience outside temperatures above 29.5 degrees Celsius during her pregnancy, an adult whose mother experienced ten such days could expect to achieve, other things being equal, standardised scores that were 4.8% of a SD lower. However, the health effects of heat exposure in utero can be so severe that, in the case of sub-Saharan Africa, there is some evidence that extreme temperature spikes

[5] Superfund locations in the U.S. contain high concentrations of hazardous pollutants that require long-term assessments and clean-up. Persico, Figlio and Roth (2020) demonstrate that the effects in their study are not driven exclusively by heavy metals (e.g., lead) and thus confirm that some of the effects arise from other gaseous air pollutants. Larger estimates for the Superfund sites are likely to be due to the abnormally high quantity of toxic pollutants emitted at these locations.

during pregnancy are associated with improved literacy rates for adults due to foetal selection (Wilde, Apouey and Jung, 2017[60]).[6]

Table 1. Negative effects of in-utero exposure to adverse environmental conditions on child and adult cognition, as a percentage of standard deviation

	Childhood and adolescence	Adulthood
Temperature	NA	4.8
Pollution	3.4 - 11	NA

Note: The effect of in-utero temperature exposure on adulthood is that due to ten additional days above 29.4 degrees Celsius, and excludes the positive effects found on later-life literacy in sub-Saharan Africa. The effect of in-utero pollution exposure on childhood and adolescent cognition is that due to a standard deviation increase in pollution exposure during gestation or being conceived within 2 miles of a Superfund site. The effects depicted in this table are upper and lower bounds found in the literature based on several country estimates and are likely to differ between countries.

Source: Effect sizes aggregated from (Molina, 2021[58]; Sanders, 2012[57]; Bharadwaj et al., 2017[36]; Persico, Figlio and Roth, 2020[37]; Peet, 2021[55]).

16. The negative effects of in-utero environmental conditions on cognitive abilities have long-term indirect effects on outcomes that are dependent on prior achievement and cognitive abilities such as labour market outcomes (Colmer et al., 2020[61]; Isen et al., 2017[62]; Isen, Rossin-Slater and Walker, 2017[63]). Children who experience adverse conditions in utero often come from disadvantaged backgrounds and are further exposed to adverse environmental conditions while growing up. In the short-term this can result in lower test scores (Marcotte, 2017[64]; Persico and Venator, 2019[39]). In the long-term, impaired health and cognitive development can impact students' future cognitive outcomes by lowering educational attainment, the quality of education and future wages, reducing skill accumulation over the life course (Cho, 2017[44]; Park, 2020[46]; Graff Zivin et al., 2020[3]; Graff Zivin et al., 2020[45]; Ebenstein, Lavy and Roth, 2016[6]).

17. In the short-term, estimates from the U.S. and Chile suggest that a one-unit SD increase in PM2.5, CO, and NOx on the day of standardised tests typically lowers test scores of primary school students by between 2% and 6% standard deviations (Marcotte, 2017[64]; Rojas-Vallejos et al., 2021[65]). These results are in line with correlational estimates (Miller and Vela, 2013[66]). Similarly, taking a cognitive exam on a day with ambient temperatures of 32 degrees Celsius results in 12% of a SD lower test scores of American students compared to taking the test on a day with a temperature of 22 degrees Celsius (Zivin, Hsiang and Neidell, 2018[67]). This figure is in line with the 13.5% SD decline estimated from a meta-analytic review of experimental studies (Yeganeh et al., 2018[68]). These repeated short-term effects on cognition can accumulate over time, leading to long-term learning losses.

18. In the long-term, attending school downwind of a major highway typically leads to an annual learning decline of 4% standard deviations relative to attending an upwind school in the United States, an effect due to the fact that attending a downwind school is equivalent to a 25% increase in pollution exposure

[6] These results appear to occur because extreme temperatures during conception skew the gender ratio towards female, as male foetuses are more sensitive to early health shocks. The surviving male foetuses who reach full conception exhibit greater human capital outcomes such as better health and increased educational attainment due to selective pressures and stronger health in-utero; these explanations are consistent with several of the study's findings, including that the long-term positive effects of temperature spikes in-utero such as decreased disability or higher educational attainment are much larger or only significant for males.

(Heissel, Persico and Simon, 2020[69]).[7] Additionally, attending a school within 1 mile of Toxic Release Inventory (TRI) sites, i.e. a site that releases large amounts of pollution into the local air and water, lowers test scores by 2.4% of a SD during and after the year of the site opening, with primary school students experiencing larger effects (Persico and Venator, 2019[39]).[8] Similarly, across developed and developing countries, experiencing ten additional school days with temperatures above 26.7 degrees Celsius in each of the past three to four years lowers the performance on standardised tests of secondary school students by between 2% and 3% SDs (Park et al., 2020[43]; Garg, Jagnani and Taraz, 2020[42]; Park, Behrer and Goodman, 2020[70]).

Table 2. Negative effects of postnatal transitory and cumulative pollution and temperature exposures on cognition in school-aged children, as a percentage of standard deviation

	Transitory	Cumulative
Temperature	12 - 13.5	2 - 3
Pollution	2 - 6	2.4 - 4

Note: The transitory effect of temperature is that due to experiencing a transitory temperature of 32 degrees Celsius or above. The transitory effect of pollution is that due to a one-unit standard deviation increase in transitory pollution exposure. The cumulative effect of temperature is the effect of ten additional hot days (or hot school days) with temperatures of 26.7 degrees Celsius or above in the past 3 to 4 years. The cumulative effect of pollution is the annual effect due to a 25% increase in pollution exposure or that due to attending a school within one mile of a TRI site. The effects depicted in this table are upper and lower bounds found in the literature based on several country estimates and are likely to differ between countries.
Source: Effect sizes aggregated from (Park, Behrer and Goodman, 2020[70]; Park et al., 2020[43]; Marcotte, 2017[64]; Zivin, Hsiang and Neidell, 2018[67]; Garg, Jagnani and Taraz, 2020[42]; Rojas-Vallejos et al., 2021[65])

19. Towards the end of secondary school, transitory pollution and temperature extremes on the day of high-stakes exams may significantly influence the performance of students. In Israel, a one-unit SD increase in ambient PM2.5 (AQI)[9] lowers student performance on university entrance exams by about 4% of a standard deviation (Ebenstein, Lavy and Roth, 2016[6]). Similar estimates are found in Korea due to a one-unit SD increase in PM10 (Cho, 2021[71]).

20. Additionally, regions that are prone to wildfires or engage in agricultural burning can experience elevated levels of PM2.5. In China, estimates of the effects of a one-unit SD increase in PM2.5 (29.6 µg/m3) due to agricultural fires suggest declines as high as 13.6% of a SD on high-stakes exam performance (Graff Zivin et al., 2020[45]). The higher effect observed in China could be due to a larger standard deviation and higher baseline levels of air pollution in the country, or because PM from fires is found to be more harmful to human health than PM from other sources (Aguilera et al., 2021[72]).

21. High temperatures can also affect student performance on high-stakes exams. In the United States, exposure to a one-unit SD increase in ambient temperature (3.5 degrees Celsius) on the day of exams typically leads to 5.5% SD decrease in performance (Park, 2020[46]), with estimates of 5.8%

[7] By the author's estimates, attending a downwind school is equivalent to a 25% increase in pollution exposure.

[8] In this study, a TRI site opening is found to increase pollution by 10% of a standard deviation, which implies that a one-unit SD increase in pollution is associated with a 24% of a SD decrease in test scores. However, these large effects may be driven by the fact that TRI sites release various types of toxic substances, including lead, which may have larger effects than other air pollutants such as PM2.5.

[9] AQI values for PM2.5 are calculated from a formula that converts micrograms (µg/m3) into a 1–500 index value,; the effects of AQI are roughly the same estimated effects as PM2.5 in this study due to the high correlation between the former and AQI An PM2.5 AQI above 50 is considered a threshold for unsafe levels (Ebenstein, Lavy and Roth, 2016[6])

SD decrease due to an increase of one-unit SD in temperatures (2 degrees Celsius) found in China (Graff Zivin et al., 2020[3]). In Korea, the cumulative effects of summer heat suggest that an additional ten days above 34 degrees Celsius reduce performance on high-stakes examinations taken in the fall by between 4.2% and 6.4% of a standard deviation (Cho, 2017[44]).

22. Students' impaired performance on high-stakes exams can decrease their chances of graduating secondary school and attending tertiary level educational institutions (Ebenstein, Lavy and Roth, 2016[6]; Graff Zivin et al., 2020[3]; Zivin, Hsiang and Neidell, 2018[67]; Park, 2020[46]). Differences in achievement due to extreme temperatures and high levels of pollution can result in suboptimal allocation of learning opportunities at the tertiary level with students exposed to extreme temperatures and high levels of pollution being less likely to be allocated places at university or to be allocated places at lower quality institutions given their potential. Since exposure to extreme heat and high levels of air pollution tend to affect socio-economically disadvantaged students, students living in disadvantaged neighbourhood or in deprived communities to a larger extent than they affect their more advantaged peers, environmental conditions are likely to exacerbate existing inequalities (Ebenstein, Lavy and Roth, 2016[6]). When students continue into tertiary level education, adverse environmental conditions can continue to further impact their learning and performance. In the United Kingdom, a one-unit SD increase in PM10 reduces performance on university final semester exams by 6.5% of a SD (Roth, 2018[50]), a smaller effect size compared to experimental estimates 15% of a SD decline on fluid intelligence due to increases of one-unit SD in PM2.5 in Brazilian university students (Bedi et al., 2021[73]).

Table 3. Negative effects of transitory and cumulative pollution and temperature exposures on high-stakes examinations, as a percentage of standard deviation

	Transitory	Cumulative
Temperature	5.5 – 5.83	4.2 - 6.4
Pollution	4 – 6.5	NA

Note: The transitory effect of temperature on high-stakes exams is that caused by a one-unit standard deviation increase in ambient temperature during exam taking. The transitory effect of air pollution on high-stakes exams is that caused by a one-unit standard deviation increase in pollution during exam taking. The cumulative effect of temperature is that caused by ten additional days with maximum daily temperature above 34 degrees Celsius during the summer, relative to days with a maximum temperature between 28 and 30 degrees Celsius, on math and English tests. The effects depicted in this table are upper and lower bounds found in the literature based on several country estimates and are likely to differ between countries.
Source: Effect sizes aggregated from (Ebenstein, Lavy and Roth, 2016[6]; Graff Zivin et al., 2020[3]; Park, 2020[46]; Cho, 2017[44]; Cho, 2021[71]; Graff Zivin et al., 2020[45]).

23. The effects of air pollution and temperatures on cognition continue in adulthood, where transitory pollution and temperature conditions may decrease the quantity and quality of adult engagement with cognitively demanding activities (Archsmith, Heyes and Saberian, 2018[8]; Chang et al., 2019[74]; Dong et al., 2021[75]; Huang, Xu and Yu, 2020[76]; Li et al., 2021[77]). The repeated effects of adverse environmental conditions may accumulate, resulting in long-term cognitive skill depreciation (Zhang, Chen and Zhang, 2018[7]; Zhang, Chen and Zhang, 2021[78]). In China, exposure to ten additional days with a temperature above 28 degrees Celsius in the year prior to cognitive tests is associated with a 1.3% and 1.6% lower verbal and math test scores, respectively, relative to days with temperatures between 12 and 16 degrees Celsius (Zhang, Chen and Zhang, 2021[78]). Similarly, while a one-unit SD increase in the average daily air pollution is associated with a 1.2% SD decrease in the verbal scores of adults, the same increase over a 3-year period has impacts as large as 11% standard deviations (Zhang, Chen and Zhang, 2018[7]). The magnitude of these effects increases as people age and is as large as 88% SDs for men aged 45 to 54 with less than a lower secondary education, providing support of previous associations of

pollution and cognitive decline in the elderly (Clifford et al., 2016[79]; Weuve et al., 2012[80]; Power et al., 2011[81]; Ranft et al., 2009[82]).

24. Moreover, long-term exposure to some pollutants such as PM2.5 and NO2 is associated with an increased risk of neurodegenerative diseases including Alzheimer's and related dementia, even at moderate levels of air pollution (Kasdagli et al., 2019[83]; Fu et al., 2019[84]; Chen et al., 2017[49]; Jung, Lin and Hwang, 2015[85]). Meta-analytic estimates of cohort studies suggest that a long-term increase of PM2.5 concentrations by 10 µg/m3 is associated with an increased odds of developing Alzheimer's and dementia by a factor of 3.26 and 1.16, respectively, with individuals in severely polluted countries facing bigger risks (Fu et al., 2019[84]). Importantly, the effects discussed here are those at baseline for pollution and temperature, respectively. Individuals exposed to high levels of pollution and extreme temperatures simultaneously may experience even larger cognitive losses, although the magnitude of multiplicative effects has been unexplored.

Table 4. Negative effects of transitory and cumulative pollution and temperature exposures on adult cognition, as a percentage of standard deviation

	Transitory	Cumulative
Temperature	8.8	1.3 - 1.6
Pollution	1.2	11

Note: The transitory effect of temperature is that on math scores due to experiencing a temperature above 32 degrees Celsius on the test date relative to a day with between 22 and 24 degrees Celsius. The cumulative effect of temperature is that of ten additional days with temperatures above 28 degrees Celsius in the prior year on verbal and math test scores relative to days between 12 and 16 degrees Celsius. The transitory effect of pollution is that on verbal scores due to experiencing a one-unit standard deviation increase in the air pollution index on the day of testing. The cumulative effect of pollution is that on verbal scores due to experiencing a one-unit standard deviation increase in the 3-year average air pollution index. The effects depicted in this table are upper and lower bounds found in the literature based on several country estimates and are likely to differ between countries.
Source: Effect sizes aggregated from (Zhang, Chen and Zhang, 2018[7]; Zhang, Chen and Zhang, 2021[78]).

2.1. Heterogeneity of effects across various settings and threshold effects

25. The effects of pollution and extreme temperatures on cognitive development can differ significantly across regions due to cross-country environmental, socioeconomic and institutional differences, making extrapolation across various settings and subgroups difficult. Moreover, the relationship between pollution levels and temperatures and cognition could be non-linear, with stronger effects observed at higher temperatures and pollution levels. For example, decreases in cognitive acuity could occur when pollution levels are moderate, but additional effects on health symptoms at higher pollution levels could further compromise achievement.

26. In Israel, taking a high-stakes exam on a day with PM2.5 levels of between about 12 µgm/3 and 24 µgm/3 typically decreases test scores by 6.4% of a standard deviation, while taking the exam on a day with PM2.5 levels of above 24 µgm/3 results in a 9.5% of a SD decline (Ebenstein, Lavy and Roth, 2016[6]).[10] In Korea and the United Kingdom, taking high-stakes or tertiary level exams on days with PM10 levels between 50 and 75 µgm/3 lower test scores by between a 10% and 14% of a standard deviation, compared to between a 13% and 21% of a SD decline due to PM10 levels above 75 µg/m3 (Roth, 2018[50]; Cho, 2021[71]). Importantly, these estimates are at levels below current United States Environmental Protection

[10] These estimates are relative to a day of between 0 and 12 µgm/3 M2.5 levels. PM2.5 levels are approximate based on the PM2.5 AQI levels used in this study using the EPA's conversion calculator.

Agency (EPA) daily guidelines for PM2.5 and PM10. Based on estimates from the U.S. and China, the transitory and cumulative effects of heat on learning and high-stakes performance are roughly linear starting at temperatures of about 26 degrees Celsius (Park et al., 2020[43]; Zivin, Hsiang and Neidell, 2018[67]; Graff Zivin et al., 2020[3]; Park, 2020[46]).

27. Additionally, the magnitude of the effects of environmental conditions may differ significantly across countries due to the mechanisms by which they occur. For example, an additional ten days with temperatures above 26.7 degrees Celsius lowers performance on test scores of the Programme for International Student Assessment (PISA) tests by 2.1% of a SD in poorer countries, with insignificant effects found in richer countries (Park, Behrer and Goodman, 2020[70]).[11] These differences may exist due to several reasons.

28. For example, low-income and rural settings may suffer from an additional income effect due to high temperatures (Garg, Jagnani and Taraz, 2020[42]; Hu and Li, 2019[59]). Specifically, in rural parts of China and India, the effects of temperature on cognition are more pronounced in regions that have not undertaken heat-resistant crops, the lack of which results in lower crop yields during the growing season, reducing the demand for agricultural workers and lowering family income of agricultural households. In turn, lower family income reduces overall family resources for investment into education, such as nutrition and school attendance, lowering cognitive development in the long-term (Garg, Jagnani and Taraz, 2020[42]; Hu and Li, 2019[59]). Furthermore, a high prevalence of poverty and poor state support and information infrastructures may prevent many families from making protective investments such as air conditioning and air filters or contribute to higher costs for exercising avoidance behaviours such as staying at home when temperatures and air pollution are high (Balakrishnan and Tsaneva, 2021[86]; Barwick et al., 2019[87]).[12] In turn, families in developing countries may be less able to protect against early-life health shocks (Currie and Vogl, 2013[88]).

29. Additionally, developing countries are often burdened with weak regulatory infrastructures due to lack of funding and expertise, as well as dependence on foreign income in pollution-intensive industries, which has made pollution control difficult (Blackman, 2010[89]; Sarkodie and Strezov, 2019[90]). Thus, developing countries often have higher baseline pollution loads (Arceo-Gomez, Hanna and Oliva, 2012[91]), as well as lower baseline levels of cognitive skills due to historically lower levels of educational attainment (Balakrishnan and Tsaneva, 2021[86]), which can further contribute to larger declines in long-term cognitive development as compared to developed countries.

30. Within countries, colder cities and counties experience larger cognitive declines from high temperatures, providing evidence of successful adaptation strategies such as air conditioning undertaken in regions with historically high temperatures (Cho, 2017[44]; Park et al., 2020[43]; Zhang, Chen and Zhang, 2021[78]). However, even in affluent countries and regions with high rates of air conditioning penetration such as the U.S., estimates under median climate change projections of 2.8 degrees Celsius warming suggest 3% of a SD lower academic achievement due to temperatures by 2050 (Park et al., 2020[43]).

31. The effects of pollution on long-term cognition can be found even at relatively low levels. For example in Ontario, Canada, which hosts among one of the lowest air pollution levels in the world, long-term interquartile increases in PM2.5 (4.8μg/m3) and NO2 (28.73 μg/m3) concentrations are associated

[11] In this study, poor countries are defines as countries whose per capita income was less than USD 14,000 in 1995, while rich countries are defined as countries whose per capita income in was greater than USD 14,000 in 1995.

[12] Avoidance behaviours may take the form of staying home on a work day when temperatures and pollution are high. In addition to higher costs to avoidance behaviour, individuals in developing countries and particularly rural areas have less information about air quality and weather conditions due to a very low rate of air quality monitoring systems (Barwick et al., 2019[278]).

with a 4% and 10% higher incidence of dementia, respectively (Chen et al., 2017[49]).[13] In order to put in place strategies to protect individuals from experiencing negative cognitive effects because of environmental conditions, it is important not only to quantify these effects but also identify why these effects occur. Effective adaptation strategies can only be implemented once mechanisms are clearly described. The next section considers the direct and indirect mechanisms through which temperatures and pollution levels determine suboptimal skills development and skills activation.

Table 5. Air quality guidelines, EPA and WHO 2021

Guidelines	Pollutant					
	PM2.5	PM10	O3	NO2	CO	SO2
EPA daily	35 µg/m3	150 µg/m3	70 ppb, 8-hour mean	188 µg/m3	9 ppm, 8-hour mean	75 ppb; 1-hour mean
EPA annual	12 µg/m3	NA	NA	100 µg/m3	NA	NA
WHO daily	15 µg/m3	45 µg/m3	100 µg/m3, 8-hour mean	25 g/m3, 1-hour mean	4 mgm3	40 µg/m3
WHO annual	5 µg/m3	15 µg/m3	60 µg/m3, 8-hour mean	10 µg/m3	NA	NA

Note: Daily values represent thresholds that average levels over a 24-hour period should not exceed more than between one to four times per year, except when otherwise specified. Annual values typically represent annual average values not to be exceeded that year. The WHO annual guidelines for ozone represent maximum values during peak season, which is defined by the six consecutive months with the highest six-month running average ozone concentrations.
Source: WHO global air quality guidelines (WHO, 2021[9]) and EPA national air quality guidelines (EPA, 2021[92]).

[13] In this study, the average cumulative 5-year baseline level of PM2.5 and NO2 were 10.4µg/m3 and 16.2ppb (33.253 µg/m^3) respectively.

3 Health as a key mechanism shaping the effects of air pollution and temperature on cognitive potential

3.1. The short-term physiological impact on cognitive acuity

32. Environmental conditions can have direct impacts on both the short-term and long-term cognitive ability of individuals through their effects on the central nervous system, with children and the elderly being especially vulnerable (Allen et al., 2017[93]; Brockmeyer and D'Angiulli, 2016[94]; Power et al., 2016[95]; Taylor et al., 2016[96]; Shehab and Pope, 2019[97]). Pollutants and high temperatures can influence short-term cognition in several ways. First, air pollutants such as carbon monoxide can prevent the body from releasing enough oxygen to the brain and in turn produce neurological symptoms such as headaches, dizziness and weakness that can impair cognitive performance (Kampa and Castanas, 2008[2]). Second, due to their small size, PM2.5 particles can directly alter the blood brain barrier and cause a neuroinflammation response in the brain (Genc et al., 2012[98]). Third, exposure to high temperatures can have acute effects on attention, memory and information-processing speed (Walter and Carraretto, 2016[99]) which may operate through impairment in the brain blood flow (Taylor et al., 2016[96]). Fourth, higher temperatures can increase CO2 in the blood, inducing headaches and potentially worsening task performance (Lan et al., 2020[100]; Wargocki and Wyon, 2007[101]).

33. Complex cognitive skills that heavily rely on working memory, sustained attention, or arithmetic efficiency are more impaired during heat stress relative to tasks such as visual orientation, reaction time and simple arithmetic (Taylor et al., 2016[96]; Gaoua et al., 2011[102]; Hancock, Ross and Szalma, 2007[103]). In fact, the short-term effects of high temperatures on cognition in school children and adults tend to be most pronounced when performance in math is considered and are weakest for verbal performance (Cho, 2017[44]; Garg, Jagnani and Taraz, 2020[42]; Zivin, Hsiang and Neidell, 2018[67]; Zhang, Chen and Zhang, 2021[78]). These findings provide further support for a neurological mechanism that suggests the brain regions responsible for solving math and analytical problems are more sensitive to heat (Garg, Jagnani and Taraz, 2020[42]).

3.2. The long-term impact on brain development

34. In-utero and repeated post-natal exposure to adverse environmental conditions may directly impair the way the brain develops and functions in the long-term (Babadjouni et al., 2017[104]; Clifford et al., 2016[79]; Heusinkveld et al., 2016[105]; Wilker et al., 2015[106]; Pujol et al., 2016[107]). Although the precise mechanisms are not fully understood, several mechanistic underpinnings have been proposed in the literature (Genc et al., 2012[98]), (Liu and Lewis, 2013[108]).

35. First, maternal exposure to smaller particles such as PM2.5 during gestation may cause damage to the development of foetal neural cells or induce epigenetic changes that impact neurological

development (Saenen et al., 2015[109]; Janssen et al., 2015[110]; Lanphear, 2015[111]). Epigenetic changes refer to long-term changes in gene expression, in other words, how an individual's DNA interacts with the environment to determine the probability that an outcome will occur. Epigenetic changes can lead to positive outcomes and many are part of normal developmental trajectories. Some changes are reversible, like DNA methylation. At the same time, some epigenetic changes can lead to negative long-term outcomes. For example, a decrease in the expression of certain genes important for normal neurodevelopment can impair neurodevelopmental processes.

36. Second, children breathe in larger volumes of air than adults at a time when many parts of their immune system and brain are still developing. This makes them more vulnerable to inflammation in the brain due to high levels of pollution resulting from relatively high air intake among children than adults as well as the fact that children may be more likely to absorb relatively smaller particles than adults. These two factors may result in a loss of neural tissue in the prefrontal and frontal cortices brain structures in the longer term (Brockmeyer and D'Angiulli, 2016[94]). The prefrontal cortex matures throughout childhood and adolescence and well into young adulthood, making it especially susceptible to environmental stressors in ways that other parts of the brain might not be. These brain structures are fundamental for 'higher-order' decision-making, attentional, emotional and memory processes, and are particularly sensitive to adverse neurochemical environments (Arnsten, 2009[112]).

37. Third, high levels of polycyclic aromatic hydrocarbons (PAH) and PM2.5 during gestation and throughout childhood have been associated with reduced density of white matter[14] in the brain (Calderón-Garcidueñas et al., 2016[113]; Peterson et al., 2015[114]). In turn, reduced white matter and related brain abnormalities are linked to impaired executive function, cognitive decline, and ultimately dementia and neurodegenerative diseases such as Alzheimer's (Prins and Scheltens, 2015[115]; Verdelho et al., 2010[116]; L et al., 2013[117]).

38. While the biological effects of repeated exposures to moderately high temperatures have been underexplored, experiencing a core body temperature of 40 degrees Celsius or above for even short periods of time can lead to neuronal death and permanent neurological damage, impairing long-term cognitive function (Walter and Carraretto, 2016[99]).

Box 1. Mitigating the impact of heat on math ability by re-organising when and where learning takes place

In the short-term, high temperatures have significant effects on math skills and performance, with small or no effects on verbal and language skills (Zhang, Chen and Zhang, 2021[78]; Zivin, Hsiang and Neidell, 2018[67]). For example in the United States, a daily temperature between 30 and 32 degrees Celsius, relative to a day with temperature between 20 and 22 degrees Celsius, typically results in 12% of a SD decrease in math scores for children aged 5 and above, with insignificant effects on reading (Zivin, Hsiang and Neidell, 2018[67]). In China, larger effects on math due to high temperatures are found to persist in the long-term and also significantly affect adult cognition (Zhang, Chen and Zhang, 2021[78]).

As math is a fundamental foundational skill, mitigating the effect of future increases in temperature will be crucial to ensure that children and adults are able to adequately develop, maintain and build upon math abilities throughout the life course. Re-organising when and where arithmetic learning takes place may help reduce overall exposure and thus mitigate the largest effects on cognition. For example, education systems in the northern hemisphere may consider scheduling math courses during the winter months, when annual temperatures are lower. Additionally, setting math courses to take place in the

[14] White matter is brain tissue that contains nerve fibres. Fibres connect nerve cells and are covered in myelin, which gives the white colour connotation. White matter enables signalling between nerve cells to occur.

mornings, when temperatures are typically at their lowest daily levels during the school day, can reduce daily exposure to high temperatures. Ensuring that classrooms have cooling devices such as air conditioning can also significantly attenuate the effects on cognition (Park et al., 2020[43]).

If school-level resources are scarce, re-organising classroom allocation so that math-intensive courses take place in the coolest classrooms, such as those facing north, may further reduce the impact of heat on math performance. As the effects of heat also impact the productivity in office workers (Seppänen, Fisk and Lei, 2006[118]; Wargocki and Wyon, 2017[119]), lowering exposure to high temperatures in the workplace may play a role in limiting any long-term effects on analytical skills during adulthood. Similarly to school-level re-organisation, setting up dedicated rooms for when staff engage in tasks that require sustained attention and arithmetic efficiency can ensure that individuals are able to concentrate and engage in such tasks effectively. Importantly, schools and employers must ensure that children and adults who are more vulnerable to the effects of heat receive additional support and accommodation.

3.3. The short and long-term impacts on developmental health and related effects on cognition

39. High temperatures and pollution levels can lead to adverse near-term physical health outcomes such as pre-term birth, low birth weight and other congenital abnormalities (Currie et al., 2015[120]; Kuehn and McCormick, 2017[121]; LB, AG and S, 2011[122]; Currie and Walker, 2011[123]) that impact cognitive ability throughout the life course (Currie et al., 2014[54]).

40. In the United States, exposure to ten additional days above 29.4 degrees Celsius during pregnancy is associated with between a 0.03% to 0.09% (about 1 and 3 grams) decline in birth weight relative to days with average temperatures of between 7.2 degrees Celsius and 18.3 degrees Celsius (Deschênes, Greenstone and Guryan, 2009[124]), with higher estimates found in developing countries (Andalón et al., 2016[125]; Chen et al., 2020[126]; Molina and Saldarriaga, 2017[127]). Similarly, a one-unit SD increase in average CO levels during the third trimester is associated with a 2.1% SD (13.15 gram) decline in the birth weight of infants (Currie, Neidell and Schmieder, 2009[128]), with effects in line with a meta-analysis of observational studies (Stieb et al., 2012[33]). The reduction in birthweight due to environmental conditions can occur due to a number of reasons, such as biological mechanisms, neonatal stress, reduced health care and food insecurity and pollution and temperature-induced behavioural changes in pregnant mothers (Chen et al., 2020[126]; Andalón et al., 2016[125]; Molina and Saldarriaga, 2017[127]).

41. In turn, causal estimates from Chile and the United States suggest that children born with a low birth weight (<2500 g) or a very low birth weight (<1500 g) score between 10% and 40% standard deviations lower on math and language scores during early schooling relative to their peers (Bharadwaj, Eberhard and Neilson, 2018[56]; Figlio et al., 2014[129]).[15] Evidence from Chile suggests that parents attempt to mitigate these health and cognitive effects by engaging in more compensatory behaviours, such as time spent reading, with their low birth weight children (Bharadwaj, Løken and Neilson, 2013[130]; Bharadwaj, Eberhard and Neilson, 2018[56]). However, the cognitive link appears to continue into adulthood, with a meta-analytic review indicating that increasing birthweight from very low to average (about 3500 g) is associated with a 24.6% SD increase in general or fluid intelligence for adults (Grove et al., 2017[131]).

42. Environmental conditions experienced in-utero may also influence height, which is linked to health, cognitive skills and labour-market outcomes in later life and is a commonly used proxy for early health

[15] Meanwhile, meta-analytic reviews of observational studies that include pre-term birth (≤33 weeks' gestational age) in addition to low and very low birth weight indicate decreases of between 38% and 83% standard deviations throughout compulsory schooling (Aarnoudse-Moens et al., 2009[275]) (Kormos et al., 2013[277]) (Barre et al., 2011[276]).

investments in developing countries (Case and Paxson, 2008[132]; Currie and Vogl, 2013[88]; Guven and Lee, 2012[133]; Lundborg, Nystedt and Rooth, 2014[134]). In Indonesia, children who were exposed to the 1997 Indonesian forest fires during gestation were about between 10% and 20% standard deviations (1.5 and 1.6 cm) shorter at age ten and seventeen respectively, compared to non-exposed children (Rosales-Rueda and Triyana, 2020[135]). [16] In China, a one-unit SD increase in heat exposure during gestation results in a similar decrease in height as well as a 6.5% higher risk of illiteracy at around 37 years of age, an effect largely operating through reduced income (Hu and Li, 2019[59]). In turn, estimates from the United Kingdom suggest that children who are one-unit standard deviation taller at age seven also experience 10% of a SD higher test scores at ages 7 and 11 relative to their shorter counterparts (Case and Paxson, 2008[132]).

43. In addition, in-utero and early childhood exposure to air pollution has been linked to impaired development of lung function and other related health conditions (Clark et al., 2010[136]; Deng et al., 2015[137]; Hehua et al., 2017[34]; Leon Hsu et al., 2015[138]; Rosales-Rueda and Triyana, 2020[135]). For example, 10-year-olds exposed to forest fires in-utero or the first 2 years of life had 5 to 6 percentage points lower lung capacity than their non-exposed counterparts (Rosales-Rueda and Triyana, 2020[135]). In turn, transitory exposures of PM2.5 and O3 result in twice as large or only significantly impaired cognitive performance for students with respiratory issues (Ebenstein, Lavy and Roth, 2016[6]; Marcotte, 2017[64]).

44. In the long-term, 10% lower particulate matter pollution during the year of birth increases earnings by 1% at age 30 in the United States, with evidence that part of the effects operate through impaired health and lower labour force participation (Isen, Rossin-Slater and Walker, 2017[63]). Additionally, experiencing ten additional days with temperatures above 32 degrees Celsius in-utero is associated with a decrease of 1% of annual earnings for 30-year-old adults in the United States, with similar effects found in Ecuador (Fishman, Carrillo and Russ, 2019[139]; Isen et al., 2017[62]).

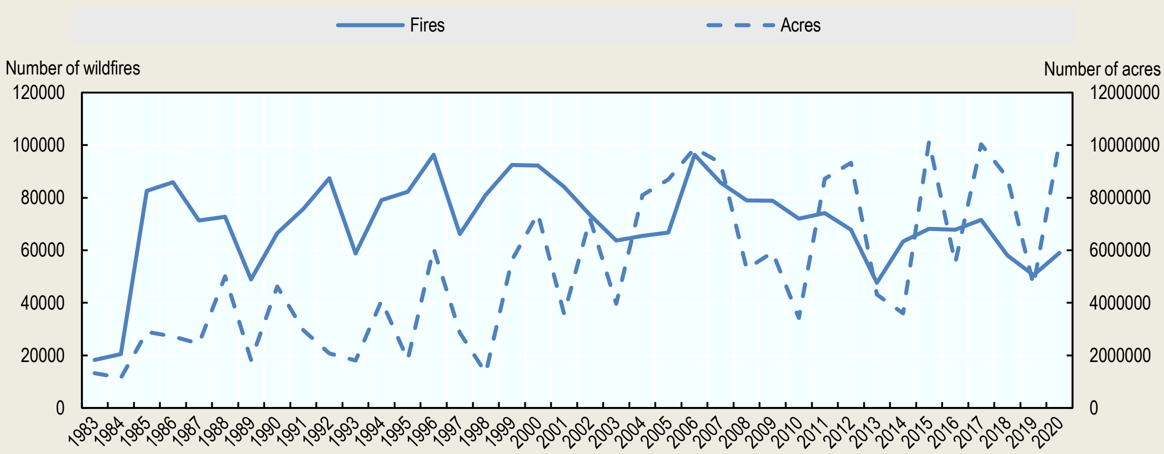
Box 2. Wildfires, particulate matter and the potential of online learning

Destructive wildfires have become increasingly common, with countries in the Mediterranean and others such as Chile, Australia, and the United States experiencing record-breaking wildfire disasters in recent years (OECD, 2021[140]). In the United States alone, 7.4 million children annually are exposed to unhealthy levels of PM2.5 due to fires (Rappold et al., 2017[141]).[17] Wildfires affect the respiratory health of surrounding populations, in part due to the large amounts of particulate matter they release (Reid et al., 2016[142]; Liu et al., 2015[143]). Figure 4 shows the number of wildfires and the number of acres burned from 1983 until 2020 in the United States. While the number of total wildfires has remained relatively stable, the number of acres burned has seen an upward trend since the 1980s, consistent with other evidence that wildfires are increasing in intensity, with more than 50% of the acres burned due to human-induced climate change (Schoennagel et al., 2017[144]). Recent evidence suggests that while PM2.5 has been decreasing in most of the United States due to reduced emissions, it has been increasing in wildfire-prone areas such as the Northwest, with projected increases in temperature likely to further exacerbate wildfire severity (Gutierrez et al., 2021[145]; IPCC, 2021[14]). This increase in burning could offset the decrease in PM emissions achieved by the country by 2050 (McClure and Jaffe, 2018[146]; Ford et al., 2018[147]).

[16] Forest fires are a large source of particulate matter pollution. In their study, the authors define exposure to the forest fires of the local aerosol index above 1.5 (range zero to six) for at least three days in a month during gestation which is correlated with PM pollution during the fires. A value close to six during the fires indicated levels of PM10 levels more than 2,000 mg/m3.

[17] This statistic is based on data from 2008 to 2012. The threshold for high exposure to fire-PM2.5 was annual levels of 1.5 µg/m3 or above.

Figure 4. The number of wildfires and acres covered in the United States, between 1980 and 2020



Note: The vertical y-axis on the left hand side represents the absolute number of annual wildfires in the United States since 1983. The vertical y-axis on the left hand side represents the annual number of acres that have been burned by wildfires since 1983.
Source: United States National Interagency Fire Center (NIFC, 2021[148]), https://www.nifc.gov/fire-information/statistics

Early evidence suggests that PM2.5 from wildfires could have as much as ten times larger negative impacts on the respiratory health of children and adults than PM2.5 from alternatives sources, as well as larger effects on high-stakes exams (Aguilera et al., 2021[72]; Aguilera et al., 2021[149]; Graff Zivin et al., 2020[3]).[18] Given that children spend a large portion of their early life in the classroom, schools and educational systems and must put in place mitigation and adaptation measures in order to protect the health and learning of students and vulnerable adults.

For one, building schools away from wildfire- and pollution-prone areas may be an important method of reducing exposure (Persico, Figlio and Roth, 2020[37]) Additionally, improving air filtration systems, adopting use of portable air cleaners and providing surgical masks and N95 respirators in schools can protect against inhaling fire-related particles, although more evidence is needed to understand the full effects of face coverings for young children (Holm, Miller and Balmes, 2020[150]; Goh et al., 2019[151]; Xiang et al., 2021[152]). Furthermore, allowing for flexibility of when and how classes take place can ensure that children are protected during long wildfire seasons without losing instructional time due to school closures.

For example, switching to online provision of course material and digital learning as an alternative to classroom-based learning during significantly polluted weeks or months could help avoid ambient exposures. Initial studies of the effects of the shift to online learning during the COVID-19 crisis indicate a 8% of a SD learning loss due to a 8-week lockdown and a decrease in assignment completion and larger variations in test scores within schools, with the largest effects felt by disadvantaged students (Tomasik, Helbling and Moser, 2020[153]; Engzell, Frey and Verhagen, 2021[154]). However, recent evidence suggests that at least for adults, the decrease in cognitive performance due to shifting online may become smaller over time as individuals adapt (Künn, Seel and Zegners, 2021[155]). Additionally, the pandemic has improved understanding of the technological, pedagogical and other factors that can contribute to making online learning successful, such as improving teacher preparedness to use digital tools (Dhawan, 2020[156]; OECD, 2021[157]). Nevertheless, such a shift would require awareness of the disparities that may arise, such as lower technological infrastructure in the home of disadvantaged children, as well as provision of additional guidance and support to vulnerable students (Bacher-Hicks, Goodman and Mulhern, 2021[158]; OECD, 2021[157]).

Finally, data collection and dissemination of air quality conditions during wildfire episodes using low-cost sensors should be made widely accessible to teachers, administrators, students and parents, and particularly pregnant mothers, in order to help guide decision-making and induce avoidance behaviours, such as staying indoors, whenever possible (Holm, Miller and Balmes, 2020[150]).

[18] In China, the effects of wildfire-induced PM2.5 on reduced performance on high-stakes examinations are significantly larger than those found due to PM2.5 in other countries from other sources (Graff Zivin et al., 2020[3]). However, this difference may be attributable to other country-specific mechanisms such as lower protective investments in classrooms.

4 Air pollution and temperature as determinants of investments in skills

4.1. Educational investments during compulsory schooling: absenteeism and the quality of learning

45. Lifelong learning and skill development is based upon the foundational skills and learning habits that children develop when they are young (OECD, 2021[159]). During early schooling, children's academic performance can determine further educational placement, as well as their academic self-concept, confidence and general disposition towards learning (Francis et al., 2020[160]; Houtte, Demanet and Stevens, 2012[161]; Steenbergen-Hu, Makel and Olszewski-Kubilius, 2016[162]). However, contemporaneous environmental conditions can affect the quantity and quality of educational and cognitive investments made by school-aged children, compounding any cognitive losses that may have occurred due to adverse developmental health and influencing their future learning trajectories. Contemporaneous air pollution can temporarily exacerbate existing health conditions such as asthma or contribute to the onset of acute respiratory symptoms such as wheezing and coughing in children (Gehring et al., 2010[163]; Guarnieri and Balmes, 2014[164]; McConnell et al., 2010[165]). In the United States for example, a one-unit SD increase in CO levels is associated with a 37% increase in asthma cases among young children (Schlenker and Walker, 2016[166]). In turn, children who are sick may exhibit increased school absenteeism (Currie et al., 2009[41]; Mohai et al., 2011[167]; Chen, Guo and Huang, 2018[40]).[19]

46. In the United States, an additional day of CO concentrations between 6.75 and 9 ppm is associated with a 5% increase in absenteeism during primary school, with larger effects of 9% estimated when concentrations are above EPA guidelines (Currie et al., 2009[41]). Additionally, moving downwind of a major highway during lower secondary school typically results in 9.5% increase in a student's absence rate (Heissel, Persico and Simon, 2020[69]). In China, a one-unit standard deviation increase in the daily air quality index (AQI) [20] increases the respiratory illness rate by 10% and the total absence rate average by

[19] It is also possible that absences increase during adverse pollution and temperature episodes due to avoidance behaviours, if parents avoid sending their children to school on days with high temperature and pollution levels. While there is indeed evidence that parents undertake avoidance behaviours to prevent child exposure to unhealthy pollution levels, such behaviours have mostly been found around discretionary activities such as going to the Zoo or sports games. When avoidance is more costly, as may be the case for school attendance, parents and children may be less likely to change their behaviours to reduce adverse environmental exposures (Neidell, 2009[270]; Janke, 2014[271]; Graff Zivin and Neidell, 2009[272]).

[20] AQI is an air pollution index that is set by government agencies according to national air pollution standards. In China, this index replaced the previous API index in 2016, and is based on six pollutants: SO2, NO2, PM10, PM2.5, CO, and O3, and thus these results should be interpreted as the composite effect of all six pollutants. AQI levels are measured from 0 – 100 and considered safe up to 100, with levels above 100 considered as a threshold for the onset of adverse health effects.

7 percent, with larger effects found for younger students (Chen, Guo and Huang, 2018[40]).[21] The absence rate is driven by respiratory illnesses, suggesting low levels of avoidance behaviour (Chen, Guo and Huang, 2018[40]). Reduced attendance due to environmental conditions can affect learning and academic achievement by decreasing class time and teacher-student interactions, causing students to fall behind and perform worse on tests (Heissel, Persico and Simon, 2020[69]). Chronic absenteeism, defined as missing 10% or more of the school year, is associated with approximately a 10% and 8% standard deviation decrease in math and reading scores, respectively, of elementary school-aged children in the United States (Gottfried, 2015[168]). Absenteeism also leads to negative externalities: the classmates of children who are chronically absent can experience a reduction in test scores that is approximately half the size of the reduction experienced by the absent children themselves (Gottfried, 2015[168]) since oftentimes teachers have to repeat material several times and classroom dynamics are disrupted.

47. In low-income settings, a decrease in the quantity of educational investments such as school attendance and health investments could also arise due to an income effect (Jacoby and Skoufias, 1997[169]; Garg, Jagnani and Taraz, 2020[42]). For example, in India, an additional ten days with temperatures above 29 degrees Celsius can result in a 10% decrease in the crop yields in districts which are not heavily reliant on heat-resistant crops (Garg, Jagnani and Taraz, 2020[42]). This can decrease the local demand for agricultural labour and thus prompt income shocks among agricultural households, reducing the income available for educational investments. Consequently, an additional ten days above 29 degrees Celsius during the growing season lowers test scores by between 6% and 10% of a standard deviation, an effect operating through the prior year's heat on current year school attendance and children's body mass index (Garg, Jagnani and Taraz, 2020[42]). Policies can reduce this effect: a national income guarantee program that provides 100 days of paid work to rural households has been found to attenuate the effects on test scores by more than 50% for up to seven years (Garg, Jagnani and Taraz, 2020[42]).

48. In addition to reducing the quantity of educational investments, adverse environmental conditions may also reduce the quality of learning. These effects may arise if illnesses due to pollution and heat influence the quality of attention students are able to devote to classroom instruction and self-study. For example, asthma and wheezing are associated with behavioural and cognitive impairments (Calam, 2003[170]; Irani et al., 2017[35]; Feitosa et al., 2011[171]). Furthermore, environmental conditions may have a direct effect on mood, behaviour and attention (Cho, 2017[44]; Noelke et al., 2016[172]; Zijlema et al., 2016[173]). Increased heat-related fatigue, sleep deprivation and thermal discomfort due to high temperatures may also result in distraction and a decreased motivation to exert cognitive effort (Cho, 2017[44]; Wargocki and Wyon, 2017[119]).

49. A cohort study from Barcelona found that a one-unit SD increase in NO2 was associated with a 5% SD reduction in the hit reaction time of primary school students, a signal of inattention (Sunyer et al., 2017[38]). Additionally, attending a school downwind of a nearby major highway throughout primary and secondary education can increase behavioural incidents by 4 percentage points in the United States (Heissel, Persico and Simon, 2020[69]). These effects may contribute to a lower ability of students to absorb new material or concentrate during school or studying time, leading children to perform worse on cognitive tests (Sunyer et al., 2017[38]; Heissel, Persico and Simon, 2020[69]; Persico and Venator, 2019[39]). In the long-term, the effects of repeated exposures to adverse ambient conditions on the quality of class time may accumulate, leading to significant losses in learning and skill development (Park et al., 2020[43]).

50. The cumulative negative effects of heat on practice standardised tests in the United States and international PISA tests during secondary schooling are present only during school days, and absent when considering weekend and holiday temperatures (Park et al., 2020[43]; Park, Behrer and Goodman, 2020[70]). These findings imply that in the long run, the quality of instructional time spent in the classroom is an

[21] Alternatively, this result is equivalent to a 10-unit increase in AQI leading to 3.31% increase in the respiratory illness rate and a 2.31% increase in the total absence rate.

important channel through which high temperatures disrupt learning (Park et al., 2020[43]). The same channel is not present in India, where heat's effect on cognitive ability does not depend temporally on the day of the week but rather on the effects incurred on income during the crop growing seasons (Garg, Jagnani and Taraz, 2020[42]). However, in Korea, high summer temperatures have a negative effect on university entrance exams taken in the fall, indicating that summer heat may influence either the quantity or quality of student's preparation for high-stakes exams (Cho, 2017[44]).

Box 3. Reducing the cognitive burden of high pollution levels and extreme temperatures through adaptive technologies

Children and adolescents spend a significant portion of their lives in classrooms. Thus, ensuring that schools and education systems are adequately prepared and supplied with the technology to deal with the burden of air pollution and high temperatures may be one way in which policy makers can mitigate against the early environmental impact on cognition. **Air conditioning** and **air filters** are two of the main technologies that may confer large health and cognitive benefits.

Air filters trap small particulates that may easily pass indoors. In the U.S., replacing filters with high-efficiency air filters (minimum efficiency reporting value > 12) in schools is estimated to reduce the asthma burden due to PM2.5 by 13% per year (Martenies and Batterman, 2018[174]). These health effects are likely to confer additional cognitive benefits. In fact, early estimates suggest that the installation of air filters in schools can raise math scores by 20% of a standard deviation over 4 months at an annual cost of only USD 1,000 per class (Gilraine, 2020[175]). However, filters must be replaced frequently in heat, ventilation and air conditioning (HVAC) systems in order to avoid accumulated particles diffusing from filters attached to air conditioning units (Wargocki, Wyon and Fanger, 2004[176]).

Additionally, air conditioning can offset a majority of the cognitive losses due to heat (Cho, 2017[44]; Isen et al., 2017[62]; Park et al., 2020[43]; Zhang, Chen and Zhang, 2021[78]). In the U.S., home and school air conditioning offset 41% and 57%, respectively, of the learning losses encountered on hot school days, with similar effects found in China (Park et al., 2020[43]; Zhang, Chen and Zhang, 2021[78]). Construction projects installing air conditioning units in schools that did not previously have them were found to increase reading scores by 15% standard deviations in Connecticut (Neilson and Zimmerman, 2014[177]). Although such school renovations present high up-front costs, they may be more cost-effective in improving test scores than class-size reductions and are highly scalable compared to other educational interventions as they require straightforward technical modifications (Stafford, 2015[178]; Kraft, 2020[179]). However, although the use of technologies such as air conditioning can importantly reduce the negative effects of high temperatures on cognition, they are also energy-intensive and can potentially contribute to global warming. When new school buildings are planned, location should be identified so as to minimise exposure to pollutants and design solutions should be implemented to reduce exposure to high temperatures.

In addition to air filters and air conditioning, **retrofitting school bus engines** of an entire district**,** which may decrease PM emissions by as much as 60% to 90%, is associated with improvements in reading of 9% standard deviations (Austin, Heutel and Kreisman, 2019[180]). Additionally, night-time ventilative cooling, which refers to opening windows or using low-energy cooling devices during the night, has been found to be a cost-effective way of improving the productivity of office workers (Seppanen, Fisk and Faulkner, 2003[181]). Cool roofs, which can be achieved by retrofitting rooftops with cooling materials or white paint, have also been shown to improve thermal comfort and reduce energy load by lowering air conditioning use in European office and school buildings (Costanzo, 2016[182]). Passive measures such as installing low-energy windows and removing classroom and office furniture or devices that trap heat, such as printers, can additionally lower energy generation (Toyinbo et al., 2016[183]).

Importantly, any policy design that aims to improve the health and performance outcomes of children and adults should consider personal exposure to environmental conditions rather than aggregate indoor or outdoor levels (Kelly and Fussell, 2019[184]; Zhan et al., 2018[185]). In European cities, for example, more than 90% of the variation in air pollution exposure of individuals is determined by individual characteristics such as employment status and occupation, rather than pollution differences between cities (Schweizer et al., 2006[186]). Additionally, a study from Portugal found that rather than classrooms, cafeteria rooms had the highest levels of ultrafine particles, while being outdoors during the school day sometimes contributed up to 70% of total daily dose of pollution (Slezakova, de Oliveira Fernandes and Pereira, 2019[187]). Thus, improving learning outcomes depends on consideration of the outdoor-indoor environmental relationship as well as the activities of the targeted population and the microenvironments within which they take place (Demirel et al., 2014[188]; Van Ryswyk et al., 2013[189]), (Schweizer et al., 2006[186]), .

4.2. High stakes testing, educational attainment and labour market sorting

51. Temperature and pollution levels have economically meaningful effects on the scores of university entrance exams and subsequent educational attainment (Ebenstein, Lavy and Roth, 2016[6]; Graff Zivin et al., 2020[3]; Graff Zivin et al., 2020[45]; Park, 2020[46]). In China, exposure to a one-unit SD increase in temperature (2 degrees Celsius) and a one-unit SD increase in the difference between upwind and downwind fires during the high-stakes National College Entrance Examination (NCEE) at baseline is associated with a 1.2% and .021% decrease in the probability of getting into first-tier universities, respectively (Graff Zivin et al., 2020[3]; Graff Zivin et al., 2020[45]). [22] In the U.S., a one-unit SD increase in temperature (2.4 degrees Celsius) is associated with a 3 percentage points lower likelihood of graduating on time (Park, 2020[46]). In Israel, a one-unit SD increase in PM2.5 (AQI) exposure across a student's high-stakes *Bagrut* exams is associated with a .15 years decline in tertiary education (Ebenstein, Lavy and Roth, 2016[6]).

52. Beyond foundational learning during compulsory schooling, performance on high-stakes exams plays an important role in placing students on individual learning trajectories. At the end of secondary school, students in many countries are asked to take high-stakes exams such as the SATs in the United States, the Gaokao in China, the Bagrut in Israel, and the Suneung in Korea, in order to gain access to prestigious tertiary level institutions by displaying their cognitive potential vis a vis other prospective students (Linn, 2016[190]).[23] Admission into prestigious universities is often explicitly or implicitly conditional upon achieving high scores on such exams, affecting the quantity and quality of future educational investments and the long-term accumulation of cognitive skills. This transition period is also a time when the learning opportunities of advantaged and disadvantaged students becomes increasingly disparate, explaining a large part of the inequalities in literacy achievement between the two groups (OECD, 2021[159]). Thus, any additional influence from adverse environmental conditions has the potential to exacerbate existing inequalities.

53. While the precise physiological channels through which the effects occur are difficult to disentangle, students are aware of the potentially economically meaningful outcomes that may result from their performance, making it likely that the effects operate through a direct cognitive pathway beyond decreased effort and mood (Park, 2020[46]; Graff Zivin et al., 2020[3]). Early evidence from the effects of indoor PM2.5 on the increased errors of advanced German chess players, who have strong motivation to perform cognitively in high-stakes settings, provides further support that a short-term, direct transitory

[22] The principal driver of the latter results is particulate matter during agricultural fires.

[23] Linn (2001) provides a useful history of the debate around standardised testing and its distributional effects.

cognitive effect drives at least part of the decline in the scores of university entrance exams (Künn, Palacios and Pestel, 2019[191]). Through their effects on high-stakes performance, contemporaneous environmental conditions can thus play a role in determining the individual learning trajectories of students as they enter adulthood and transition into the work place. In fact, on average across OECD countries, adults without a tertiary degree are 50% more likely to be disengaged from adult learning (OECD, 2021[159]). This can exacerbate inequalities over the life cycle, as students from disadvantaged backgrounds experience larger declines in their high-stakes test scores as well as a lower ability to capitalize their scores and educational attainment into future learning and higher wages (Ebenstein, Lavy and Roth, 2016[6]).

Box 4. Re-organising high-stakes exams to reduce inequalities

High-stakes exams at the end of secondary school are used around the world as a signal of student cognitive ability, and in some countries such as China, as the primary admissions criteria for admission into higher education (Graff Zivin et al., 2020[3]). However, random disturbances on the day or week of high-stakes exams, including higher levels of transitory air pollution and temperatures can affect students' performance on such exams, with long-term economically significant consequences (Ebenstein, Lavy and Roth, 2016[6]). As socio-economically disadvantaged students are more likely to attend schools with lower adaptive technologies and live in areas with worse environmental conditions, high-stakes exams can exacerbate existing inequalities by lowering tertiary educational attainment and the quality of that education.

Schools and education systems could take several measures to attenuate the impact of adverse environmental conditions on the high-stakes performance of disadvantaged students to ensure that all students have an equal chance to perform to their potential. For one, limiting the pollution around testing sites and requiring that all testing sites have adequate indoor protections, such as air conditioning and air filters, can reduce unequal exposure during test taking. Exams could be rescheduled to early in the day to avoid extreme temperatures, although the relative benefit of reduced heath should be weighed against the negative effects of an early start time on cognitive performance for adolescents (Carrell, Maghakian and West, 2011[192]). Additionally, because re-scheduling and retaking exams can be costly in terms of both finances and time, reducing barriers to retaking exams can ensure that disadvantaged students have the same opportunities to re-take and prepare for exams as their advantaged counterparts (Ebenstein, Lavy and Roth, 2016[6]).

Finally, as the academic year typically finishes between May and July, high-stakes exams are typically taken in the early summer months, when temperatures tend to reach high levels in the northern hemisphere (European Commission/EACEA/Eurydice, 2021[193]). Adjusting the general schedule of the academic year and the timing of high-stakes according to local climate may help in reducing students' exposure to adverse environmental conditions. In the Netherlands, for example, the dates of school holidays already differ depending on region in order to control peaks in holiday traffic (European Commission/EACEA/Eurydice, 2021[193]). Allowing further flexibility of such policies to take into account when temperatures and pollution levels are high can reduce the overall health and cognitive burden on students.

4.3. Contemporaneous environmental conditions during adulthood: the quantity and quality of cognitive investments

54. A large part of adult learning and cognitive skill development comes from on-the-job informal learning (e.g. learning from co-workers) and non-formal learning (e.g. on-the-job training) (OECD, 2021[159]). As many countries are experiencing declines in fertility and increases in life expectancy, as well as rapid technological changes, an increasing number of adults are expected to require upskilling and reskilling in order to remain relevant in the labour market for longer (OECD, 2019[194]). Thus, the effects of environmental conditions on workplace productivity and performance may reduce the overall cognitive development and skill accumulation of adults, with economically significant implications (Heal and Park, 2016[195]). Adults who engage in learning at work experience similar challenges due to environmental conditions. On the one hand, individuals who experience health symptoms and decreased motivation due to environmental conditions may take more days off work or decrease the amount of hours worked during a standard workday, reducing their quantity of learning investments (Chang et al., 2019[74]). Less time at work would in fact likely result in lower absolute levels of engagement in non-formal and informal learning even if the share of time dedicated to these activities remained the same. However, such share would likely be cut further to compensate for time lost to illnesses. Moreover, absences due to ill health would likely result in disrupted participation in learning opportunities thus lowering their effectiveness. On the other hand, environmental conditions can also impair the concentration, mood and cognitive acuity of adults, reducing the quality of learning that occurs even when individuals work their typical hours. These effects may accumulate over time, lowering cognitive skill attainment over the life course.

55. First, adults exposed to adverse environmental conditions may have higher rates of worker absenteeism or reduce the amount of hours they engage with work activities (Aragón, Miranda and Oliva, 2017[196]; Chang et al., 2019[74]; Adhvaryu, Kala and Nyshadham, 2022[197]). These effects may occur because of environment related-sickness, or if parents or caretakers stay home from work more often in order to care for young children or elderly adults who are more susceptible to the health effects of pollution and temperature (Aragón, Miranda and Oliva, 2017[196]). In China, working on a day with an air pollution index (API)[24] of between 150 and 200 (values at which the health of the general population begins to be affected), results in on average about 5%, or about 3.5, fewer calls made by a call center worker (Chang et al., 2019[74]). These effects are driven by an increase in the frequency or length of breaks taken when air pollution levels are high.

56. Similarly, early evidence from private financial investors in Germany, highly-skilled and remunerated professionals, indicates that a one-unit SD increase in daily ambient PM10 levels leads to a 8.5% decline in the willingness to log in to brokerage accounts and conditional on logging in, about a 1% decline in the willingness to make trades (Meyer and Pagel, 2017[48]). These results suggest that adults may experience a reduced willingness to engage in cognitively demanding activities when pollution levels are high. In the long-term, repeated daily exposures to high pollution and temperature levels could have cumulative effects on the willingness of adults to engage in cognitive activities at work as well as outside of work. Since lack of practice can lower the extent to which individuals can acquire new skills but also a decline in the skills they have, individuals exposed to adverse environmental conditions could experience long-term declines in their cognitive skill development due to a decrease in the quantity of cognitive investments.

[24] The API only includes three air pollutants: SO2, NO2 and PM10, and ranges from zero to 500. Values of between 51 to 100 indicate “Moderate” air quality levels, while values of between 100 and 150 deemed unhealthy for sensitive groups, with effects on the general population emerging at levels of 150 and above (Chang et al., 2019[74]). The API was replaced by the AQI in 2016, which includes three additional pollutants (CO, O3 and PM2.5).

57. Second, high temperatures and pollution levels influence the *way* in which adults engage with cognitive activities by impacting their mood or decision-making abilities (Dong et al., 2021[75]; Bellani et al., 2021[198]; Huang, Xu and Yu, 2020[76]; Chew, Huang and Li, 2021[199]; Heyes and Saberian, 2019[5]). In the United States, a one-unit SD increase in CO concentrations (.139 ppm) leads to decreases of 4.2% SD in the number of correct calls made by baseball umpires, highly-skilled professionals trained to make important decisions in a short time span (Archsmith, Heyes and Saberian, 2018[8]). In Canada, a one-unit SD increase in PM2.5 (3.91 µg/m^3) lowers the quality of speeches made by members of parliament by 1.1% of a SD, an effect equivalent to about 1 month of education (Heyes, Rivers and Schaufele, 2019[200]).[25,26] High ambient temperatures have also been found to impact the quality of performance in cognitively demanding occupations, even in indoor "climate-controlled" settings with high air conditioning penetration (Heyes and Saberian, 2019[5]). In the U, a one-unit SD increase in temperature (8.7 degrees Celsius) decreases the likelihood that an immigration judge makes a decision favourable to their applicant 4.5% of a SD, indicating a decrease in judge's objective decision-making ability (Heyes and Saberian, 2019[5]). Estimates from settings outside of the labour market support these findings. A recent experiment conducted with university students from China found that a one-unit SD increase in ambient PM2.5 concentrations (120 µg/m^3) led to a 66% SD decrease in contribution during a public goods game and a 55% SD decrease in altruistic giving during a dictator game (Chew, Huang and Li, 2021[199]). Additionally, German chess-players who use advanced problem-solving and analytical skills to make quick strategic decisions have been found to make meaningful errors due to increases in indoor levels of $PM_{2.5}$ and CO_2 (Künn, Palacios and Pestel, 2019[191]).

58. Evidence from financial occupations suggests that at least part of the effects on decreased quality of work are also driven by the impact of environmental conditions on mood or a "dispositional effect" (Dong et al., 2021[75]; Huang, Xu and Yu, 2020[76]; Chew, Huang and Li, 2021[199]).[27] In China, a one-unit SD decrease in AQI is associated with a 8.34% SD decrease in the dispositional effect by affecting the short-term mood of investors (Li et al., 2021[77]). Early estimates from the United States suggest that a one-unit SD increase in PM2.5 levels in New York City lowers same-day market returns by 11.9% and that these results are driven by an increase in risk-aversive behaviour of investors (Heyes, Neidell and Saberian, 2016[201]). Overall, these findings suggest that the quality of performance in a variety of cognitively demanding tasks is impacted by environmental conditions, in part by influencing decision-making abilities and the disposition of adults. Over time, the impact on daily motivation, mood, and decision-making could decrease the quality of effort people put into their roles in the workplace or on learning new skills and engaging with cognitive activities. However, a lack of panel data linking long-term skill attainment and environmental conditions has impeded efforts to estimate these effects.

[25] While this effect appears to be relatively small, this is partially due to the extremely low levels of pollution found in Ottawa. During the sample of this study, the mean of PM2.5 was around 4.86 µg/m3 with a standard deviation of 3.91. Alternatively, an increase of 10 µg/m3 of PM2.5 is associated with a 2.8% SD decrease in speech quality.

[26] The quality of speeches was measured via textual analysis, which converted verbal statements made by parliament members into Flesch-Kincaid grade-level indices. The Flesch-Kincaid grade-level index reflects the complexity of tests by estimating the number of years of education (based on the United States grade level scale) one would need to correctly understand a text.

[27] In behavioural finance, the disposition effect refers to a propensity of financial brokers to sell assets that have increased in value and retain assets that have lost value (Weber & Camerer, 1998).

5 The indoor environment as a mediator of ambient environmental conditions

59. Ambient temperature and pollution levels influence the quality of indoor environments, where individuals in developed economies spend approximately 90% of their time, either in work buildings, school classrooms, or at home (EPA, 2021[202]). Some air pollutants such as PM2.5 can easily travel indoors due to their small size, while others, such as ozone, cannot (Bo et al., 2017[203]; Leung, 2015[204]). This is consistent with findings that declines in cognitive performance in indoor environments are larger or only significant for ambient PM as compared to ozone (Bedi et al., 2021[73]; Meyer and Pagel, 2017[48]; Chang et al., 2016[205]; Marcotte, 2017[64]; Künn, Palacios and Pestel, 2019[191]). In many cases, ambient particles have higher concentrations indoors as compared to outdoors (Chen and Zhao, 2011[206]).

60. Most of the evidence on ambient environmental conditions considers the aggregate impact that ambient conditions have on cognitive development that occurs primarily indoors, thus estimating the net effects to include any adaptations strategies adopted by different populations. However, the indoor environment in itself can have an additional impact on learning and cognitive skill development. In addition, human behaviour changes in response to climate change (e.g., moving indoors) may have implications for **indoor air quality (IAQ)** (Leung, 2015[204])**.** Although indoor-outdoor pollution levels are correlated (Künn, Palacios and Pestel, 2019[191]), factors such as ventilation, air conditioning, air filters and building characteristics can mediate the interaction and effects of ambient temperature and pollution levels that are found indoors (Leung, 2015[204]; Majd et al., 2019[207]; Braniš, Řezáčová and Domasová, 2005[208]). Thus, this interaction is a mediating channel by which ambient environmental conditions can affect cognitive development.

Box 5. Indoor air quality, ventilation, CO_2 and temperature

Indoor air quality (IAQ) refers to "the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants" (EPA, 2021[202]). It is the combination of (a) indoor pollution from indoor sources (e.g., chemical, and biological contaminations from furnishing, building materials, appliances) and (b) indoor pollution that originated from ambient pollutants, and (c) their interactions with a variety of processes such as ventilation, temperature, building characteristics and occupant activity and density (Leung, 2015[204]; Kelly and Fussell, 2019[184]). The indoor air in schools around the world has been found to be unsatisfactory and linked to asthma and other health issues (Annesi-Maesano et al., 2013[209]; Mendell and Heath, 2005[210]; Majd et al., 2019[207]; Chatzidiakou, Mumovic and Summerfield, 2012[211]; Oliveira et al., 2019[212]). For example in 2014, around 65% of classrooms in the WHO European region were estimated to have PM2.5 concentrations higher than the daily maximum per WHO guidelines at the time (25 μg/m^3) (Csobod et al., 2014[213]).

A primary mediating factor in the relationship between ambient temperature and pollution levels and their indoor counterparts is **ventilation:** the flow of air into and out of a space. Adequate ventilation improves IAQ by diffusing the concentrations of indoor pollutants and introducing fresh air (Toyinbo et al., 2016[183]). Alternatively, low ventilation rates can contribute to thermal discomfort and higher indoor CO2 concentrations (Fisk, 2017[214]). In fact, the most common reason for high temperatures in classrooms is low ventilation (Wargocki and Wyon, 2007[101]). Often measured as the level of CO2 concentrations in a closed area, ventilation is the most commonly used proxy for assessing IAQ (Stafford, 2015[178]). Commonly referred to standards for ventilation rates in schools are 7 liters per second (L/s) and 8 liters per second (L/s) in the United States and Europe, respectively (Fisk, 2017[214]). However, rates in American and European schools are regularly below these standards (Toyinbo et al., 2016[183]; Fisk, 2017[214]; Alexander and Lewis, 2014[215]; Annesi-Maesano et al., 2013[209]) and many classrooms exceed the maximum standard for CO_2 concentrations (1000 ppm), with maximum values found ranging from 1400 to as much 5200 ppm (Fisk, 2017[214]).

Higher ventilation rates are associated with increased student attendance and improved cognitive performance on school tests based on cross-section and intervention studies (Mendell et al., 2015[216]; Fisk, 2017[214]). Empirical estimates from the United States suggest that the average school construction project aimed at improving IAQ through ventilation leads to 7% and 11% SDs improvements in math and reading scores, respectively (Stafford, 2015[178]). [28] Outside of school environments, a one-unit standard deviation increase in indoor CO_2 levels (~300 ppm) is associated with a 1.8 percentage point increase in the probability of advanced chess-players making a meaningful error during competitive tournaments (Künn, Palacios and Pestel, 2019[191]), indicating impaired decision-making of adults during highly cognitive activities. Additionally, increasing ventilation by 10 L/s improves performance of office work by 6% as long as new air filters were installed (Wargocki, Wyon and Fanger, 2004[176]).

However, the effects on health and IAQ and performance are also partially dependent on the mode of ventilation and other factors such as occupancy rate and occupant activity (Toftum et al., 2015[217]). Mechanical ventilation refers to either systems that extract indoor pollutants (i.e., mechanical exhaust ventilation) or systems that both remove indoor pollutants and concurrently supply fresh indoor air (i.e., mechanical supply and exhaust ventilation or balanced ventilation) (Toyinbo et al., 2016[183]). Natural ventilation, typically achieved by opening windows and doors of classrooms, refers to “the introduction of outdoor air into a building driven by natural produced pressure differentials” (ASHRAE, 2009[218]). While outdoor air supply to buildings is an important component of ventilation, it must be balanced with the evidence that allowing outdoor air into buildings can add to the burden of indoor air pollution (Leung, 2015[204]). Estimates suggest that in the United States, the net annual costs per person of improving ventilation to adequate levels would be less than 0.1% of current public spending on elementary and secondary education (Fisk, 2017[214]).

Concerns over lack of ventilation in classrooms and the associated sanitary risks during the COVID-19 pandemic have increased awareness regarding the importance of indoor air quality and CO2 concentrations among educators, families and decision makers. Some schools and education systems have invested in the purchase of CO2 monitors, devices that can signal when air quality deteriorates and therefore ventilation is required. Such monitors could prove useful well beyond the pandemic, improving indoor air quality and reducing disrupted learning by encouraging adequate ventilation (Open Access Government, 17 January 2022[219]).

61. Only a few studies use panel data of indoor pollution levels to study the effect on cognition, in large part because these levels are rarely measured and recorded (Sunyer et al., 2017[38]; Roth, 2018[50]; Künn,

[28] For reference, the average ventilation project was priced at around USD 300,000.

Palacios and Pestel, 2019[191]). In the United Kingdom, a one-unit SD increase in indoor PM_{10} levels of university classrooms can lower exam scores by as much as 6.4% of a standard deviation. Evidence from German chess-players also suggests a one-unit SD (13.19 µg/m^3) increase in indoor PM2.5 during competitive tournaments is associated with approximately a 10% SD increase in meaningful errors (Künn, Palacios and Pestel, 2019[191]).

62. A large array of field intervention and experimental studies have examined the effect of indoor temperatures on cognition in school and office environments (Wargocki and Wyon, 2013[220]; Wargocki, Porras-Salazar and Contreras-Espinoza, 2019[221]; Zhang, de Dear and Hancock, 2019[222]; Fisk, 2017[214]). A meta-analysis of these studies suggests that lowering the temperature from 30 degrees Celsius to 20 degrees Celsius is associated with a 20% improvement in the performance on school tasks that involve learning and cognitive exertion (Wargocki, Porras-Salazar and Contreras-Espinoza, 2019[221]). For adults, the performance of office workers is estimated to increase about 9% following similar decreases in temperature (Wargocki and Wyon, 2017[119]), although there is evidence that there are differences between men and women in ideal thermal conditions in office spaces for comfort and productivity (Chang and Kajackaite, 2019[223]). Additionally, decreasing humidity levels when temperatures are high has been found to mediate the impact on cognitive impairment (Tian, Fang and Liu, 2020[224]).

6 Disparities in the health and cognitive effects of environmental conditions across groups

6.1. Socioeconomic and ethnic disparities

63. The negative effects of environmental conditions can affect some groups more than others, with important distributional consequences. First, the air and temperatures individuals are exposed to from birth onwards are the result of various interrelated social and economic processes. For example, in North America, disadvantaged and minority households and students are more likely to live, work, attend schools and be born in areas with higher pollution levels (Chakraborty and Zandbergen, 2007[225]; Currie, 2011[226]; Banzhaf, Ma and Timmins, 2019[227]; Persico, Figlio and Roth, 2020[37]). Similar patterns of unequal pollution exposure have been found in Asia and Africa (Hajat, Hsia and O'Neill, 2015[51]) and the WHO European region, but may differ based on the pollutant considered (Fairburn et al., 2019[228]).[29] In addition to higher exposures, poor households may be less able make protective and compensatory investments, such as additional tutoring, in response to any cognitive losses experienced due to environmental conditions (Park et al., 2020[43]; Graff Zivin and Neidell, 2013[4]).

64. In fact, adverse environmental conditions can have larger impacts on the test scores of students from lower socio-economic backgrounds from the day they are born, with inequalities increasing as individuals age.[30] In Chile, the effects of exposure to CO during pregnancy on cognitive ability are more than twice as large for children of mothers without a secondary school diploma (Bharadwaj et al., 2017[36]). In China and India, cognitive losses due to environmental exposures operate in part via an income effect which overwhelmingly affects poor agricultural households (Garg, Jagnani and Taraz, 2020[42]; Hu and Li, 2019[59]). In Israel, the impact of contemporaneous PM2.5 exposures on high-stakes exams is larger for students of low socioeconomic status (SES) and each point is even "higher-stakes" for low SES students due to the latter's reduced ability to rely on social capital and financial advantages during the transition to the labour-market, compared to their high SES counterparts (Ebenstein, Lavy and Roth, 2016[6]). These inequalities continue to widen as people age, as exposure to high levels of pollution has a larger impact on the verbal abilities of less-educated older adults (Zhang, Chen and Zhang, 2018[7]).

65. In addition, recent evidence suggests that environmental conditions play a non-negligible role in the racial-achievement gap in the United States (Park, 2020[46]; Park et al., 2020[43]; Persico, Figlio and Roth, 2020[37]). In the United States, Black children are more likely to experience a higher incidence of

[29] (Fairburn et al., 2019[228]) find that although many studies suggest ethnic minorities in the WHO European Region experience greater exposure, these results differ by the minority group in consideration.

[30] However, there are exceptions to these trends. For example, results from the United States by (Heissel, Persico and Simon, 2020[69]) suggest that in the United States, more advantaged and white students experience larger reductions in test scores due to pollution exposure, compared to less advantaged and Black students, but that the latter are more likely to be written up for behavioural incidents and have more absences due to pollution.

asthma, effects which appear to be explained in large part by the residential locations of minorities (Alexander and Currie, 2017[229]). Additionally, between 3% and 7% of the gap on standardized tests between white and Black and Hispanic students can be explained by the effects of heat on learning during compulsory school (Park et al., 2020[43]). These effects are driven by lower school-level investments such as air conditioning and the geographical distribution of minorities in hotter regions across the United States (Park et al., 2020[43]). Estimates from Florida suggest that pollution from Superfund sites *alone* could account for at least 2% of the Black-white test score gap in the state (Persico, Figlio and Roth, 2020[37]). In fact, recent evidence suggests that the effects of pollution on reduced attainment of tertiary level education may be intergenerational, indicating that the environment may present an additional and under-explored avenue from which intergenerational racial inequalities persist (Colmer et al., 2020[61]).

Box 6. The long-term impacts of the United States Clean Air Act of 1970

In the past several decades, most developed countries have succeeded in reducing air pollution (OECD, 2021[12]). However, despite lower pollution levels, in some countries such as the United States, minorities and those of low socioeconomic status remain significantly more likely to reside and work in areas with high pollution levels (Banzhaf, Ma and Timmins, 2019[227]). This unequal pollution exposure affects not only the health of disadvantaged communities, but may also play a role in continuing and exacerbating a cycle of poverty and deprivation. Thus, lowering pollution exposure and improving access to adaptation technologies for the most vulnerable is likely to have the additional benefits of reducing socioeconomic inequalities and levelling the playing field for all.

One such clear example of this is the **United States Clean Air Act of 1970 (CAA).** The CAA was a major federal law aimed at reducing the health and welfare burden due to air pollution in the United States. The legislation established the first National Ambient Air Quality Standards (NAAQS) for harmful air pollutants and mandated and enforced that counties with ''nonattainment status,'' those with pollution levels above the standards, lower their emissions (Currie and Walker, 2019[230]). In its first three years after implementation, the law is estimated to have reduced pollution levels by more than 10% in nonattainment counties (Isen, Rossin-Slater and Walker, 2017[63]). Several amendments following its implementation have included more stringent regulation of criteria air pollutants, including ozone and PM2.5 (Currie and Walker, 2019[230]). The legislation and its amendments have led to important improvements in several health outcomes, including reducing infant mortality and cardiovascular hospitalisations (Chay and Greenstone, 2003[231]; Nethery et al., 2020[232]). But beyond its impact on health, the CAA may have also led to improvements in outcomes relevant to long-term cognitive development and inequalities, including wages, educational attainment and upward economic mobility (Isen, Rossin-Slater and Walker, 2017[63]; Colmer et al., 2020[61]; Currie, Voorheis and Walker, 2020[233]; Colmer, Voorheis and Williams, 2021[234]).

First, for cohorts born in nonattainment counties after the law went into effect, the subsequent reduction in pollution was associated with a 0.7% increase in the amount of quarters worked and a 1% increase in mean annual earnings at age 29 to 31, equivalent to about USD 4,340 per person (Isen, Rossin-Slater and Walker, 2017[63]). These effects appear to be driven by increased educational attainment, a decrease in disability, and increases in income levels among individuals at the bottom tail of the earnings distribution (Isen, Rossin-Slater and Walker, 2017[63]). Second, early evidence also suggests that the effects may span across generations. Estimates indicate that the reduction in air pollution (8 μg/m3) from the CAA during parental gestation is associated with between 2.1 and 2.6 percentage points increase in the likelihood of their children attending university (Colmer et al., 2020[61]). The increase in university attendance is driven by increased family resources and investments, such as reading to children, rather than biological channels (Colmer et al., 2020[61]).

These findings have significant distributional implications. While the CAA has led to significant convergence in the Black-White PM2.5 exposure gap in the United States, in 2015 this difference in exposure remained large at 0.5 µg/m3 (Currie, Voorheis and Walker, 2020[233]). This unequal exposure to pollution may contribute to exacerbating the cycle of existing socioeconomic and ethnic inequalities. In fact, early evidence from pollution reductions due to the CAA 1990 amendments suggests that racial gaps in prenatal pollution exposure may explain as much as 20% of the current Black-White earnings gap (Colmer, Voorheis and Williams, 2021[234]). Thus, legislation specifically targeting counties and areas with the highest levels of air pollution may help reduce income disparities and improve the long-term outcomes of vulnerable groups.

6.2. Gender disparities

66. The effects of adverse environmental conditions on cognitive ability may also differ by gender. Males are thought to be more susceptible to detrimental intrauterine environments (Sandman, Glynn and Davis, 2013[235]; DiPietro and Voegtline, 2017[236]), and may therefore experience larger cognitive deficits due to high temperatures and air pollution exposures during gestation. A review of the health effects of pollution throughout the life course suggests that while during gestation and early childhood, boys are more susceptible to the health effects of pollution, women may be more vulnerable in adulthood, potentially due to greater exposure in socially derived roles (e.g., pollutants present in cleaning products or cooking fumes) (Clougherty, 2010[237]). This is supported by recent findings that women experience higher rates of and more severe asthma symptoms than males *after* puberty, but not before (Dharmage, Perret and Custovic, 2019[238]; Zein and Erzurum, 2015[239]). Furthermore, air pollution could influence the mental health and well-being of men and women by shaping their fertility (Carré et al., 2017[240]) and, by doing so, shape their ability to engage effectively in cognitively demanding tasks. Although air pollution influences the reproductive chances of both men and women, the impact of impaired fertility on mental health and well-being could differ by gender.

67. However, the distributional impacts on cognitive ability by gender are likely to differ based on the underlying mechanisms by which they exert their effects, as well as country-specific social and institutional differences. In India, school-aged girls experience larger cognitive declines due to contemporaneous pollution conditions, which may be explained in part due to their lower baseline levels of health and education (Balakrishnan and Tsaneva, 2021[86]). In Israel, the effects of pollution on performance on high-stakes exams are between two and four times larger for boys than girls, consistent with a significantly higher incidence of asthma in male Israeli adolescents (Ebenstein, Lavy and Roth, 2016[6]). However, performance losses due to pollution have a greater detrimental impact on the likelihood of matriculation, enrolment and completion of postsecondary education among girls than boys. Similarly, while estimates from the Philippines and Mexico suggest that pollution in-utero and early childhood affects the cognitive ability of boys and girls equally, the effects on women in terms of reduced schooling and income are more salient during the transition to the labour-market (Molina, 2021[58]; Peet, 2021[55]).

68. Further into late adulthood, cumulative exposure to high levels of particulate matter in China have larger effects on the cognitive ability of older males in comparison to females, an effect which is thought to operate by greater white matter abnormalities due to pollution in the brain of males as compared to females (Zhang, Chen and Zhang, 2018[7]).

7 Limitations to estimates

69. There are several limitations to the estimates presented in this paper. First, although attention was paid to present estimates from studies with identification strategies that aim to capture causal effects, the quality of the empirical studies is not homogeneous. In particular, because of the inherent complexity associated with partitioning the unique contribution of exposure to averse environmental conditions on long-term outcomes – such as the risk of suffering from dementia in old age – evidence based on individual studies and modelling approach may not adequately reflect underlying relationships. Moreover, even if unbiased, such estimates may have a large margin of error associated, such that effects, even when statistically significantly different from zero at conventional levels, could range from the very small to rather large.

70. As air quality is capitalized into housing prices (Chay and Greenstone, 2005[241]), residential decisions influence exposure to pollutants and are associated with several household characteristics such as socioeconomic status (SES) that are themselves associated with cognitive development and are difficult to account for (Sharkey and Faber, 2014[242]). Such location sorting can contribute to endogeneity bias and make causal interpretation difficult (Graff Zivin and Neidell, 2013[4]; Currie et al., 2014[54]). Avoidance behaviours as well as compensatory and protective investments can lead to an underestimation of the true magnitude of environmental conditions on cognition/learning by biasing estimates downwards. However, they also indicate the net magnitude of the effects as they are given current adaptation strategies (Graff Zivin and Neidell, 2013[4]). Behavioural adaptations can also be exploited for designing policies.

71. Measurement error in matching achievement and productivity data to individual pollution exposures is a potential additional source of bias. While many industrialized countries have advanced and widespread pollution and weather monitoring systems, these stations may not be in ideal locations for precise pollution or temperature assignment (Park et al., 2020[43]). Studies that evaluate medium and long-term effects with community-level pollution data often rely on assumptions that all students have had the same early life environmental exposures, discounting the possibility of migration or differential activity and residential patterns between students which is likely to misrepresent personal exposures (Sanders, 2012[57]; Marcotte, 2017[64]).[31] Many estimates only include one or a few air pollutants, which allows for the possibility for omitted variable bias and attributing cognitive effects to the 'wrong' culprit, as air pollutants (and temperature) have significant interactions with each other (Graff Zivin and Neidell, 2013[4]). This is often due to a lack of data on certain toxins, and may be problematic for examining the prevalence of various pathways through which the effects occur, and understanding the magnitude of the effects of individual toxins relative to others (Ebenstein, Lavy and Roth, 2016[6]).

72. Finally, the paper details evidence on the effects of temperatures and air pollution on cognitive development but does not review evidence on other environmental conditions. Despite important reductions in air pollution over the past decades, some communities continue to experience high levels of

[31] Some studies have thus relied on land-use regression models (e.g., Guxens et al., 2014; Forns et al., 2018) or interpolation techniques (e.g. Miller & Vela, 2013) to estimate exposures, with notable exceptions such as Currie et al. (2009b), who assign pollution exposure during pregnancy based on maternal residential addresses and Perera et al. (2003) and their follow-up studies which ask mothers to carry around a small personal air pollution monitor in their backpacks during pregnancy.

air pollution, and in all OECD countries average levels of air pollution are well above recommended thresholds. Moreover, extreme temperature events are becoming more common. Nonetheless, however important, these are only two of the environmental conditions that, if unaddressed, could negatively impact cognitive development and human capital accumulation. For example, environmental disasters such as earthquakes and floods have similarly been found to induce health shocks and reduce cognitive performance in countries such as Pakistan and Ecuador (Andrabi, Daniels and Das, 2021[243]; Rosales-Rueda, 2018[244]). Additionally, exposure to nuclear fallout and heavy metals such as lead, even at relatively lower levels than previously considered harmful, can negatively impair IQ and cognition (Almond, Edlund and Palme, 2009[245]; Black et al., 2019[246]; Lanphear et al., 2005[247]). Water pollution is also a growing concern. Chemical pollutants, such as polybrominated diphenyl ethers (PBDEs), which are added to some manufactured products such as furnishings and electronics, can build up in the drinking water of some fish and mammals and have raised concerns regarding their link to neurodevelopment (Vrijheid et al., 2016[248]) (Lam et al., 2017[249]) . This increased awareness of the impact of a variety of environmental pollutants on a diverse set of outcomes relevant to human health is important in order to encourage progress in modelling their true social and economic costs (Alberini, 2017[250])(OECD, 2017).

8 What next? Policy relevant research gaps

73. Estimates suggest that, compared to children born in the 1960s, children born at the onset of the COVID-19 pandemic in 2020 may experience 6.8 times more heatwaves across their lifetime. Should countries be successful in limiting warming to 1.5 degrees Celsius above pre-industrial levels, they can reduce additional lifetime exposure to heatwaves by 45% (Global Commission on Adaptation, 2019[251]). This work makes clear that on top of actions aimed at reducing global warming, it is important to consider a variety of actions ranging from system-level policies to classroom-level adaptations to reduce the impact of temperature extremes and air pollution on learning and cognitive development.

74. Understanding the link between outdoor conditions, the indoor environment and human adaptation is crucial if societies will be able to adequately prepare for the climate change challenges of the coming decades. The body of empirical evidence in this area is growing by the day and complex frameworks are being developed to fully consider the effects climate change may have on indoor environmental quality, health, school performance and productivity (Vardoulakis et al., 2015[252]; Fisk, 2015[253]; Salthammer et al., 2018[254]; Steinemann, Wargocki and Rismanchi, 2017[255]; Deschenes, 2014[256]). This paper makes clear that any new changes in technology induced by climate change adaptation must consider the impact on human capital (Nazaroff, 2013[257]; Fisk, 2015[253]). In considering this impact and the costs that will be incurred due to lost skill development on individual- and societal-levels, further research must fill several gaps.

75. First, the estimates currently available and discussed in this paper are those of pollution and temperature considered independently and at baseline. While there is some evidence of an interactive effect on mortality outcomes (Cheng and Kan, 2012[258]; Burkart et al., 2013[259]; Tian et al., 2018[260]) evidence on less extreme outcomes such as asthma and particularly cognition remain limited (Anenberg et al., 2020[261]). Given that rises in temperature may also indicate rising surface-level ozone concentrations (Shen and Mickley, 2017[262]), potential for multiplicative effects on health and cognition should be explored. This is important because if the same levels of air pollution are associated with worse outcomes at higher temperatures, the expected benefits arising from successful policies implemented in the past decades to improve air quality may not materialise. Furthermore, alternative adaptation strategies should also be factored in modelling exercises. For example, it is now increasingly recognised that behavioural responses to increased temperatures - such as spending more time indoors – impact indoor pollution concentrations (Nazaroff, 2013[257]). Designs meant to reduce energy usage led to poor indoor air quality in the past, with potentially far reaching consequences for individual health and human capital accumulation. A comprehensive understanding of the impact on human health and cognitive development of heat exposure, pollution exposure and adaptation responses is a pre-condition for the development of effective solutions. Furthermore, considering the effects of adverse environmental conditions on human capital development is essential to estimate the economic viability of interventions. There are no precise estimates of the economic consequences of lower human capital development due to adverse environmental conditions. However, because human capital is key to economic growth, the economic benefits associated with higher levels of human capital in the absence of adverse environmental conditions are likely to go a long way

towards offsetting the costs associated with the implementation of policies aimed to reduce environmental degradation.

76. Second, just as policy analysts recognise that climate change and climate change mitigation policies, by inducing profound structural changes could lead to job displacement and reallocation creating vulnerability for workers in some industries, the distributional impact of air pollution, temperatures and of adaptation strategies should be explored further. For example, it is possible that men may experience greater cognitive reductions in school as a result of adverse environmental conditions but that women bear a greater burden in the labour market (Ebenstein, Lavy and Roth, 2016[6]). As schools in socio-economically disadvantaged neighbourhoods are often those with greater pollution exposure, with fewer natural cooling (trees and parks nearby outside of city centres), and tight budgets, financial support to cover the cost of the maintenance and filter replacement of air filters and air conditioning should be considered alongside capital investment in the appliances.

77. Additionally, the impact of in-utero and early childhood exposure to high temperatures on school age cognitive performance as well as behavioural and emotional outcomes has not been fully explored in the literature. Impaired mental health may also be an additional pathway through which environmental conditions affect cognitive skill accumulation (Chen, Oliva and Zhang, 2018[263]). Behavioural adaptations to temperature and pollution such as increased parental and teacher investments are costly and may further exacerbate inequalities due to unequal resources, but the magnitude of their costs and the extent to which they worsen existing inequalities is not fully understood. Finally, while some studies estimate the cumulative effects of environmental conditions for school-aged children, apart from estimates from China (Zhang, Chen and Zhang, 2018[7]; Zhang, Chen and Zhang, 2021[78]), the long-term cumulative impact on adult cognitive skills in other countries remains largely unknown.

78. Climate change is one of the greatest threats facing humanity, with far-reaching and devastating impacts on people, the environment, and the economy. Lessons from the past suggest that while technological innovations and human progress created many of the environmental problems that plague our earth, they also have the potential to solve these problems. The capacity to solve highly complex problems, to process vast amounts of information, to engage in interpersonal communication and social cooperation are some of the distinct human abilities that have led to human progress over millennia. What this work makes clear is that climate change and persistent levels of environmental pollution not only threaten human health but also human cognition and, with it, our very own capacity for averting environmental degradation.

Annex A. Supplementary information

Table A.1. Major air pollutants, their sources and their effects on health

Pollutant	Outside Source(s)	Health symptoms
PM2.5 fine particulate matter (2.5 microns or smaller)	variety of human activity – e.g., traffic, construction, fires, reactions with other pollutants	Short-term health symptoms include eye, nose, throat and lung irritation, coughing, sneezing, runny nose and shortness of breath Long-term health symptoms include asthma, respiratory disease and premature morality
PM10 coarse particulate matter (10 microns or smaller)	traffic, domestic fuel burning, wildfires, natural dust and salt, construction; soil and dust resuspension	Short-term health symptoms include coughing, wheezing Long-term health symptoms include high blood pressure
CO carbon monoxide	motor vehicles that burn fossil fuels; thermal combustion is the most common source	Fatigue, dizziness, headache, confusion, and sometimes loss of consciousness due to carbon monoxide poisoning
NO2 nitrogen dioxide	Ground level emissions of fossil fuel burning; industrial sources; transport sector	Irritant to eyes, nose, throat and respiratory tract
O3 ozone	chemical reaction between oxides of nitrogen and VOCs; high temperatures accelerate its production	Exacerbation of asthma, difficulty breathing, inflamed and damaged airways
SO2 sulphur dioxide	burning of fossil fuels (coal, oil, diesel) and other industrial activities	Asthma, wheezing, shortness of breath, chest tightness, respiratory irritation, bronchitis
PAH mixtures polycyclic aromatic hydrocarbons	motor vehicle exhaust, cigarette smoke, wood smoke, or fumes from asphalt roads; reactions with other pollutants (i.e., NO2, SO2); interactions with temperature	Lung cancer (due to inhalation), the formation of DNA adducts (DNA bound to a cancer-causing chemicals) via other ingestion methods.

Note: The sources and health symptoms aggregated in this table are those cited for each pollutant. There may be other sources and symptoms that are not included in this table.
Source: (Fan and Lin, 2011[264]; Abdel-Shafy and Mansour, 2016[265]; Curtis et al., 2006[266]; WHO, 2021[9])

Table A.2. Heat waves and their effects on health

	Health symptoms
Heat waves	Heat cramps, exhaustion, and dehydration; cardiovascular, respiratory, and cerebrovascular disease; worsening of pre-existing conditions such as diabetes, heat-related mortality

Note: The definition of a heat wave varies based on local climate. Generally, the World Health Organization defines a heat wave as a period of at least two days with temperature above the 90th percentile of the monthly distribution.
Source: (Hajat and Kosatky, 2009[267]; WHO, 2015[268])

Table A.3. Empirical studies of air pollution and cognitive tests

Author(s); source of variation	Location; Sample	Methods	Results
Bedi et al. (2021); wind-induced variation in PM2.5 exposure during a variety of cognitive exams.	Brazil; range of cognitive test results for 446 university students over 54 lab sessions during a 3-year period.	OLS and IV (wind direction and wind speed) controlling for meteorological conditions and year-month and day-of-week fixed effects.	a one-unit SD increase in PM2.5 on the day of tests is associated with a 15% SD drop in test performance measuring fluid intelligence.
Bharadwaj, P. et al.residual variation in the CO (and correlated pollutants)	Santiago, Chile; nationally standardised school test scores for 4th graders born 1992 – 2001 who have siblings for a total sample of 193,138 students.	OLS and siblings fixed-effects models controlling for demographic, time and seasonality variables, as well as ozone levels.	A one-unit SD increase in CO in the third trimester is associated with a 3.4% standard deviation decrease in 4th grade math scores.
Cho, H. (2021); day-to-day variation in PM10 levels during high-stakes high school exams	Korea; test scores on high-stakes university entrance exams of 290,859 high school seniors in 227 schools between 2010 and 2015.	OLS regressions include school- and year- fixed effects, and weather controls.	Taking a high-stakes test when one-hour average PM10 concentration is 75 g/m3 or above is associated with a 13% of a SD decline in reading scores relative to a concentration below 25 g/m3.
Ebenstein, A., V. Lavy and S. Roth (2016); PM2.5variation across the same student taking multiple high-stakes Bagrut exams	Israel; all Bagrut exams taken by high schoolers between 2000 and 2002 for a total sample of ~400,000 exams taken by 55,796 students at throughout Israel.	Student fixed-effects models regress Bagrut exam scores on average temperature at school at the time of testing and include student-, city-fixed effects and location, time, and weather controls.	A one-unit SD increase in PM2.5 (denoted by AQI) during test taking of high-stakes exams results in a 3.9% reduction in student performance.
Graff Zivin, J. et al. (2020); variation in wind-direction during agricultural fires as a proxy for PM2.5 exposure	China; scores on high-stakes National College Entrance Examination (NCEE) from 2005 - 2011 for a sample of ~1.4 million test-takers from 159 counties.	Regress NCEE test scores on the number of upwind and downwind fires during high-stakes tests within a county controlling for county- and province-by-year-by-track fixed effects.	A one-unit SD increase in PM2.5 exposure (+29.6 g/m3) proxied by agricultural fires) during high-stakes NCEE lowers average test scores by 13.6% SDs.
Heissel, J., C. Persico and D. Simon (2020); variation in within-student wind patterns for schools 0.4 miles upwind or downwind major highways during compulsory schooling due to a policy-induced move	United States; math and reading results of the Florida Comprehensive Assessment Test (FCAT) for students in grades 3 to 10 who took the tests between 2001 and 2012, for a total sample of 107,463 students.	Differences-in-differences & fixed-effects models linking within-student differences in test scores before versus after changing schools for children who attend a downwind relative to an upwind school, controlling for a variety of time-varying and time-invariant school and year characteristics, individual characteristics, and the number of highways within 1 mile.	Attending school downwind of a major highway (approximately a 25% increase in pollution) typically leads to an annual learning decline of 4% standard deviations
Marcotte, D. (2017); variation in within-student exposure to ozone and PM2.5 throughout test-taking in kindergarten and elementary school.	United States; math and reading score tests of children in kindergarten, 1st and 2nd grade who started kindergarten in 2010-11 and were assessed twice per each year thereafter from 20 counties across the United States for a total sample of 1450 students.	A series of regressions linking math and reading performance to pollution levels at the time of testing, including student-fixed effects and controlling for local economic and weather conditions and family socioeconomic characteristics.	A 100% increase in PM2.5 on the day of tests is associated with declines of 1 - 2% on math and reading tests for elementary school students and a 100% increase in ozone is associated with declines of 10% for asthmatic students (with no significant effects found for non-asthmatics).
Molina, T. (2021); within-municipality variation in thermal inversion exposure across birth cohorts	Mexico; scores on Raven's fluid intelligence scores who were at least 15 years old when they took the test and at a mean age of 17.2, for a total sample of 10,848 individuals.	Regress test scores on thermal inversion counts over several three-month periods prior to and after a child's birth, controlling for month-, year-, and municipality-fixed effects and weather variables.	In Mexico, a one-unit SD increase in thermal inversions, a proxy for CO and PM10 pollution, during the second trimester of pregnancy is associated with declines of 11% SDs on Raven's fluid intelligence.
Persico, C. and J. Venator (2020); variation in the timing of Toxic Release Sites (TRI) opening and closing in	United States; test scores on the Florida Comprehensive Assessment Test (FCAT) for grades 3 through 12 for total test score observations of ~650,000.	Event study and differences-in-differences, regressions control for student-fixed effects and zip code and time-fixed effects.	Attending a school within 1 mile of TRI sites, which release large amounts of pollution into the local air and water, is associated with 2.4% lower test scores during and

Florida between 1999 and 2012			after the year of the site opening.
Persico, C., D. Figlio and J. Roth (2020); variation to a within-family comparison of children conceived before, during, and/or after Superfund site cleanup	United States; FCAT scores of children child born in the state of Florida between 1994 and 2002 and educated in Florida public schools from 1996 through 2012 in families with at least one child conceived during and one after Superfund site clean up (N = 12, 546 families)	Treatment-on-treated (TOT) models that assign initial Superfund proximity to all siblings within a family, controlling for family fixed effects, regressions control for birth month and year, birth order, birth spacing, and gender	Children conceived to mothers living within 2 miles of a Superfund site before it was cleaned have between 6.8% and 11% of a standard deviation lower test scores than their siblings who were conceived after the site was cleaned.
Roth, S. (2018); within-student day-to-day variation in indoor pollution exposures during multiple college exams.	United Kingdom; exams taken by university students from a UK university during the 2012/2013 school year for a total sample of 2,418 students and 11,443 exam observations.	Regression estimates subject-, student- fixed effects, controlling for time-varying factors and weather variables an CO2 to proxy human behaviour.	A one-unit SD increase in PM10 reduces performance on university final semester exams by 6.5% of a SD.
Sanders, N. (2012); county-level variation in the severity of the 1980's recession and related changes in manufacturing employment	United States; cohorts born in 1979 – 1985 in at 416 schools in 30 counties for a total sample of ~100,000 per year.	OLS and 2SLS link changes in county-level annual TSP during year of birth to school-level tenth-grade standardised test scores. TSP levels are instrumented by changes in manufacturing employment.	A one-unit standard deviation decrease in TSP during the year of birth is associated with between 2% and 6% of a SD increase in high-school test scores for OLS and IV estimates, respectively.
Stafford, T. (2015); quasi-natural experiment where renovations explicitly designed to improve IAQ were completed	United States; grades 3 through 5 test scores on nationally administered tests for 65 schools that received IAQ renovations between 2002-2007.	Individual-fixed effects regressions for each type of 6 total renovations link performance on normalised elementary school tests after renovation, including controls for unobserved school, student, time and district effects.	The average ventilation improvement project, priced at about USD 300,000 improved math scores by 7% SDs and reading scores by 11% of a SD, while the average mold remediation project (~ USD 500,000) improved math and reading scores by 15% and 14% of a SD, respectively.
Zhang, X., X. Chen and X. Zhang (2018); variation in transitory and cumulative air pollution exposures for the same individuals over time	China; nationally representative sample of math and verbal test scores from China Family Panel Studies (CFPS) survey rounds between 2010 and 2014 for a total of 31,959 observations.	Match city-level air pollution exposures (API) during the time and location of test taking with for various age groups to estimate individual-fixed effects of cumulative pollution exposure, controlling for contemporaneous exposure and demographic, weather and time variables.	A one-unit SD increase in the 7-day mean of China's Air Pollution Index (API) is associated with lower verbal test scores of 2.6% of a SD, while a SD increase in the 3-year average API prior to test-taking is associated with a 10.8% of a SD decline.

Table A.4. Empirical studies of high temperatures and cognitive tests

Author(s); source of variation	Location; Sample	Methods	Results
Cho, H. (2017); school-level daily variation in summer temperature	South Korea; high-school seniors in 1729 schools in 164 cities for a total of ~1.3 million observations.	Cohort analysis; regresses test scores on the number of days temperature is in relative bins including school-, city- and year-fixed effects	An additional day with a maximum daily temperatures above 34 degrees Celsius during the summer (relative to range of 28 and 30 degrees Celsius) is associated with 4.3% and 6.5% of a SD reduction in math and English university entrance exams, respectively (with no significant effects on reading scores).
Garg, T., M. Jagnani and V. Taraz (2020); within-child variation of temperature on the day of tests	Andhra Pradesh, India; test-scores of school-aged children born between January 1994 and June 1995 (n = 1,008) and between January 2001 and June 2002 (n = 2,011) with at least 3	Regress math and reading test scores on the number of days on temperature on the day of the test including child-fixed effects and controlling for weather and time variables.	Ten additional days with average daily temperature above 29 degrees Celsius relative to between 15 and 17 degrees Celsius reduce math and reading test performance by between 2 and 3% of a SD.

	tests from YSL survey data.		
Zivin, J., S. Hsiang and M. Neidell (2018); random fluctuations in weather across test interviews	United States; nationally representative survey sample of children tested over age 5 in math and reading dimensions for a total sample size of 8,003 children.	Regress test scores on temperature on the day of survey and includes child-fixed effects, controlling for various location, time and meteorological variables.	Increasing the outdoor temperature from 22 degrees Celsius to 32 degrees Celsius on the day of testing is associated with 12% of a SD lower math test scores.
Graff Zivin, J. et al. (2020); variation in county deviations from the mean temperature after adjusting for shocks	China; students enrolled into university during 2005 – 2011 from 2227 counties for a total sample of ~ 2 million per year.	OLS regresses individual-level exam scores on daily average temperature of the 2 testing days in June, including county- and year- fixed effects and controlling for weather variables.	A one-unit SD increase in temperature (2 degrees Celsius) on the days of testing decreases test performance on NCEE high-stakes exams by 5.83% SD and decreases the probability of getting into tier-1 universities by 1.2%.
Park, R. (2020); within-student day-to-day and year variation in temperature during the week of June Regents exams	New York, United States; high-stakes Regents exam scores (on taken by NYC public school students between 1999-2011	Regresses standardised exam score on temperature near schools during exams including subject-, student-year-, and year- fixed effects, and weather and air quality controls.	A one-unit SD increase in temperature during exams is associated with 5.5% of a SD lower test scores and a 3% lower likelihood of graduating on time.
Park, R. et al. (2020); within-student variation in temperature over successive school years	United States; PSAT standardised test scores of high-school re-takers between 2001 and 2014 for a total sample of almost 10 million students.	Regresses math and reading PSAT scores of re-takers on the average maximum temperature experienced during school the year prior to testing to include student-fixed effects and controlling for a variety of potential confounders.	A one-unit SD increase in cumulative heat exposure (A .5 degrees Celsius hotter school year) in the year prior to the test is associated with lower math and reading PSAT scores by .2% of a SD.
Park, R., A. Behrer and J. Goodman (2020); variation in the timing of hot days within a given calendar year and within-country temperature fluctuations over time	International analysis; includes 58 countries that participated in PISA between 2000 and 2015;	Regressions link within-country temperature fluctuations over time to within-country fluctuations in PISA test scores, controlling for country- and time-varying confounders.	Ten additional school days with temperatures above 26.7 degrees Celsius per year lower performance on PISA exams by between 2% and 3% SDs.
Zhang, X., X. Chen and X. Zhang (2021); within-individual variations in exposure to extreme temperatures over eight years	China; cognitive test results from the China Family Panel Studies (CFPS) to all individuals aged 10 and above	Regressions link geographical location and temperatures and tests and include regressions include individual fixed effects, county fixed effects, year, month, and day-of-week fixed effects.	Exposure to temperatures above 32 degrees Celsius on the day of tests relative to a day in with temperatures between 22 and 24 degrees Celsius is associated with declines in math scores of 8.8% of a SD.

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