Heterogeneous Effects of Air Pollution on Physical Tasks: Evidence from Amateur Track and Field

Francesco Granella*

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Abstract

Although a large share of the world's population is employed in manual labor, our understanding of the productivity costs of air pollution for physically intensive work remains limited. This paper estimates the effect of fine particulate matter (PM 2.5) on purely physical tasks by analyzing half a million amateur track and field competition results, a setting where cognition plays a minor role. Exploiting the panel nature of the data and high dimensional fixed effects, I find that a 10 $\mu g/m^3$ increase in PM 2.5 reduces performance by 1% of a standard deviation. The effect grows with the duration of effort, indicating that productivity losses may be larger for occupations requiring low-intensity and sustained effort, such as construction workers.

Keywords: Air pollution; Productivity; Health

JEL Classification: I18, J24, Q51, Q53

1 Introduction

A large share of the world's population is hired in manual labor, in both developed and developing economies. At the same time, air pollution is pervasive throughout the globe,

*Bocconi University and RFF-CMCC European Institute on Economics and the Environment. francesco.granella@phd.unibocconi.it. I thank Valentina Bosetti, Francis Dennig, Benjamin Jones, Frances Moore, Elena Verdolini, and participants at the annual meetings of the European Association of Environmental Economists (EAERE) and Southern Economic Association (SEA) for useful comments. This research was supported by the EU H2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no. 681228 GEMCLIME.

often at unhealthy concentrations. In urban centers, blue-collar workers can be exposed to high concentrations of industrial pollution as PM 2.5 easily penetrates indoor for its small diameter (He et al., 2019); in rural areas, unregulated biomass burning is a significant source of harmful airborne pollutants (Rangel and Vogl, 2018; Graff Zivin et al., 2020; He et al., 2020).

While a growing number of studies find that fine particulate matter (PM 2.5) reduces cognitive performance[1], to date the evidence on the causal effects of ambient air pollution on the physical component of tasks remains limited.[2] This paper estimates the effects of PM 2.5 on physical tasks where cognition plays a marginal role and task content is easily codified. I assemble a dataset on the universe of track and field competitions held in Italy from 2005 to 2019 and match individual performances with air pollution data. In this environment, young individuals repeatedly perform highly standardized tasks (running, jumping, throwing) under varying environmental conditions. Leveraging the panel structure of the data, I estimate the effect PM 2.5 on performance using a set of high dimensional fixed effects.

I find that an increase in PM 2.5 of 10 $\mu g/m^3$ reduces performance by 1% of a standard deviation, equivalent to a loss of one-third of a percentile in nationwide rankings. Conversely, ozone does not have a discernible effect when accounting for concentrations of particulate matter. The detrimental consequences of PM 2.5 on performance appear at medium level of concentrations between 25 and 50 $\mu g/m^3$. The overall effect is the same for males and females, and greater for high-ability athletes. While the data comes from competitions held in Italy, there are no apparent reasons for the link between air pollution and athlete performance to be specific to the Italian context.

I then investigate the effect of PM 2.5 by type of physical requirement to inform the productivity losses of common occupations. Short-lasting competitions require explosive

[1]Evidence covers standardized tasks such high-stake exams (Ebenstein et al., 2016; Persico and Venator, 2019; Graff Zivin et al., 2020) cognitive tests (Bedi et al., 2021), brain games (Nauze and Severnini, 2021), chess matches (Künn et al., 2019), and referee calls in baseball games (Archsmith et al., 2018). Air pollution, in particular PM 2.5, has also been found to interfere with decision making, more broadly defined. For instance, Burkhardt et al. (2019) and Bondy et al. (2020) find that PM 2.5 increases violent crimes, but not property crimes. Heyes et al. (2016) link increases in PM 2.5 in Manhattan with reduced returns in the New York Stock Exchange. Chen (2019) provides a detailed summary of the physiological and psychological pathways through which pollution is believed to affect cognitive performance and behavior.

[2]Beyond direct productivity losses, exposure to PM 2.5 reduces life expectancy. It is estimated the fifth leading cause of premature mortality worldwide (Cohen et al., 2017).

strength, whereas longer races require stamina and are more dependent on the pulmonary and cardiovascular systems, which, following the medical literature, bear most of the effects of PM 2.5 (Pope and Dockery, 2006).[3] In line with expectations, I find larger impacts of PM 2.5 on the performance of longer-lasting races. The results suggest that jobs requiring prolonged physical effort incur, under the same conditions, greater productivity losses than jobs requiring short bursts of intense exercise. Most athletes in the sample are below working age, thus the generalization of results to manual laborers should be done with care. Yet, to an extent, results can be informative for jobs with prolonged efforts: for instance, according to the Bureau of Labor Statistics, in the United States stamina is an important ability for as many as 8.5 million workers in the country (Table 9). Explosive strength is important for half a million workers.[4] More generally, 13.7% of all civilian jobs and 45.5% of jobs in Construction and Extraction require heavy work (Table 11) (U.S. Bureau of Labor and Statistics).

This paper enters the stream of literature on the consequences of air pollution on labor productivity. Several works have found that PM 2.5 hampers productivity in a variety of settings where physical effort is important, such as in a packing plant (Chang et al., 2016) or in textile and garment plants (Adhvaryu et al., 2018; He et al., 2019). Their external validity is however limited by the narrow scope. One exception is offered byFu et al. (2021), who expand previous work and estimate nationwide effects on short-run productivity for China's manufacturing sector. They report suggestive evidence that PM 2.5 reduce both cognitive and physical productivity. Nevertheless, generalization of results remain challenging without an understanding of the mechanisms at work. Unpacking the causal links is still work in progress. While the evidence on cognitive effects is growing (*e.g.* Ebenstein et al. (2016); Graff Zivin et al. (2020); Bedi et al. (2021); Carneiro et al. (2021); Nauze and Severnini (2021)), less is known about the impacts on physical productivity.

[3]The Occupational Information Network (O*NET) of the U.S. Bureau of Labor Statistics describes the abilities, defined as "enduring attributes of the individual that influence performance", required by 923 occupations, quantifying the importance and level required of each ability. It defines explosive strength as "the ability to use short bursts of muscle force to propel oneself (as in jumping or sprinting), or to throw an object". Stamina is defined as "The ability to exert yourself physically over long periods of time without getting winded or out of breath".

[4]Important is here defined as a 3 or more on a 1-5 scale from 'Not Important'(1) to 'Extremely Important' (5).

Sports have proven attractive grounds for economists to do research (Kahn, 2000) for their richness of data and, in particular, the availability of readily-observed productivity measures. As Archsmith et al. (2018) puts it, sports provide a "microcosm for things that might be happening more broadly in society", context rather than an object. For instance, several sports contexts have been used to link air pollution to productivity, providing new understanding of the mechanisms depending on the context, method, and analysis. Data on distance running has been employed to study peer effects (Emerson and Hill, 2018) and the gender gap in competitiveness (Frick, 2011). In the literature covering the productivity effects of air pollution, most papers have used data from professional athletes, for whom data is more abundant. Archsmith et al. (2018) finds that baseball umpires are more likely to make incorrect calls when exposed to higher CO and PM 2.5. Lichter et al. (2017) find that the productivity of football players is hampered by particulate matter.

Closest works to this paper are Marcus (2021), Austin et al. (2019), and Mullins (2018). Marcus (2021) studies the link between ozone and cardiopulmonary performance of school children aged 10 to 15, assessed yearly by the California Department of Education measured with a test of aerobic capacity. She finds that an increase in ozone from 0-25% of the U.S. National Ambient Air Quality Standards to levels above the safety standard increases the share of students with poor aerobic capacity by 5.4 percentage points. Austin et al. (2019) estimate the changes in cardiopulmonary fitness of students aged 8 to 14 in Georgia, USA, induced by the retrofitting of diesel school buses and the subsequent improvement in air quality inside the vehicles. They find that school district-average VO_2max would improve by 4% if a district retrofitted 100% of its fleet.[5]

Mullins (2018) estimates the effects of ground ozone, a pollutant often linked to heat and sunlight, on the performance of US collegiate track and field athletes.[6] In contrast to Mullins (2018), this paper assesses the impacts of PM 2.5, a pollutant that can penetrate indoor and is the fifth leading cause of premature death worldwide due to a combination of near-ubiquity and harming potential (Cohen et al., 2017).[7] In addition, I consider a

[5] VO_2max is the maximum rate that oxygen can be taken into and used by the body during exercise (Hill and Lupton, 1923).

[6] Sexton et al. (2021) use the same data as Mullins (2018) to study effect of heat on physical performance.

[7] In a robustness check, Mullins (2018) controls for multiple pollutants, including both coarse and fine particulate matter (PM 10 and PM 2.5), whose coefficient are not statistically significant. However, the

population of mostly amateurs, whose team membership or income (such as scholarship) are not tied to performance, diluting concerns of positive self-selection on fitness.[8]

The next section discusses the main characteristics of track and field competitions that are relevant to this study. Section 3 describes the data, and Section 4 presents the empirical strategy. Section 5 discusses results, and Section 6 the robustness checks. Section 7 concludes.

2 Track and field competitions as standardized physical tests

The use of sports data in economics is not novel (Kahn, 2000). Beyond the contributions of Mullins (2018) discussed above, the most similar work in this regard is Lichter et al. (2017), who quantify the effect of PM 10 on the productivity of professional soccer players, measured as the number of passes per match. However, the interaction of team strategies and individual responses does not allow for separating physical effects from behavioral responses, although they provide suggestive evidence that both factors are at work.[9] Productivity spillovers between players further complicate the attribution of individual productivity (Arcidiacono et al., 2017).

Ideally, a researcher could retrieve a pollution-physical productivity function asking subjects to perform a measurable and standardized task at randomly supplied pollution levels. Such an experiment would, however, raise ethical concerns of primary importance.

Track and field is a set of individual sports disciplines that require running, jumping, or throwing in a very standardized setting. Competitions are held on a stadium track, or its inner field, whose characteristics are regulated in detail by international standards (World Athletics, 2019). As an illustration, the inside lane of a running track must be 400 meters long, and each lane must be 1.22m $\pm$ 0.01m wide; equipment, such as hurdles and throwing implements, must respect standards of shape and weight (World Athletics,

latter are correlated as PM 10 is a superset of finer PM 2.5. Including both in the regression, Mullins (2018) ensures that the coefficient for ozone is not driven by particulate matter. On the other hand, it cannot be ascertained whether the lack of significance for PM 2.5 is explained by lack of causality, or standard errors inflated by the correlation with PM 10.

[8] With the exception of a few elite athletes, who are hired for a moderate stipend.

[9] Track and field competitions differ from road races as the former take place in standardized stadiums while the latter on unstandardized road courses. Guo and Fu (2019) find a negative effect of air pollution on the performance of marathon runners in races events in China. However, and self-selection out of a marathon, before or during the race, makes causal identification challenging.

2020). Performance of all track events (foot races) are measured electronically, whereas all field events (jumps and throws) are measured manually yet precisely. While regular competitions can be held in indoor tracks, this study is restricted to outdoor contests as air quality in indoor tracks can be worsened in unmeasurable ways by the smoke of starting guns and can differ substantially from outdoor conditions. Road competitions such as marathons are excluded from this study as they take place on non-standardized race courses.[10]

The cognitive efforts in track and field events are minimal. First, athletes compete individually, irrespective of the performance of other team members.[11] Second, they typically compete in running the fastest, jumping the longest or highest, and throwing the farthest. A notable exception is mid- and long-distance races. In conditions where victory is more important than timing, the stronger athletes might strategically slow down the race pace if they believe they have an edge in a closing sprint. These conditions are most common at the end of the sports season when peak events are held; throughout the season, strategic races are comparatively less common as athletes chase qualifying timings for championships of varying degrees. Section 6 shows that results are not driven by mid- and long-distance events.

Males and females are usually equally represented and perform the same or very similar tasks (see Figure 7 in Appendix for a breakdown of types of competitions by gender). This contrasts with other occupational contexts in the literature on pollution and physical performance. For instance, among agricultural laborers studied by Graff Zivin and Neidell (2012) women are more likely to harvest crops that require less energy. The textile workers examined by He et al. (2019) are predominantly females.

In Italy, track and field competitions are supervised by the Italian Athletics Federation (FIDAL), which guarantees the uniformity and the validity of results through its referees. Athletes are members of clubs, whose catchment area is typically local and are independent of the school system. Entry barriers into the sport are very low, and competitions are comparably accessible across socio-economics backgrounds. However, it should be noted that the average age of track and field competitors is low, in the teens.

[10] The setting and design of road competitions make good environment to address different questions, such as peer effects in productivity (Emerson and Hill, 2018).

[11] With the exception of *relay* runs, in which each member of a team runs part of the race. Relays are excluded from this study.

Individuals positively select into the sport, but conditional on being in the sport, selection into competing is small.

3 Data

3.1 Track and field

The analysis uses data on the universe of regular track and field competitions held in Italy from 2005 to 2019. Results are systematically collected by FIDAL in near real-time and are made available on its website.[12] Most outdoor competitions take place from April to September.

Race distances and equipment vary with category and gender to accommodate for physiological differences. For example, the 100-meter dash is typically not run until 16 years old; the equivalent competition for a 14-year old is the 80-meter dash. To ensure comparability across events, age categories, and gender, results are transformed into a standardized score. For every event, years of age, and gender, I trim the top 99 and bottom 1 percent to exclude outliers, then demean and divide by the group standard deviation. The objective of field events is to jump or throw the farthest, whereas in races athletes aim for the shortest time. Therefore, the standardized result of races is reversed in sign so that greater values reflect higher performance for both jumps, throws, and races. The dependent variable is constructed as

$$\widetilde{Y}_{i,age(t),event,gender(i)} = \frac{Y_{i,age(t),event,gender(i)} - \mu_{age(t),event,gender(i)}}{\sigma_{age(t),event,gender(i)}} \cdot Event\ type_{event} \tag{1}$$

where $Y_{i,age(t),event,gender(i)}$ is the performance of athlete i on day t on event *event*. $\mu_{age(t),event,gender(i)}$ and $\sigma_{age(t),event,gender(i)}$ are the mean and standard deviation of results in groups defined by age, event and gender.[13] $Event\ type_{event}$ is equal to 1 for jumps and throws (field events), to -1 for races (track events).

[12] Data have been scraped from the FIDAL website at http://www.fidal.it/.

[13] In a comparable setting, Mullins (2018) standardize results with respect to world records. However, world records do not exist for many events in which younger athletes participate.

The standardization leads to a straightforward interpretation of regression results: a change in standardized score $\widetilde{Y}$ is equivalent to a change in unstandardized result Y as percent of a standard deviation in the reference group:

$$\Delta\widetilde{Y}_{i,age(t),event,gender(i)} = \frac{\Delta Y_{i,age(t),event,gender(i)}}{\sigma_{age(t),event,gender(i)}}.$$

FIDAL only records information on the city in which races have been held, though not on the location of the stadium. However, it maintains a geo-localized database of track stadiums in Italy. To precisely assign pollution readings to race days, I assign to each city, whenever possible, the geographic coordinates of track stadiums. In case a city contains more than one stadium, and it is impossible to assign results to a specific one, that city is excluded. Thus, a few stadiums are excluded from the sample.[14] The location of municipalities with track and field events in the final dataset is shown in Figure 1.

The result is an unbalanced panel of 95336 athletes, for more than half a million competition results in 3555 stadium-race days in 137 stadiums. Given the disproportionately large number of young athletes, the average age is 15.2, and about 90% of them take part in 59 competitions or fewer during the period and cities covered by the database.[15] About half of the events are races, 27% are jumps, 23% are throws. Female athletes make up 48% of the sample (Table 1).

3.2 Pollution

Daily pollution readings of PM 2.5 and ozone measured at monitoring stations come from AirBase, the European air quality database maintained by the European Environment Agency. Where hourly readings are available, a daily measure of PM 2.5 is constructed as the average of hourly measures from 10 AM to 6 PM, as track and field competitions take place mostly during the afternoon. The maximum reading is used instead for ozone. For every race day, PM 2.5 and ozone readings from monitoring stations within 10 kilometers are interpolated at track stadiums with inverse distance weighting. Hence, pollution in the data varies by stadium and day.

[14] The pollution monitoring network is denser in the more polluted and populated North (Figure 6).

[15] Data for a large number of athletes aged 35 and older had to be discarded for lacking a precise date of birth.

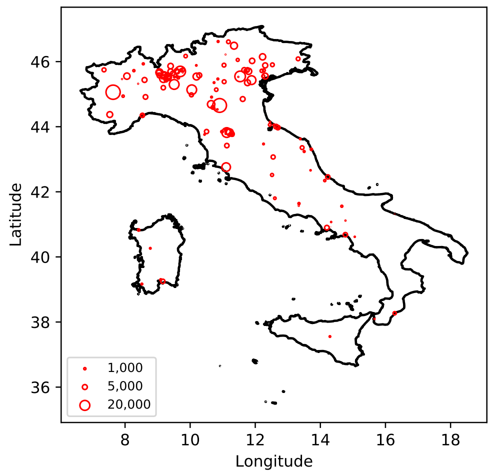

Figure 1: Location of Italian track and field stadiums in the data. Circle size indicates the amount of observations per each stadium.

Table 1: Descriptive statistics

	Mean	Std. Dev.	Median	Minimum	Maximum	N.
Std result	0.03	0.98	0.09	-5.66	3.39	553,171
PM 2.5	14.35	8.36	13.00	0.00	147.04	553,171
Ozone	108.31	28.36	106.40	7.00	247.45	509,494
Female	0.48	0.50	0.00	0.00	1.00	553,171
Age	15.24	3.45	14.78	5.30	40.37	553,171
Temp. max	23.94	5.06	24.32	5.64	37.52	553,171
Precipitation	2.43	5.21	0.19	0.00	48.49	553,171
Wind	2.04	0.76	1.95	0.13	7.95	553,171
Wind assist	0.02	0.55	0.00	-7.50	8.20	553,171
Duration, minutes	0.84	2.35	0.00	0.00	29.70	553,171

Note: Standardized competition results *Std result* are defined as results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group. PM 2.5 and ozone are expressed in $\mu g/m^3$; temperature in degree Celsius; precipitation in millimeters; wind in m/s.

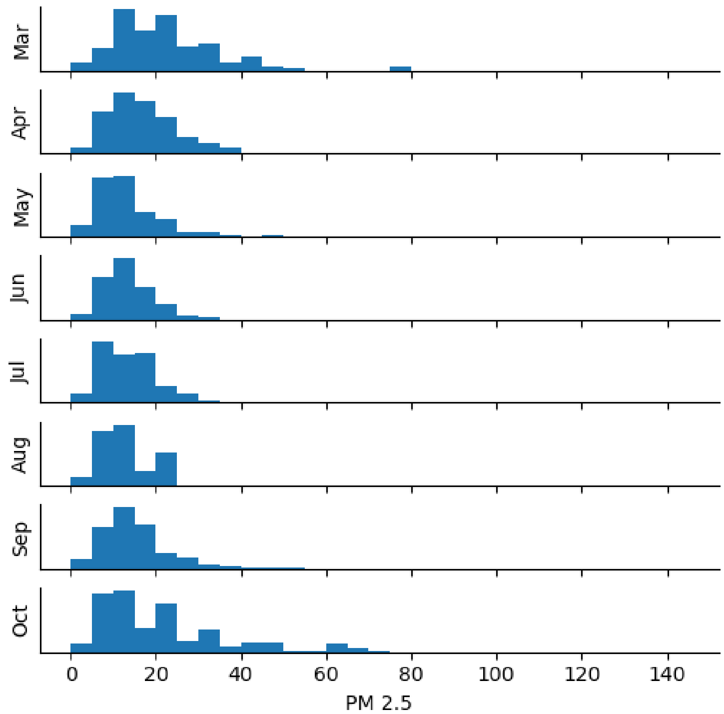

Figure 2: Within-month distribution of PM 2.5. Most competitions occur from April to September, when concentrations of PM 2.5 are lower.

A considerable share of the Italian population is exposed to harmful levels of air pollution. According to the European Environment Agency, 75% of the urban population in Italy was exposed to concentrations of PM 2.5 above EU standards (Ortiz, 2020). The more densely populated Northern regions are some of the most polluted regions in OECD countries. However, track and field competitions take place mostly from April to September, when concentrations are lowest. The average PM 2.5 concentration in the data is 14.4 $\mu g/m^3$, and surpasses the EU annual limit value of 25 $\mu g/m^3$ in about 9% of observations (Figure 2).

3.3 Weather data

The performance of track and field athletes is sensitive to environmental conditions beyond air pollution, such as temperature, relative humidity, precipitation and wind. At the same time, atmospheric conditions are key to the process of pollution formation, transport and dispersal.

I combine performance data and pollution readings with atmospheric conditions from ERA5-Land hourly reanalysis data on a 0.1° by 0.1° grid (Copernicus Climate Change Service, 2019). I construct measures of mean temperature, total precipitation, mean wind speed, and mean relative humidity from 12 PM to 9 PM. Like air pollution, weather conditions are interpolated at stadiums with inverse distance weighting.

Performance in a number of events is particularly susceptible to the wind blowing in favor or against the direction of an athlete.[16] International standards mandate that results in these events cannot be valid as a record on any level if the tailwind exceeds 2 m/s. However, results are still valid for establishing rankings within the competitions. Thus, wind speed during such events is measured inside the stadium with anemometers and recorded with individual results. It can take positive values (tailwind) or negative ones (headwind). For all other events, the variable is set to zero. To distinguish it from the meteorological wind described above, I will refer to this variable as *wind assist*.

4 Empirical strategy

The richness of the data allows identifying the effects of PM 2.5 on track and field competitions using a high-dimensional set of fixed effects. First, I exploit the panel nature of the data and include individual fixed effects. Athletes compete multiple times at varying environmental conditions throughout their career. The analysis relies on variation in performance and air pollution within individuals.

Second, to adjust for the confounding role of atmospheric conditions, I introduce a flexible specification of weather variables. Controls include wind assist, fixed effects for 2° C bins of maximum temperature and their interaction with wind speed, relative humidity, and binned precipitation.[17]

[16] Namely: races until 200 meters of length, the triple jump and the long jump. The benefit or burden of wind blowing is clear in events where the athlete moves in one direction. When races involve running one or more laps of a track, a stable wind blows cyclically both in favor and against athletes.

[17] Temperature bins at extreme temperatures, with fewer observations, are wider. Bins are constructed as: (0 10], (10, 14], (14, 16], (16, 18], (18, 20], (20, 22], (22, 24], (24, 26], (26, 28], (28, 30], (30, 32], (32, 34], (34, 36], (36, 40]. Cumulative precipitation in millimiters is binned in the following intervals: no precipitation, (0,1], (1, 5], (5, 10], (10, 100].

Third, concentrations of PM 2.5 are lowest during summer, when the most important competitions are held and the sport season peaks. The relationship between PM 2.5 and performance might be downward biased unless the two trends are accounted for. For this reason, all specifications include fixed effects for year, week, and day-of-the-week.

Finally, stadiums and their locations may correlate in unobserved ways with performance and pollution levels. A large city might host high-level competitions and suffer from high levels of pollution, for instance. I include stadium fixed effects to account for stadiums' constant characteristics, their surroundings, or the competitions they host. Athletes can travel to other cities to compete. I interact stadium fixed effects with fixed effects for athletes' team, a proxy for the city of origin. Given that Italian track and field teams are predominantly local, the interactions capture changes in performance caused by traveling from the team's home city to the stadium, and any potential home advantage. Two thirds of the overall variation in PM 2.5 and half of the variation in performance come from within individuals-stadiums cells, further reducing the risk of confounding effects caused by traveling (Figure 12 in Appendix) .

Most competitions take place in warm months, when solar radiation accelerates chemical reactions to form ozone, a pollutant known to irritate lung airways and increase respiratory problems (Neidell, 2009), and reduce aerobic capacity (Mullins, 2018; Marcus, 2021). Given the negative temporal correlation with PM 2.5, omitting ozone from Equation 2 may lead to underestimation of the true effect of PM 2.5 on performance. All specifications adjust for concentrations of ozone.

The baseline specification then looks like:

$$\begin{aligned}\tilde{Y}_{i,s,t} =& \beta_1 PM2.5_{s,t} + \beta_2 Ozone_{s,t} + Time'_t\gamma_1 + Weather'_{t,s}\gamma_2 + \gamma_3 Wind\ assist_{i,s,t} \\ &+ \alpha_i + S_s + C_{c(i,t)} + S * C_{s,c(i,t)} + \epsilon_{i,s,t}.\end{aligned} \tag{2}$$

The dependent variable $\tilde{Y}_{i,s,t}$ is the standardized results described in Equation 1. Subscript i, s, and t respectively index individuals, stadiums, and time. For ease of notation, I omit subscripts indexing different competitions of the same individual on the same day.[18] The main parameter of interest is β_1. The vector $Time_t$ contains time-

[18]Only $\tilde{Y}$ and $Wind\ assist$ vary within an individual in a given day.

specific fixed effects and the vector $Weather_{t,s}$ contains the flexible weather controls. $Wind\ assist_{i,s,t}$ is the wind assist measured inside the stadium with anemometers. α_i indicates individual fixed effects. S_s, $C_{c(i,t)}$ and $S*C_{s,c(i,t)}$ are respectively stadium fixed effects, team fixed effects, and their interaction. Standard errors are clustered at the stadium-date level.

5 Results

Table 2 presents results for the baseline specification. I find that a 10 $\mu g/m^3$ increase in concentrations reduces performance by 1% of a standard deviation. For the median performance, this is equivalent to the loss of a third of a percentile in nationwide rankings. It should be noted that that most competitions occur in warmer months when pollution levels are relatively low.[19] Indeed 91% of performances in the data happen below 25 $\mu g/m^3$, the annual limit value set by the European Union, and more than half below 15 $\mu g/m^3$.

Column (2) tests whether the result is driven by the correlation between ozone and PM 2.5. Since fewer stadiums are within a 10 km range of an ozone monitoring station, the sample size is slightly reduced. The findings are partially at odds with Mullins (2018): in an environment with higher levels of both ozone and PM 2.5, I find no statistically discernible effect of ozone, conditional on concentrations of PM 2.5. On the other hand, he finds a discernible negative effects of ozone only for endurance events. I show in Section 5.1 that while performance losses attributable to both PM 2.5 and ozone increase with duration of effort, a proxy for reliance on the cardio-pulmonary system, the effect for PM 2.5 is substantially stronger and still discernible for short-lasting events. For comparison with studies on the effects of air pollution on cognitive abilities, Ebenstein et al. (2016) find that a 10 $\mu g/m^3$ increase in PM 2.5 is associated with a reduction of 3.9% of a standard deviation in the score of high-stake school exams in Israel. Carneiro et al. (2021) estimate the relationship between PM 10, particulate matter smaller than 10 μm and including PM 2.5, and results in Brazil's nationwide university entrance examinations. They find

[19]The average effect on performance of increase in PM 2.5 of 10 $\mu g/m^3$ is comparable to the effect of a reduction in maximum daily temperature from 24-26 degrees to 10-14 degrees (Figure 8 in Appendix). As discussed in Section 3.3, the daily maximum temperature is a better measurement of the temperature to which athletes are exposed.

that an increase of 10 $\mu g/m^3$ of PM 10 on the day of examinations leads to a reduction of 8% of a standard deviation in student' scores. When PM 10 is above 20 $\mu g/m^3$, the effect is 13%. According to Roth (2022), a 10 $\mu g/m^3$ increase in indoor PM 10 reduces test scores London-area university students taking high-stakes exams by approximately 3% of a standard deviation. Bedi et al. (2021) runs grammatical reasoning test in a lab with university students, and find that +10 $\mu g/m^3$ in PM 2.5 reduce scores by 3%.

Table 2: The impact of PM 2.5 on physical performance. Main specifications.

	(1)	(2)
	Std result	Std result
PM 2.5	-0.0010***	-0.0010**
	(0.0004)	(0.0004)
Ozone		-0.0002
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	553171	507718

Note: The table shows the effects of contemporaneous PM 2.5 on physical performance, measured as track and field competitions results. The unit of analysis is the competition result of an individual. The dependent variable is standardized competition result, defined as results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group. PM 2.5 and ozone are expressed in $\mu g/m^3$. *Time* indicates year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. Standard errors are clustered at the stadium-date level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5.1 Aerobic and anaerobic activities

Next, I examine heterogeneous effects by duration of effort, a proxy for the reliance on oxygen intake and on the respiratory system. At low intensities of effort, the human body produces energy through the combustion of oxygen and fuel,[20] releasing carbon dioxide

[20]Glucose, glycogen, fats, and proteins.

and water as byproducts. This energy production process is termed "aerobic" for the usage of oxygen. While efficient, it is relatively slow as it relies on the circulatory system to deliver oxygen to the working muscles before producing. When significant energy is required for a short burst of activity, muscles fall back on the internal storage of fuel and rapidly but inefficiently produce new fuel. Lactic acid, a byproduct, accumulates until force generation and energy production are inhibited. This energy production process is termed the "anaerobic" pathway as it takes place in the absence of oxygen (Spurway, 1992).

Anaerobic and aerobic pathways are not mutually exclusive, and which supply route is prioritized depends in part on the intensity of the work and partly on the duration of the work. [21] In 400-m track running, which on average lasts about a minute in my data, the anaerobic (aerobic) component is responsible for approximately 40/60% for males and 45/55% for females; in 800-m running (2 and a half minutes in my data) the contribution shifts to 60/40% and 70/30% for males and females respectively (Duffield et al., 2005).

The main hypothesized channel through which PM 2.5 alters the body's normal functioning is through inflammation in the lungs and reduced oxygen intake (Pope and Dockery, 2006).[22] The expectation is that longer-lasting competitions, where oxygen intake is an important element, will have larger losses to PM 2.5.

Following this rationale, I compute heterogeneous effects by the typical duration of a competition, calculated as the average duration of a given event by age and gender. Figure 3 shows that the marginal effect of PM 2.5 on performance is negative and increases in magnitude as the average duration of an event increases. The effect is twice as large for events lasting on average 4 minutes than for very short events (Table 3).[23] The negative effect of ozone on performance also grows with the duration of effort, consistent with Mullins (2018); however, the magnitude is substantially smaller and statistically discernible only for competitions that last on average 3 minutes or longer. This suggest that ozone affects mostly aerobic activities.

[21] Intensity and duration are inversely proportional, as the accumulation of lactic acid limits energy production

[22] Some particles can pass from the airways directly into the bloodstream (Brook et al., 2010)

[23] The coefficient for duration is positive and significant. Recalling that the identifying variation is within-individual, this means that, on average, individuals perform better, relative to themselves, in longer-lasting events.

While generalization of results should be done with care, given the young age of individuals considered, the estimates suggest that tasks relying on pulmonary system and oxygen intake bear greater costs of air pollution. The findings can be seen in light of the work done by the US Bureau of Labor Statistics, which for each of almost a thousand occupations defines the importance of different physical abilities, and the level of ability required. According to the Bureau, in the United States *stamina* is an important ability for as many as 8.5 million workers in the country (Table 9); *explosive strength* is important for half a million workers. [24] More generally, 13.7% of all civilian jobs and 45.5% of jobs in Construction and Extraction require heavy work (Table 11) (U.S. Bureau of Labor and Statistics).

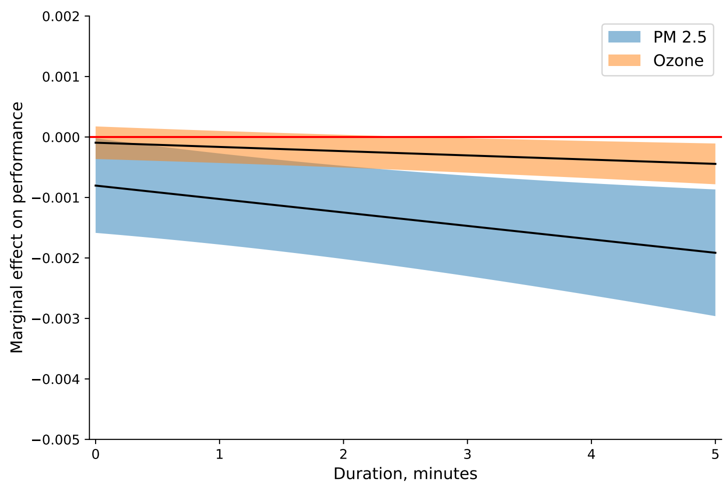

Figure 3: Marginal effect of PM 2.5 and ozone on performance by average event duration.

[24] *Important* is here defined as a 3 or more on a 1-5 scale from 'Not Important'(1) to 'Extremely Important' (5).

Table 3: Heterogeneous effects by task requirements.

	(1) Std result	(2) Std result
PM 2.5	-0.0008**	-0.0008**
	(0.0004)	(0.0004)
Duration, minutes	0.0120***	0.0180***
	(0.0017)	(0.0030)
PM 2.5 × Duration, minutes	-0.0003***	-0.0002**
	(0.0001)	(0.0001)
Ozone		-0.0001
		(0.0001)
Ozone × Duration, minutes		-0.0001***
		(0.0000)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	553171	507718

Note: The table shows the effects of contemporaneous PM 2.5 and ozone on physical performance, measured as track and field competitions results. The unit of analysis is the competition result of an individual. The dependent variable is standardized competition result, defined as results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group. *Duration* is the average duration of competitions (in minutes) for groups defined by age, gender, and event. PM 2.5 and ozone are expressed in $\mu g/m^3$. *Time* indicates year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. Standard errors are clustered at the stadium-date level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5.2 Gender, ability effects, and nonlinearities

To test whether the performance cost of PM 2.5 differs across individuals, I explore the heterogeneity across gender and ability (Table 4). There exists little large scale causal evidence on the costs of pollution by gender, in particular on physical abilities. It appears that PM 2.5 has no different impact on the performance of females and males, as Columns (1) and (2) show.

Columns (3) and (4) interact PM 2.5 with an indicator for athletes that perform in the top decile at least half of the time when compared to their peers. The latter identifies high ability athletes that systematically perform well. The performance loss caused by PM 2.5 is greater for top athletes, approximately 2.5 times as large. One possible explanation is that low ability athletes have more margin to compensate losses from air pollution.

Economics theory states that protection from air pollution should be set so that the marginal cost of investment matches the marginal benefits. Threshold effects and non-linearities in productivity losses imply that protective investments should not scale linearly as well. I test for non-linearity with multiple specifications, namely: restricted cubic splines with three and four knots; quadratic form of PM 2.5; binning PM 2.5 by half, tercile, and quantile. Results are shown in Figure 4. From all specifications we can deduce that exposure to PM 2.5 appears to be having a non-discernible effect at low concentrations (<25 $\mu g/m^3$), but negative effects on performance are evident at medium concentrations. Results are not driven by high concentrations of PM 2.5. Table 5 shows the estimates for a restricted sample with PM 2.5 less than 50 $\mu g/m^3$ (Column(1)); and less than 75 $\mu g/m^3$ (Column (2)). Estimated coefficients are almost unchanged.

Table 4: Heterogeneous effects by gender and ability.

	Gender		High ability	
	(1)	(2)	(3)	(4)
	Std result	Std result	Std result	Std result
PM 2.5	-0.0011***	-0.0011***	-0.0009**	-0.0008**
	(0.0004)	(0.0004)	(0.0004)	(0.0004)
Female × PM 2.5	0.0002	0.0004		
	(0.0004)	(0.0004)		
Ozone		-0.0002		-0.0002
		(0.0001)		(0.0001)
PM 2.5 × High ability			-0.0016***	-0.0015**
			(0.0006)	(0.0006)
Individual FE	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes
Weather	Yes	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes	Yes
Observations	553171	507718	553171	507718

Note: The table shows the effects of contemporaneous PM 2.5 on physical performance, measured as track and field competitions results. The unit of analysis is the competition result of an individual. The dependent variable is standardized competition result, defined as results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group. *High ability* is an indicator for athletes that perform in the top decile at least 50% of the time. *Time* indicates year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. Standard errors are clustered at the stadium-date level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5: The effect of air pollution on performance: excluding high concentrations.

	PM 2.5 $<$ 50	PM 2.5 $<$ 75
	(1)	(2)
	Std result	Std result
PM 2.5	-0.0008**	-0.0010**
	(0.0004)	(0.0004)
Ozone	-0.0002	-0.0002
	(0.0001)	(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	505347	507508

Note: The table shows the effects of contemporaneous PM 2.5 on physical performance, measured as track and field competitions results. The unit of analysis is the competition result of an individual. The dependent variable is standardized competition result, defined as results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group. Column (1) reports results after excluding events with PM 2.5 greater or equal to 50 $\mu g/m^3$. Column (2) reports results after excluding events with PM 2.5 greater or equal to 75 $\mu g/m^3$. *Time* indicates year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. Standard errors are clustered at the stadium-date level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

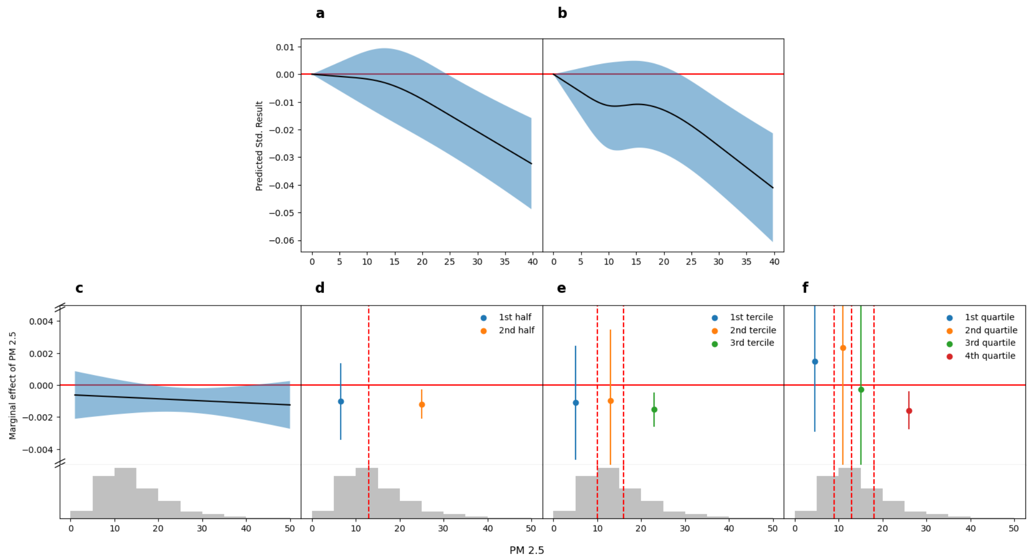

Figure 4: Nonlinear effects of PM 2.5 on performance. Panel **a** and **b** show the predicted performance estimated with a restriced cubic spline with three and four knots, respectively. Knot locations are based on Harrell's (2001) recommended percentiles. Panel **c**, **d**, **e**, and **f** report the marginal effects of PM 2.5 on performance for difference specifications: quadratic (**c**), by sample half (**d**), tercile (**e**), and quartile **(f)**. Histograms at the bottom report the distribution of PM 2.5 in the sample period. The few (0.05%) observations larger than 50 $\mu g/m^3$ have been excluded from the graphs for clarity.

6 Robustness

As noted in Section 1, races on mid and long distances can require a degree of strategy if incentives nudge competitors to run for the win, but not for the timing. In such conditions, athletes may decide to maintain an artificially slow pace throughout the race and bet on their abilities to win a late-race acceleration. This requires runners to carefully evaluate their ability to maintain an optimal pace and the ability to outperform competitors in a final sprint. It is possible that inhalation of PM 2.5 might disrupt the necessary mental processes and reduce performance in these races.

Strategic running inherently reduces performance as measured in seconds. Estimates of the impact of PM 2.5 might be biased away from zero if strategic running is more common on polluted days; for instance, if important championships are held in large and polluted cities. While such a scenario is plausible, the amount of bias should be limited once stadium and time fixed effects are included in the regression.

To address the remaining doubts, and to ensure results do not pick up a cognitive effect, I estimate the main specifications excluding all race competitions of distance over 400 meters and report results in Table 6. Table 13 in Appendix further addresses strategic behavior in multi-stage competitions including qualifiers. Results are unaltered, confirming that strategic races do not drive the observed impacts of PM 2.5.

Individuals may avoid competing in locations with high pollution levels if they fear their health is at risk (Graff Zivin and Neidell, 2013). Although unlikely given the low concentrations during spring and summer, they might choose whether and where to compete depending on factors, such as weather conditions, that correlate with pollution. The inclusion of individual fixed effects assures that the identifying variation does not come from the selection of less performing athletes into high pollution days. Nonetheless, I test whether concentrations of PM 2.5 predict participation in competitions. Table 7 reports the results of a regression of the log number of participants in a given stadium-date on PM 2.5, progressively adjusting for stadium, time of the year, and weather. If anything, on days with higher pollution, *more* athletes take part to competitions (Column (1)). However, once the invariable characteristics of stadiums are accounted for, neither PM 2.5 nor ozone predict participation to contests (Columns (2), (3) and (4)).

Finally, to further assess the robustness of results I perform a placebo test replacing contemporaneous concentrations of PM 2.5 and ozone with those observed in the same city one year later. Future concentrations do not predict competitions results (Table 8). This is reassuring that previous results are not driven by unmodeled seasonality patterns.

Table 6: Excluding events where strategic behavior is possible.

	(1)	(2)
	Std result	Std result
PM 2.5	-0.0010***	-0.0009**
	(0.0004)	(0.0004)
Ozone		-0.0002
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	468162	428623

Note: The table shows the effects of contemporaneous PM 2.5 on physical performance, measured as track and field competitions results. The unit of analysis is the competition result of an individual. The dependent variable is standardized competition result, defined as results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group. The sample excludes all race competitions of distance over 400 meters. PM 2.5 and ozone are expressed in $\mu g/m^3$. *Time* dummies include year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions.

Table 7: Testing for presence of avoidance behavior.

	(1)	(2)	(3)	(4)
	Log(Partecipants)	Log(Partecipants)	Log(Partecipants)	Log(Partecipants)
PM 2.5	0.0042*	-0.0012	0.0037	0.0008
	(0.0026)	(0.0024)	(0.0024)	(0.0029)
Ozone	0.0048***	0.0023***	0.0004	-0.0006
	(0.0008)	(0.0008)	(0.0009)	(0.0016)
Time	No	No	Yes	Yes
Weather	No	No	No	Yes
Stadium	No	Yes	Yes	Yes
Observations	3246	3246	3246	2926

Note. The table tests whether concentrations of PM 2.5 and ozone predict participation to competitions. The dependent variable is the log-number of participants to competitions in a given stadium-date. *Time* indicates year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium* includes stadium fixed effects. Standard errors are clustered at the stadium-date level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8: The impact of PM 2.5 on physical performance. Placebo test with future air pollution measures.

	(1)	(2)
	Std result	Std result
PM 2.5, 1-yr lead	-0.0005	-0.0006
	(0.0004)	(0.0004)
O3, 1-yr lead		0.0002
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	469297	430911

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: The dependent variable is standardized competition result, which is the competition results minus the average result of a group defined by age, gender, and event, and dividing by the standard deviation of results of the same group (*e.g.*, 17-old, male, long jump). *PM 2.5, 1-yr lead* and *O3, 1-yr lead* are the concentrations of PM 2.5 and ozone observed one year later. PM 2.5 and ozone are expressed in $\mu g/m^3$. *Time* dummies include year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions.

7 Conclusions

A body of studies has assessed the effect on worker's productivity of environmental stressors such as pollution and temperature. To overcome limits to portability of results, a growing number of works studies the impacts on standardized tasks as it allows comparison of outcomes between individuals with the same assignment. However, generalization does not always follow from standardization, as the mechanisms at work often remain fuzzy. Moreover, most works focus on the effects on cognition and the evidence on the productivity effects through physical channels remains limited.

This paper offers new evidence on the impacts of PM 2.5 leveraging on a large dataset of track and field competitions, a set of highly standardized and primarily physical activities. The simplicity of the tasks involved - running, jumping, throwing - and their well-understood physiology make extension to other physical activities more transparent. The richness of the data allows for assessing the link between short-term exposure to PM 2.5 and performance, and then to explore one particular driver of the effects: the duration of continuous effort and, implicitly, the reliance on stamina.

I find that an increase in PM 2.5 of 10 $\mu g/m^3$ reduces performance by 1% of a standard deviation after including a battery of fixed effects, including individual fixed effects and a flexible modeling of weather. The impact of PM 2.5 on performance grows as the duration of competitions - and the dependence on the pulmonary system - increase. The results suggest that jobs requiring exertion of muscle force continuously over time incur, under the same conditions, greater productivity losses than jobs requiring short burst of intense exercise. While track and field competitions differ from most physical work in intensity and participants, the analysis explores heterogeneity that might extend to common manual jobs. The findings highlight potentially unequal costs of air pollution across the hundreds of millions of workers worldwide employed physical labor, adding to current concerns over distributional consequences of environmental stressors (Hsiang et al., 2019).

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A Appendix

A.1 Figures

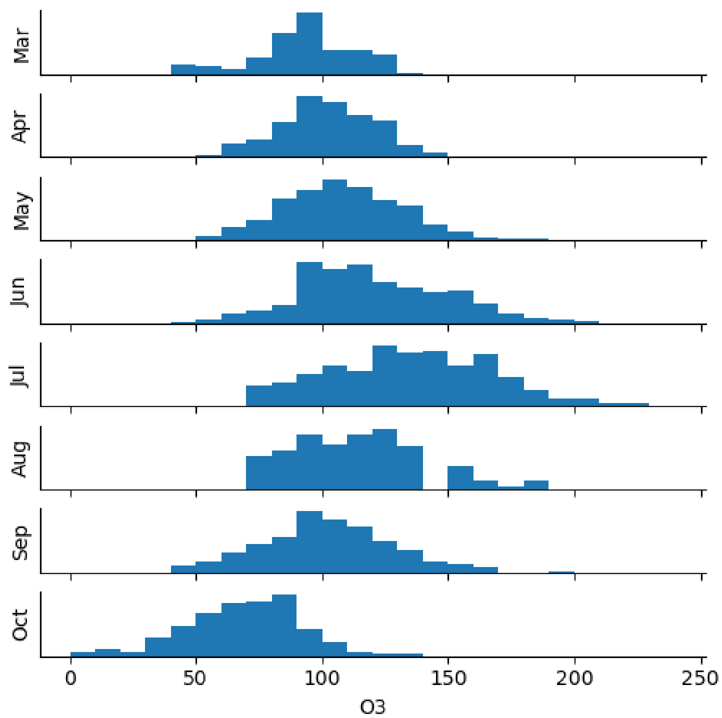

Figure 5: Within-month distribution of ozone.

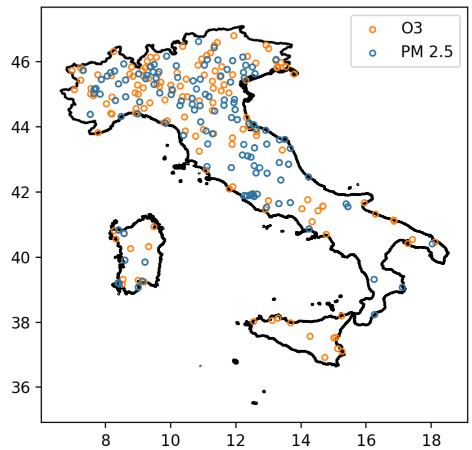

Figure 6: Location of pollution monitors in 2013. The monitor network is dense in the more populated and polluted North.

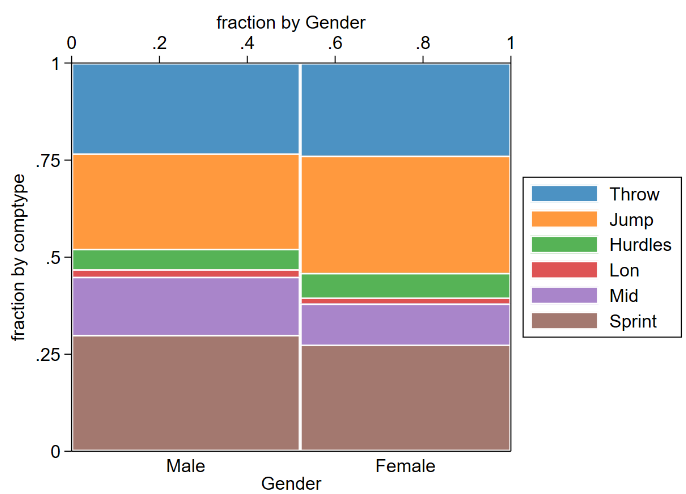

Figure 7: Share of observations by gender and type of event: races (sprints, hurdles, mid and long distance), jumps and throws.

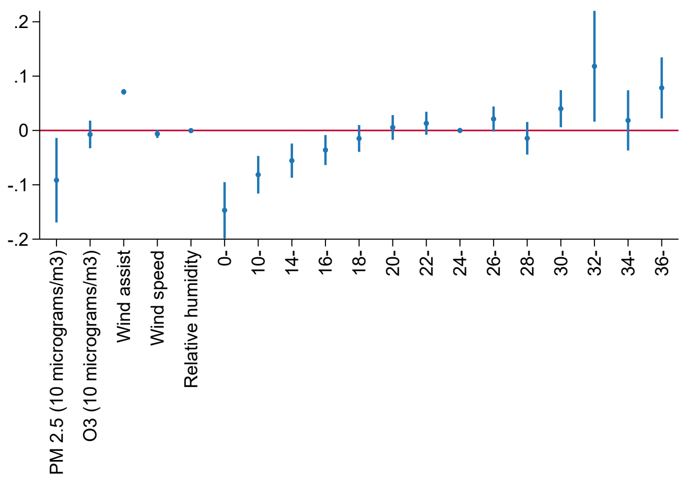

Figure 8: The impact of PM 2.5 on physical performance. Comparison with the effect of temperature. Reference temperature bin is [24-26) degrees Celsius. The dependent variable is standardized competition result, which is the competition results minus the average result of a group defined by age, gender, and event, and dividing by the standard deviation of results of the same group (*e.g.*, 17-old, male, long jump). The regression includes fixed effects for year, week, and day-of-the-week; stadium fixed effects, team fixed effects, and their interactions. Standard errors are clustered at the stadium-date level.

A.2 Tables

Table 9: Top occupations with high importance of 'Stamina', by number of workers

Occupation	Size	Importance	Level
Laborers and Freight, Stock, and Material Movers, Hand	2821700	3.12	4.12
Waiters and Waitresses	2023200	3	3.62
Construction Laborers	1285200	3.12	4.12
Maids and Housekeeping Cleaners	1212800	3	3.88
Landscaping and Groundskeeping Workers	1117800	3	3.5
Light Truck Drivers	1035800	3	3.25
Nannies	992400	3	3.38
Carpenters	942900	3.12	4.06
Police and Sheriff's Patrol Officers	671200	3	4.12
Farmworkers and Laborers, Crop, Nursery, and Greenhouse	526300	3	3.81

Size: number of workers in the occupation. Importance: the degree of importance a particular descriptor is to the occupation. The possible ratings range from 'Not Important'(1) to 'Extremely Important' (5). Level: This rating indicates the degree, or point along a continuum, to which a particular descriptor is required or needed to perform the occupation.

Table 11: Percentage of civilian jobs requiring different strength levels in selected occupations, 2016.

Occupation	Sedentary	Light work	Medium work	Heavy work
All jobs	13.30%	24.40%	45.00%	13.70%
Management	27.5	36.9	31.7	-
Architecture and engineering	24.9	25.8	41.4	-
Community and social service	24.7	36.2	34.9	-
Legal	40.3	28.9	30.8	-
Education, training, and library	-	48.9	40.7	5.2
Arts, design, entertainment, sports, and media	22.7	33.1	36.3	-
Healthcare support	-	23.3	48.1	21.9
Food preparation and serving related	-	22.2	67.2	9.8
Building and grounds cleaning and maintenance	-	13.8	69.7	15.7
Personal care and service	-	29	49.7	16.9
Sales and related	9.8	22.9	58.4	-
Office and administrative support	31.1	33.5	27.7	5.1
Construction and extraction	-	-	37.3	45.5
Installation, maintenance, and repair	-	-	49.3	35.4
Production	-	12	63.2	17.2
Transportation and material moving	2.8	10.2	47.4	32.3

Source: Bureau of Labor Statistics, U.S. Department of Labor. Dash indicates no jobs in this category or data did not meet publication criteria of the BLS.

Table 12: Decomposition of variance of PM 2.5 and performance.

	Standard Deviation	
	PM 2.5	Standardized result
Overall	8.36	0.98
Within individual	7.05	0.62
Between individuals	5.65	0.83
Within stadium	7.43	0.97
Between stadiums	4.81	0.25
Within individual-stadium	5.50	0.52

Note: The panel is unbalanced. Standardized competition result is defined as competition results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group.

Table 13: The impact of PM 2.5 on physical performance. Excluding events where strategic behavior is possible. Races over distances greater than 400 meters are excluded and for each athlete only the best result in a given day in a given event is included. For instance, qualifying rounds with poorer results than finals are excluded.

	(1)	(2)
	Std result	Std result
PM 2.5	-0.0010***	-0.0009**
	(0.0004)	(0.0004)
Ozone		-0.0002
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	463175	423859

Note: The table shows the effects of contemporaneous PM 2.5 on physical performance, measured as track and field competitions results. The unit of analysis is the competition result of an individual. The dependent variable is standardized competition result, defined as results minus the average result of a group defined by age, gender, and event (*e.g.*, 17-old, female, long jump), divided by the standard deviation of results of the same group. Races over distances greater than 400 meters are excluded and for each athlete only the best result in a given day in a given event is included. PM 2.5 and ozone are expressed in $\mu g/m^3$. *Time* dummies include year, week, and day-of-the-week fixed effects. *Weather* includes wind assist, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, relative humidity, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions.

A.3 Tasks vs occupations

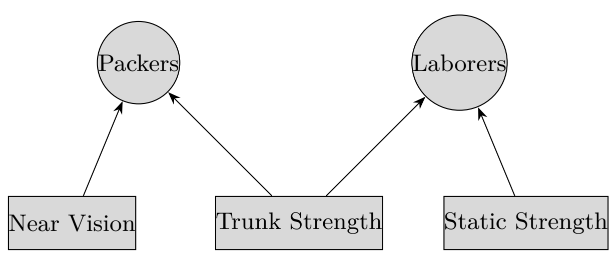

Figure 9: Example of jobs (circles) requiring an overlapping set of abilities (squares).

Suppose that we can approximate the productivity of J and Q with linear functions: $P^J = \lambda_1 A(e) + \lambda_2 B(e)$ and $P^Q = \lambda_3 B(e) + \lambda_4 C(e)$, with e representing the level of the environmental stressor. An estimate of the productivity effect of e on the output of J, $\frac{\partial P^J}{\partial e} = \lambda_1 \frac{\partial A}{\partial e} + \lambda_2 \frac{\partial B}{\partial e}$ can provide little information on the productivity effect $\frac{\partial P^Q}{\partial e} = \lambda_3 \frac{\partial B}{\partial e} + \lambda 4 \frac{\partial C}{\partial e}$. However, suppose we can observe $\frac{\partial B}{\partial e}$, the moderating effect on B alone. We can say the effect is consequential for both J and Q to the degrees λ_2 and λ_3 they rely on ability B.

Proxies for λ_2 and λ_3 can be The Occupational Information Network (O*NET) database contains hundreds of standardized and job-specific descriptors on nearly 1,000 jobs, covering the entire US economy. The database, which is freely available to the public, is continually updated with input from a wide range of workers in each occupation.