You Can't Run from Air Pollution
The Effect of Fine Particulate Matter on Physical Tasks

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Abstract

A large share of the world's population is employed in manual labor. This paper estimates the effect of fine particulate matter (PM 2.5) on purely physical tasks analyzing half a million amateur track and field competition results, a setting that allows excluding productivity effects through the cognitive channel. 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 1.1% of a standard deviation. The effect grows with the duration of effort, indicating that occupations requiring low-intensity and sustained effort may be more affected by air pollution than occupations requiring occasional short but intense bursts of energy.

Keywords: Air pollution, Health, Performance, Sports

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1 Introduction

Air pollution is pervasive throughout the globe and one of the world's top health risks (Cohen et al., 2017). The depletion of health stock caused by inhalation of air pollution can also have mild but diffused consequences, such as reducing labor productivity. A growing number of studies find that fine particulate matter (PM 2.5) reduces cognitive performance in standardized tasks such high-stake exams (Ebenstein et al., 2016; Persico and Venator, 2019; Graff Zivin et al., 2020), brain games (Nauze and Severnini, 2021), chess matches (Künn et al., 2019), and referee calls in baseball games (Archsmith et al., 2018).[1] [2]

However, a large share of the world's population is still hired in manual labor, especially in developing countries, where pollution levels are often above safety thresholds. 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). Physically demanding jobs are common in advanced economies as well. In the United States alone, around 1.4 million workers were employed as construction laborers as of 2019, a number projected to grow faster than the average job (O*NET OnLine, 2020). If the costs of pollution are heterogeneous between tasks of different nature, for instance between cognitive and physical tasks, the burden of pollution is unequally distributed across jobs even under the same levels of exposure.

Nevertheless, the evidence on the causal effects of ambient air pollution on purely physical tasks is still limited. This paper estimates the effects of PM 2.5 on physical tasks where cognition plays a marginal role for performance: track and field competitions. In this environment, individuals repeatedly perform highly standardized tasks (running, jumping, throwing) in different environmental conditions. 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. 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 1.1% of a standard deviation, equivalent to a loss of one-third of a percentile in nationwide rankings. Given that most competitions occur during spring and summer, the effect is observed at concentrations well below the annual limit value of 25 $\mu g/m^3$ set by the European Environmental Agency. Conversely, ozone does not have a discernible impact on performance. Males and females are equally represented and perform the same or very similar tasks, allowing testing for potential differences by gender. I find that the impacts of pollution are not different between males and females. The effect grows with age and is larger for high-ability athletes.

Studying productivity of standardized tasks has multiple advantages over studying the productivity of occupations that bundle distinct tasks and abilities. First, a breakdown of occupations into tasks increases the portability of results. For simplicity, consider a job J that can be broken down into tasks A, B, and C. Observing the productivity effect of an environmental stressor on the output of J can provide little information on the productivity effect on the output of a job Q that requires performing tasks B,

[1] Chen (2019) provides a detailed summary of the physiological and psychological pathways through which pollution is believed to affect cognitive performance and behavior.

[2] 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) andBondy 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.

C and D. However, imagine that we can observe the productivity effect on B alone. We can say the effect is consequential for both J and Q to the degree they rely on task B. For instance, according to the Occupational Information Network (O*NET) of the U.S. Bureau of Labor Statistics, construction laborers, warehouse workers, and reforestation workers similarly need stamina in their daily activities; similarly, judges rely on deductive reasoning as much as anesthesiologists.[3]

Second, when observing productivity at the occupation level, it is often difficult to distinguish a pure productivity effect from adaptations to changes in environmental conditions. However, the potential for adaptation is heterogeneous across occupations, industries, and income. The productivity effects of environmental stressors on tasks with a narrow margin for adaptation can be considered net-of-adaptation impacts.

To provide an example of how estimating the productivity costs of environmental factors on tasks, as opposed to occupations, can contribute to accounting for air pollution costs, I show how the impacts of PM 2.5 differ by type of physical activity, estimating heterogeneous effects by the duration of the effort. Compared to short but intense efforts, long races 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). 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 exertion of muscle force continuously over time incur, under the same conditions, greater productivity losses than jobs requiring short bursts of intense exercise.

The seminal works on the productivity costs of air pollution (*e.g.* Graff Zivin and Neidell (2012) for ozone, Chang et al. (2016); He et al. (2019) for particulate matter) have been followed by a growing focus on standardized tasks. Related works to this paper are Austin et al. (2019) and Marcus (2021), who both use data on tests of aerobic capacity of children. Marcus (2021) reports that an increase in ozone from 0-25% of the U.S. National Ambient Air Quality Standards to levels above the safety standard increases by 5.4 percentage points the share of students in her sample with poor aerobic capacity. Austin et al. (2019) instead link an improvement of VO2max, a measure of cardiopulmonary fitness, to the retrofitting of diesel school buses and the subsequent improvement in air quality inside the vehicles.

The closest study is Mullins (2018), who also studies the effects of air pollution on track and field athletes.[4] Track and field is a sport with very low entry barriers for competitions. Although athletes are positively selected on fitness, the large number of individuals increases the representativeness of results for the general population. Males and females are equally represented, allowing to test for heterogeneity across gender. This paper differs in scope as Mullins (2018) focuses on the consequences of ozone, whereas this paper assesses the impacts of PM 2.5, a pollutant that, differently from ozone, can penetrate in indoor buildings and is the fifth leading cause of premature death worldwide due to a combination of near-ubiquity and harming potential (Cohen et al., 2017).[5] Second, Mullins (2018) uses data for U.S.

[3]The same reasoning applies to environmental stressors other than air pollution, such as temperature. Higher temperatures alter the decision-making of U.S. immigration judges (Heyes and Saberian, 2019) and air pollution increases the deliberation period of Chinese judges (Kahn and Li, 2020).

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

[5]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 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.

collegiate competitions while I consider a population of mostly amateurs, whose team membership or expenses (such as scholarship) are not tied to performance[6], diluting concerns of positive self-selection on fitness. The results are partially coherent with Mullins (2018): he reports that a 10 ppm increase in ozone (approximately 20 $\mu g/m^3$) reduces performance of 1.13% of a standard deviation in endurance events with potential strategic interactions but finds no effect on shorter events. I formally test the heterogeneity of effects of air pollution by duration, a proxy for reliance on the cardio-pulmonary system, suggesting that air pollution may limit manual workers' productivity and yet indicate that not all physical jobs are equally affected. This paper additionally verifies that observed impacts are not attributable to effects on cognition. Finally, I find that, at levels of PM 2.5 well below and ozone around safety thresholds, the adverse effects on physical performance are driven by PM 2.5.

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.

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

2 Track and field competitions as standardized physical tests

The use of sports data in economics is not novel (Kahn, 2000). 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.[7]

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, 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. Road competitions such as marathons are excluded from this study as they take place on non-standardized race courses.

The cognitive efforts in track and field events are minimal. First, athletes compete individually, irrespective of the performance of other team members.[8] 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 relatively less common as athletes chase qualifying timings for championships of varying degrees. Section 6.1 shows that results are not driven by strategic events.

Males and females are usually equally represented and perform the same or very similar tasks (see Table A.3 in Appendix for a breakdown of types of competitions by gender). This contrasts with other work 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. 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

[7]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.

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

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. 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.[9] 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. Greater values stand for better results in field events, but not in track events. Standard scores of track events are hence reverted in sign. The dependent variable is constructed as

$$\begin{aligned}\widetilde{Y}_{i,age(t),event,gender(i)} &= \frac{Y_{i,age(t),event,gender(i)} - \mu_{age(t),event,gender(i)}}{\sigma_{age(t),event,gender(i)}} \text{ if field event} \\ &= \frac{Y_{i,age(t),event,gender(i)} - \mu_{age(t),event,gender(i)}}{\sigma_{age(t),event,gender(i)}} \cdot -1 \text{ if track event}\end{aligned} \tag{1}$$

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.

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

[9]http://www.fidal.it/

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

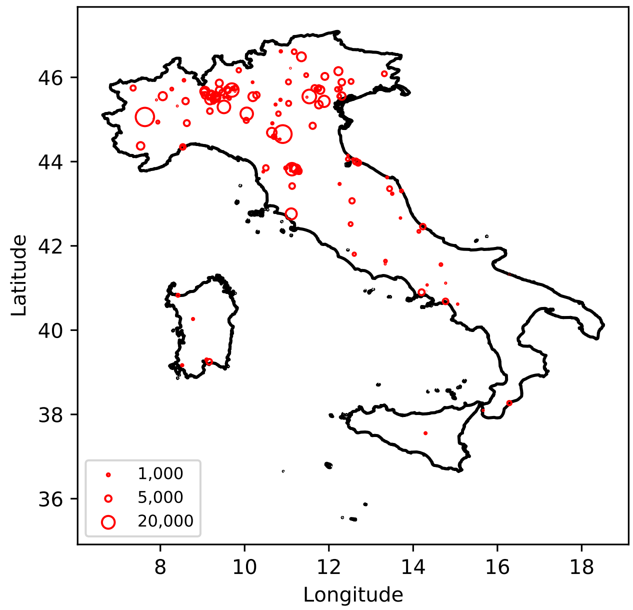

Figure 1: Location of Italian track and field stadiums in the data. Circle size indicates the amount of observations per each stadium.

a specific one, that city is excluded. Thus, a few large cities are removed from the sample.[10] 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 40 competitions or fewer during the period and cities covered by the database).[11] 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 typically take place 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.

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

[10] The most important city to be excluded is Rome. The pollution monitoring network is denser in the more polluted and populated North (Figure A.2).

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

Table 1: Descriptive statistics

	Mean	Std. Dev.	Median	Minimum	Maximum	N.
Std result	0.03	0.98	0.09	-5.66	3.39	513,639
PM 2.5	14.46	8.30	13.00	0.20	147.04	513,639
Ozone	109.37	28.12	107.69	7.00	247.45	473,742
Female	0.48	0.50	0.00	0.00	1.00	513,639
Age	15.22	3.46	14.74	5.30	40.37	513,639
Temp. max	24.15	4.99	24.46	5.64	37.52	513,639
Precipitation	1.28	2.24	0.11	0.00	10.00	513,639
Wind	2.02	0.75	1.92	0.13	7.95	513,639
Wind (on-site anemometer)	0.02	0.55	0.00	-7.50	8.00	513,639

Note. Standardized results *Std. Result* are obtained standardizing competition results by age, gender, and event.

of PM 2.5 above EU standards (Ortiz, 2020). The more densely populated Northern regions is one 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, precipitation and wind. At the same time, atmospheric conditions are key to the process of pollution formation, transport and dispersal.

I combine performance archives and pollution readings data on weather conditions. I use reanalysis data from the Gridded Agro-Meteorological Data in Europe (JRC Joint Research Center, Agri4cast), including daily meteorological parameters on a 25x25 km. I retrieve daily maximum temperature, average wind speed, vapor pressure, and cumulative precipitation. Since track and field competitions occur during the hottest hours of the day, afternoon to evening, the daily maximum temperature is a better statistic than the daily average. 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.[12] 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 on-site 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 describe above, I will refer to this variable as *on-site wind*.

[12]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.

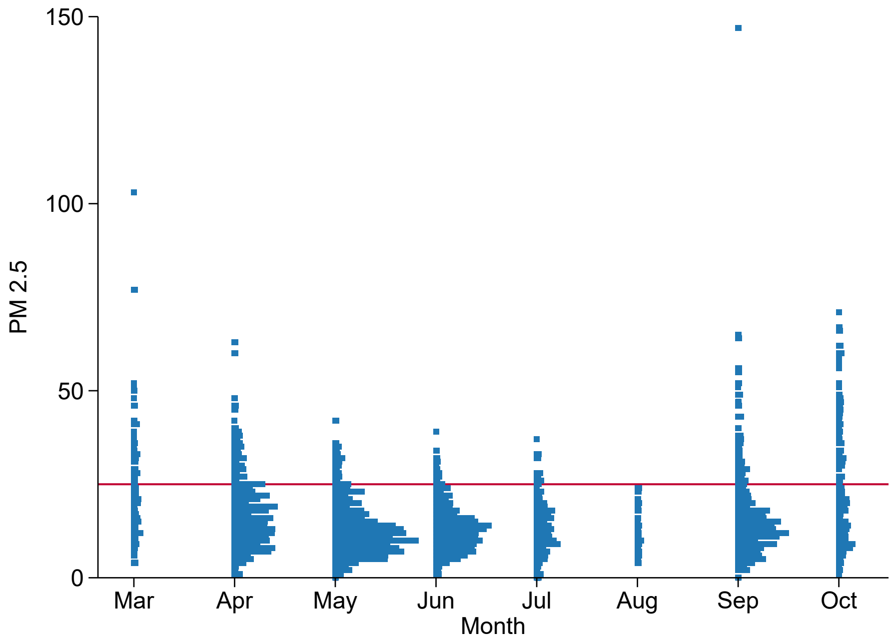

Figure 2: Distribution of PM 2.5 by month. The horizontal line at 25 $\mu g/m^3$ marks the EU average annual limit. Most competitions occur from April to September, when concentrations of PM 2.5 are lower.

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. Therefore, the analysis relies on variation in performance within individuals.

Second, to adjust for the confounding role of atmospheric conditions, I introduce a flexible specification of weather variables. Controls include on-site measures of wind in addition to fixed effects for 2° C bins of maximum temperature and their interaction with wind, vapor pressure, and binned precipitation.

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 unseen 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. I also let them interact 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.

The baseline specification then looks like:

$$\tilde{Y}_{i,s,t} = \beta_1 PM2.5_{s,t} + Time'_t\gamma_1 + Weather'_{t,s}\gamma_2 + \gamma_3 On\text{-}site\ wind_{i,s,t} \\ + \alpha_i + S_s + C_{c(i,t)} + S * C_{s,c(i,t)} + \epsilon_{i,s,t}. \tag{2}$$

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.[13] The main parameter of interest is β_1. The vector $Time_t$ contains time-specific fixed effects and the vector $Weather_{t,s}$ contains the flexible weather controls. $On\text{-}site\ wind_{i,s,t}$ is the wind speed measured on-site 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.

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 (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 are also re-estimated adjusting for concentrations of ozone.

5 Results

Table 2 presents results for the baseline specification (Eq. 2) in Column (1). I find that a 10 $\mu g/m^3$ increase in concentrations reduces performance by 1.1% of a standard deviation. For the median performance, this is equivalent to the loss of one third of a percentile in nationwide rankings.

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 at high-stake school exams in Israel. In the United States, the opening of a Toxic Release Inventory site within one mile of a school is associated with a reduction in test scores in nearby schools by approximately 2.4 percent of a standard deviation (Persico and Venator, 2019). Nauze and Severnini (2021) find that a standardized score in brain games is 0.18% of a standard deviation lower in concentrations of PM 2.5 above 25 $\mu g/m^3$.

The results are remarkable if one considers that most competitions occur in warmer months when pollution levels are relatively low. [14] 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 effect of PM 2.5 on performance is unchanged, while the effect of ozone is not statistically discernible.

[13] Only $\tilde{Y}$ and *On-site wind* vary within an individual in a given day.

[14] The effect size is 20%-25% of the marginal effect of a 1°C reduction of the daily maximum temperature (Table A.3 in Appendix). As discussed in Section 3.3, the daily maximum temperature is a better measurement of the temperature to which athletes are exposed. Results are unaltered using daily average.

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

	(1) Std result	(2) Std result
PM 2.5	-0.0011***	-0.0012***
	(0.0004)	(0.0004)
Ozone		-0.0000
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	513639	471996

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 on-site measurement of wind, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, vapor pressure, 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 Heterogeneity by task requirements

As an illustration of how a focus on narrow tasks can contribute to understanding the productivity costs of environmental stressors, I compute heterogeneous effects by the typical duration of a competition. The latter is calculated as the average duration of a given event by age and gender. The underlying logic is the following. Short- and long-lasting physical activities differ in dependence on the pulmonary and cardiovascular systems. The expectation is that the interference of PM 2.5 on the normal functioning may vary between these types of activities. Short and intense physical tasks that require explosive strength, such as those performed by police officers and firefighters (O*NET OnLine, 2020), rely on energy for movement that is produced in the absence of oxygen. On the other hand, tasks that require stamina, such as those performed by construction laborers, depend on oxygen for the chemical reactions used to produce the energy for movement.[15]

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 3 minutes than for very short events (Table 3).[16] This suggests that longer-lasting tasks that consequently rely on pulmonary capacity bear greater costs of air pollution.

[15] O*NET 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.".

[16] 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.

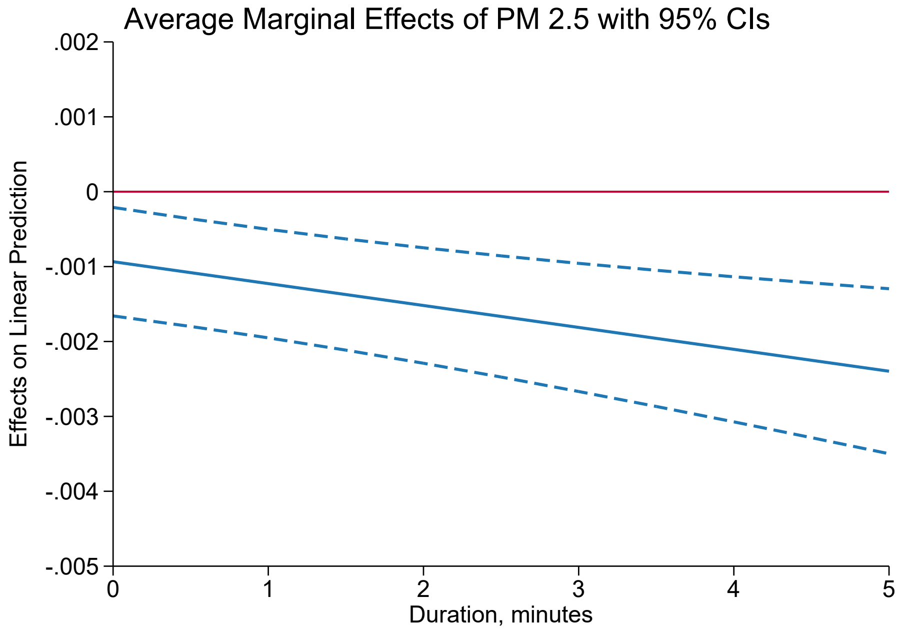

Figure 3: Marginal effect of PM 2.5 on performance by average event duration in groups defined by event, year, and gender. Dashed lines mark the 95% confidence interval.

Table 3: Heterogeneous effects by task requirements.

	(1)	(2)
	Std result	Std result
PM 2.5	-0.0009**	-0.0010**
	(0.0004)	(0.0004)
Duration, minutes	0.0120***	0.0114***
	(0.0018)	(0.0018)
PM 2.5 × Duration, minutes	-0.0003***	-0.0003***
	(0.0001)	(0.0001)
Ozone		0.0000
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	513639	471996

Standard errors in parentheses

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

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. *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 on-site measurement of wind, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, vapor pressure, 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, age, and ability effects

To test whether the performance cost of PM 2.5 differs across individuals, I explore the heterogeneity across gender, age, 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.

In Columns (3) and (4) the effect of PM 2.5 is allowed vary with age. The negative productivity effect of PM 2.5 grows larger with age.[17] This is particularly interesting as, given the younger age of athletes in the sample, growing older implies transitioning from adolescence into adulthood. However, a moderating effect of age might be compounded with a selection bias. As time passes, individuals with unobserved characteristics may drop out of the sport if their returns to time and effort are higher elsewhere. If the effect of PM 2.5 on performance is smaller for them, restricting the sample to the first year of competitions

[17] Figure A.4 in Appendix provides a visual representation of the heterogeneous effects by age. The negative effect of PM 2.5 on performance is detectable starting at approximately 14 years of age.

of each athlete, before attrition occurs, should yield a smaller coefficient. Columns (5) and (6) show this is not the case.

Columns (7) and (8) 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.

Table 4: Heterogeneous effects by gender, age, and ability.

	Gender		High ability		Age		First year	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Std result	Std result	Std result	Std result	Std result	Std result	Std result	Std result
PM 2.5	-0.0012***	-0.0013***	-0.0010***	-0.0011***	0.0020	0.0019	-0.0017***	-0.0017***
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0012)	(0.0013)	(0.0005)	(0.0006)
Female × PM 2.5	0.0000	0.0001						
	(0.0004)	(0.0004)						
Ozone		-0.0000		-0.0000		0.0000		0.0007***
		(0.0001)		(0.0001)		(0.0001)		(0.0003)
PM 2.5 × High ability			-0.0018***	-0.0015**				
			(0.0006)	(0.0007)				
Age					0.9309*	0.9034*		
					(0.4800)	(0.4934)		
PM 2.5 × Age					-0.0002**	-0.0002**		
					(0.0001)	(0.0001)		
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	513639	471996	513639	471996	513639	471996	152908	139061

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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 on-site measurement of wind, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, vapor pressure, and binned precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. Standard errors are clustered at the stadium-date level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

6 Robustness

6.1 Excluding events where strategic behavior is possible

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 5. Table A.2 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.

Table 5: Excluding events where strategic behavior is possible.

	(1)	(2)
	Std result	Std result
PM 2.5	-0.0011***	-0.0011***
	(0.0004)	(0.0004)
Ozone		-0.0000
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	435260	398929

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). 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, day-of-the-week fixed effects and an indicator from the 23rd to the 35th week, when schools are normally closed. *Weather* includes fixed effects for quintiles of maximum daily temperature and precipitation, five bins of wind speed, as well as their interactions. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions.

6.2 Avoidance behavior

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

Table 6: Testing for presence of avoidance behavior.

	(1) Log(Partecipants)	(2) Log(Partecipants)	(3) Log(Partecipants)	(4) Log(Partecipants)
PM 2.5	0.0042*	-0.0012	0.0037	0.0016
	(0.0026)	(0.0024)	(0.0024)	(0.0027)
Ozone	0.0048***	0.0023***	0.0004	-0.0008
	(0.0008)	(0.0008)	(0.0009)	(0.0014)
Time	No	No	Yes	Yes
Weather	No	No	No	Yes
Stadium	No	Yes	Yes	Yes
Observations	3246	3246	3246	2811

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 on-site measurement of wind, as well as fixed effects for 2° C bins of maximum daily temperature and their interaction with wind, vapor pressure, and binned precipitation. *Stadium* includes stadium fixed effects. Standard errors are clustered at the stadium-date level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

whether concentrations of PM 2.5 predict participation in competitions. Table 6 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 (Columns (1) and (2)). However, once the invariable characteristics of stadiums and time trends in pollution are accounted for, neither PM 2.5 nor ozone predict participation to contests (Columns (3) and (4)).

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 tests. However, in the context of air pollution, evidence on the productivity effects through primarily physical channels is 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 richness of the data allows for assessing the link between short-term exposure to PM 2.5 and performance and identifying heterogeneous effects by types of physical requirements.

I find that an increase in PM 2.5 of 10 $\mu g/m^3$ reduces performance by 1.1% of a standard deviation after including a battery of fixed effects, including individual fixed effects and a flexible specification of weather. The observed effects materialize at low levels of pollution, regularly below the average yearly limit set by the European Union. This adds to the many studies finding that air pollution standards may not coincide, but exceed, health safety thresholds.

The impact of PM 2.5 on performance grows as the duration of competitions - and the reliance 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.

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A Appendix

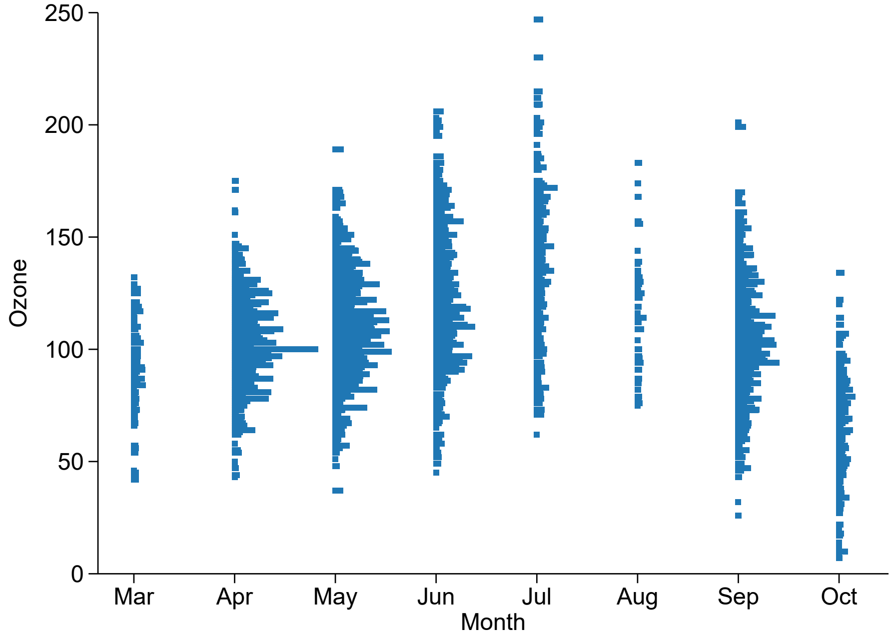

Figure A.1: Distribution of ozone by month.

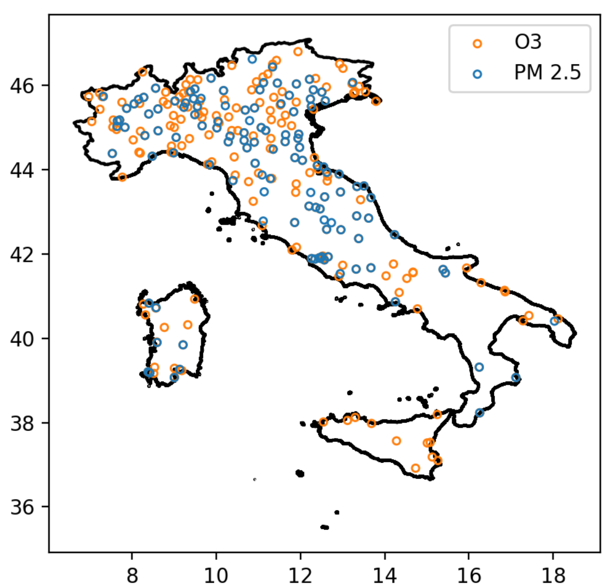

Figure A.2: Location of pollution monitors in 2013. The monitor network is dense in the more populated and polluted North.

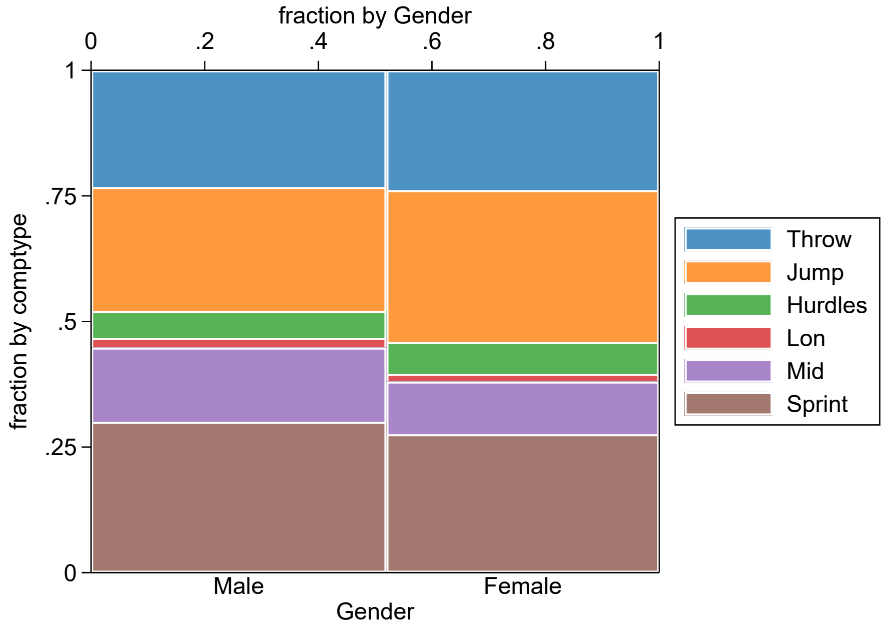

Figure A.3: Share of observations by gender and type of event: races (sprints, hurdles, mid and long distance), jumps and throws.

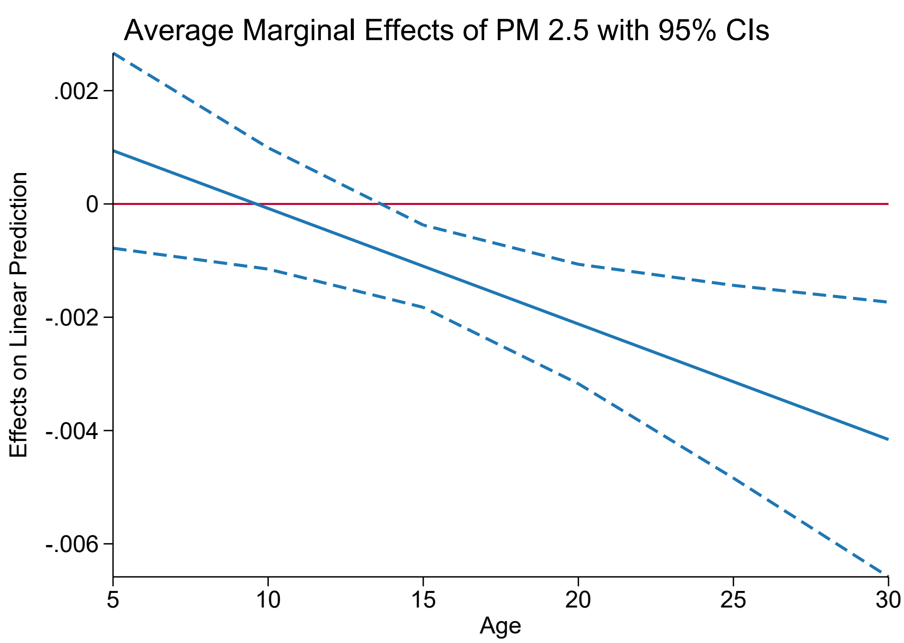

Figure A.4: Marginal effect of PM 2.5 on physical performance by age.

Table A.1: The impact of PM 2.5 on physical performance. Quadratic effects.

	(1)	(2)
	Std result	Std result
PM 2.5	-0.0009	-0.0014**
	(0.0008)	(0.0007)
Ozone		-0.0000
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	513639	471996

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 and ozone are expressed in $\mu g/m^3$. *Time* dummies include year, month, day-of-the-week fixed effects and an indicator from the 23rd to the 35th week, when schools are normally closed. *Weather* includes fixed effects for quintiles of maximum daily temperature and precipitation, five bins of wind speed, as well as their interactions. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. *Week* include week-of-the-year fixed effects. Standard errors are clustered by stadium-day.

Table A.2: 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	-0.0011***	-0.0011***
	(0.0004)	(0.0004)
Ozone		-0.0000
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Observations	430697	394547

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). The sample excludes all race competitions of distance over 400 meters and for each athlete includes only the best result in a given day in a given event. PM 2.5 and ozone are expressed in $\mu g/m^3$. *Time* dummies include year, month, day-of-the-week fixed effects and an indicator from the 23rd to the 35th week, when schools are normally closed. *Weather* includes fixed effects for quintiles of maximum daily temperature and precipitation, five bins of wind speed, as well as their interactions. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. *Week* include week-of-the-year fixed effects. Standard errors are clustered by stadium-day.

Table A.3: The impact of PM 2.5 on physical performance. Comparison with the effect of temperature.

	(1)	(2)
	Std result	Std result
PM 2.5	-0.0013***	-0.0012***
	(0.0004)	(0.0004)
Wind, m/s (on-site anemometer)	0.0713***	0.0718***
	(0.0026)	(0.0027)
Temp. max	0.0035***	0.0046***
	(0.0009)	(0.0011)
Ozone		-0.0002*
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Vapor pressure	Yes	Yes
Wind	Yes	Yes
Precipitation	Yes	Yes
Stadium, Team	Yes	Yes
Observations	513639	471996

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). *Time* dummies include year, month, day-of-the-week fixed effects and an indicator from the 23rd to the 35th week, when schools are normally closed. *Wind bins* includes fixed effects for five bins of wind speed. *Precip. bins* includes fixed effects for quintiles of cumulative daily precipitation. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. *Week* include week-of-the-year fixed effects. Standard errors are clustered by stadium-day.

Table A.4: The impact of PM 2.5 on physical performance. Placebo test with PM 2.5 leaded by one year, with month FE in place of week FE.

	(1)	(2)
	Std result	Std result
PM 2.5, 1-yr lead	-0.0004	-0.0004
	(0.0004)	(0.0004)
Wind, m/s (on-site anemometer)	0.0691***	0.0695***
	(0.0028)	(0.0029)
Ozone		-0.0001
		(0.0001)
Individual FE	Yes	Yes
Time	Yes	Yes
Weather	Yes	Yes
Stadium, Team	Yes	Yes
Month	Yes	Yes
Observations	437046	403363

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* is the concentration of PM 2.5 observed one year later. PM 2.5 and ozone are expressed in $\mu g/m^3$. *Time* dummies include year, day-of-the-week fixed effects and an indicator from the 23rd to the 35th week, when schools are normally closed. *Weather* includes fixed effects for quintiles of maximum daily temperature and precipitation, five bins of wind speed, as well as their interactions. *Stadium, Team* includes stadium fixed effects, team fixed effects, and their interactions. *Month* includes month fixed effects.