A Lab in the (Track and) Field? The Effect of Pollution on Physical Ability. Evidence from Sports Competitions

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Abstract

Considerable effort has been devoted to estimating the causal effects of air pollution on labor productivity. However, it remains unclear what physical tasks are most affected by pollution and and how existing results can be generalized. I argue that it is possible to increase the portability of findings by linking tasks to the capabilities required for performing them. I then estimates the effect of fine particulate matter on clear physical tasks: track and field competitions. I find that a 10 $\mu g/m^3$ increase in PM 2.5 reduces performance by 1% of a standard deviation and that the effect is strongest among high ability individuals. 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.

1 Introduction

Air pollution is pervasive throughout the globe and one of the world's top health risks (Cohen et al., 2017). Short-term exposure to fine particulate matter (PM 2.5) increases mortality and hospitalization rates for respiratory and cardiovascular events, in particular among vulnerable groups (Pope and Dockery, 2006; Schlenker and Walker, 2016; Deryugina et al., 2019). The depletion of health stock caused by air pollution can also have milder but more diffused consequences on the general population. Economists have found that air pollution reduces labor supply and labor productivity on top of direct health costs. Notably, Hanna and Oliva (2015) observe an increase in labor supply following an exogenous improvement in air quality. Estimation of productivity effects, however, is more challenging and requires contexts where worker tasks are clearly defined and productivity is easily observable, such as agricultural piece-rate workers (Graff Zivin and Neidell, 2012), fruit packing plants (Chang et al., 2016), garment factories (He et al., 2019), and call centers (Chang et al., 2019).

The portability of a pollution-productivity relationships remains limited, partly due to insufficient understanding of the physiological mechanisms through which air pollutants may alter normal body

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functioning and worker productivity. Nonetheless, generalizability can benefit from a "task framework" (Autor et al., 2003) that breaks down the tasks that workers perform to the skills needed to carry out these activities. [1] Mapping how pollution affects workers' capability when performing a given task becomes crucial in assessing the total economic impact of air pollution.[2] It becomes even more critical from the moment heterogeneous productivity costs across jobs bear distributional consequences.

A growing number of studies moves in this direction by establishing causal links between air pollution and cognitive abilities. Students perform worse on high-stake exams on polluted days (Ebenstein et al., 2016; Persico and Venator, 2019; Graff Zivin et al., 2020); pollution increases the chances of errors of baseball umpires (Archsmith et al., 2018) and chess players (Künn et al., 2019).[3][4] These tasks have been studied because what they measure is clear (*e.g.*, math or verbal reasoning, strategy, pattern recognition, focus) and are of interest because they are performed in other contexts, including the workplace. For instance, following the categorization of O*NET database of the U.S. Bureau of Labor Statistics, applying "general rules to specific problems to produce answers that make sense" is a key ability for judges, neurologists, air traffic controllers (O*NET OnLine, 2020a) and, arguably, to students. Thus, findings on the effects of pollution on high-stakes exams can also inform the effects on the performance of judges.[5]

However, the understanding of how pollution affects physical performance remains limited, partly due to the challenges of isolating physical and non-physical channels. Estimating the productivity costs of pollution on physical activities can be especially important for developing countries, where large parts of the population are employed in manual labor, and 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, biomass burning is a significant source of harmful airborne pollutants (Rangel and Vogl, 2018; Graff Zivin et al., 2020; He et al., 2020). Yet, 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, 2020b).

This paper brings novel evidence on the effects of PM 2.5 on primarily physical tasks using data on the universe of track and field competitions held in Italy from 2006 to 2018. The richness of the data allows identifying the plausibly causal link of air pollution on physical performance adjusting for a battery of controls, including individual fixed effects. While arguably requiring focus and concentration, track and field competitions are highly standardized individual tasks, repeatedly performed by the same person over time, and measured with high precision. They are typically non-strategicand require no relevant cognitive

[1] A task is a unit of work activity that produces output. A skill is a worker's stock of capabilities for performing various tasks (Autor and Handel, 2013).

[2] The terms *skill* and *task* are used for coherence with Autor et al. (2003). The Occupational Information Network (O*NET) database provides a detailed categorization of occupations. In the context of this paper, the most relevant distinction is the one by abilities, defined as "enduring attributes of the individual that influence performance". Abilities are grouped in cognitive abilities, physical abilities, psychomotor abilities, and sensory abilities.

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

[4] 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.

[5] A number of studies find that productivity of studies worsens on polluted days.

effort.[6] Males and females are equally represented and perform the same or very similar tasks, allowing testing for potential differences by gender.

The use of sports data in economics is not novel (Kahn, 2000). In a similar paper, Lichter et al. (2017) 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]

I find that a short-term 10 $\mu g/m^3$ increase in PM 2.5 is associated with a reduction in performance of 1% of a standard deviation. Given that most competitions occur during spring and summer, the effect is observed at concentrations below the EU annual limit value. The impacts of pollution are not different between males and females and they are larger for high ability athletes.

To provide an example of how a task framework can contribute to accounting for air pollution costs, I show how the impacts of PM 2.5 differ by type of activity, estimating heterogeneous effects by duration of the effort. Compared to short but intense efforts, long races are more dependent on the pulmonary and cardiovascular system, 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 burst of intense exercise.

This paper contributes to the literature on the productivity effects of air pollution showing how pollution lowers clear physical capabilities. Second, it suggests a way forward to enhancing the portability of a growing number of studies by decomposing jobs into specific abilities. Our analysis suggests that air pollution may limit the productivity of manual workers, but also indicates that not all physical jobs are equally affected. With caution, the results of this paper could be extended outside the domain of sports. For instance, according to O*NET, static strength is as important for construction laborers as it is for athletes and dynamic strength is as important for sports competitors as for steel workers.

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 robustness checks. Section 6 concludes.

2 Track and field competitions as standardized physical tests

Ideally, a pollution-physical productivity function could be retrieved, 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.

[6] A notable exception are race competitions over mid and long distances. The implications are discussed and addressed in Section 5.4.

[7] Track and field competitions differ from road races as the former take place in a standardized stadium 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 56 events in China. However, and self-selection out of a marathon, before or during the race, makes causal identification challenging.

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. 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. 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 indoors, this study is restricted to outdoor contests as air quality in indoor tracks can be made worse, in unmeasurable ways, due to smoke from starting guns. Road competitions such as marathons are excluded 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. 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, favorite athletes in a sufficiently long race 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.

Males and females are usually equally represented and perform the same or very similar tasks. 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.

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, and no claim of representativeness can be made. Individuals positively select into the sport. However, 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 2018. Results are systematically collected by the Italian Athletics Federation (FIDAL) almost real-time and are made available on its website. Most 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 races 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 records only 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 large cities are removed from the sample.[8] 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 62883 athletes, for more than half a million competition results in 3315 stadium-race days in 141 stadiums. Given the disproportionately large number of young athletes, about 90% of them take part in 20 competitions or fewer during the period covered by the database).[9] About half of the events are races, 26% are jumps, 22% are throws. Female athletes make up 47% of the sample (Table 1).

3.2 Pollution

Daily pollution readings from monitoring stations come from AirBase, the European air quality database maintained by the European Environment Agency. Where hourly readings are available, the daily reading 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. For every race day, PM 2.5 readings from monitoring stations within 10 kilometers are interpolated at track stadiums with inverse distance weighting. Therefore, pollution in our 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

[8]The most important city to be excluded is Rome.

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

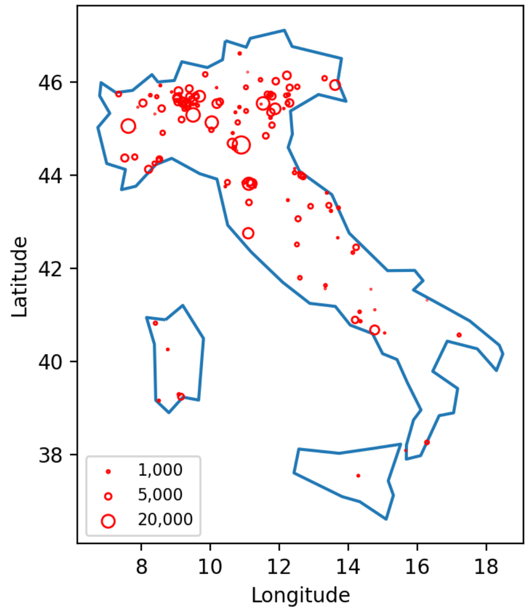

Figure 1: Location of Italian track and field stadiums in the data. Circle size indicates the amount of observations per each stadium.

Table 1: Descriptive statistics

	Mean	Std. Dev.	Median	Minimum	Maximum	N.
Std. Result	0.00	0.97	0.05	-5.24	3.74	502,529
PM 2.5	14.41	7.67	13.00	0.34	103.00	502,529
Ozone	69.58	21.00	68.87	0.81	141.54	390,979
Female	0.48	0.50	0.00	0.00	1.00	502,529
Age	15.85	5.01	14.84	5.31	46.78	502,529
Temp. max	24.30	4.82	24.59	6.93	36.66	502,529
Precipitation	2.19	6.10	0.00	0.00	101.65	502,529
Wind	2.11	0.83	1.98	0.13	8.70	502,529
On-site wind	0.02	0.56	0.00	-7.50	9.00	502,529

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

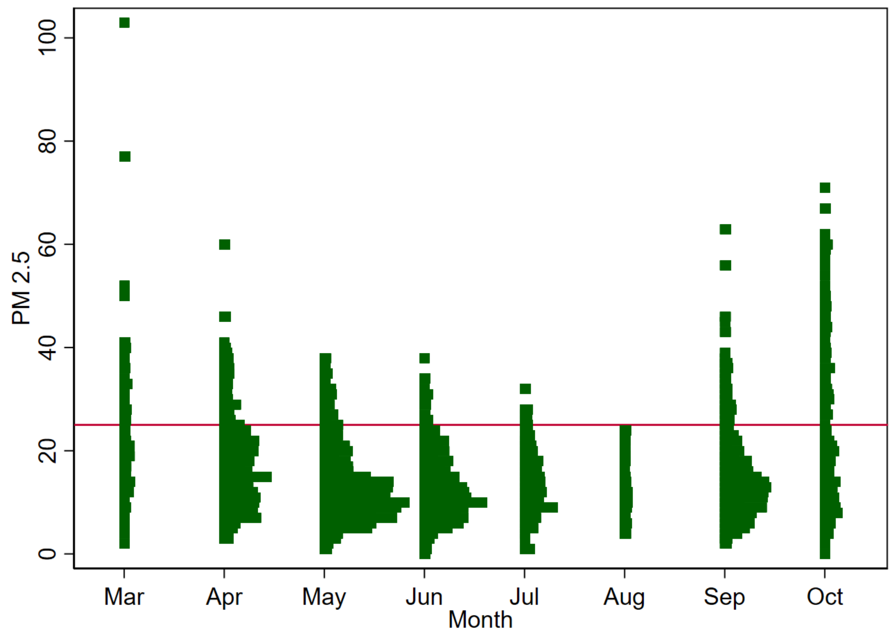

Figure 2: Distribution of PM 2.5 by month. The horizontal line at 25 $\mu g/m^3$ marks the EU average annual limit. Most competitions occur from April to September, when concentrations of PM 2.5 are lower.

of PM 2.5 above EU standards (REF). The 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 is 14.4 $\mu g/m^3$, and surpasses the EU annual limit value of 25 $\mu g/m^3$ in about 8% of observations.

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, 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. As before, 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.[10] 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

[10] Namely: races until 200 meters, 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.

within the competitions. Thus, wind speed during such events is measured on-site with anemometers and recorded along with results. For all other events, the variable is set to zero.

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, our 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 fixed effects for quintiles of maximum daily temperature and precipitation, five bins of wind speed, and their interactions.

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, month, and day-of-the-week, and an indicator for the weeks in which schools are closed. As a robustness check, I show that results are robust to introducing more stringent week-of-the-year fixed effects.

Finally, 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 due to traveling from the team's home to the stadium, and any potential home advantage.

The baseline specification then looks like:

$$\begin{aligned}\tilde{Y}_{i,s,t} =& \beta_1 PM2.5_{s,t} + Time_t'\gamma_1 + Weather_{t,s}'\gamma_2 + \gamma_3 \textit{On-site wind}_{i,s,t} \\ &+ \alpha_i + S_s + C_{c(i)} + S * C_{s,c(i)} + \epsilon_{i,s,t}.\end{aligned} \tag{2}$$

The dependent variable $\tilde{Y}_{i,s,t}$ is the standardized results described in Equation 1. i indexes individuals, s stadiums, and t time. For ease of notation, I omit subscripts indexing different competitions of the same individual on the same day. The main coefficient 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. $\textit{On-site wind}_{i,s,t}$ is the wind speed measure on-site through anemometers. α_i indicates individual fixed effects. S_s, $C_{c(i)}$ and $S * C_{s,c(i)}$ are respectively stadium fixed effects, team fixed effects, and their interaction. The error term $\epsilon_{i,s,t}$ is clustered at the stadium-day level.

5 Results

Table 2 presents results for the baseline specification (Eq. 2) in Column (1). I find a statistically significant negative effect of PM 2.5. A 10 $\mu g/m^3$ increase in concentrations reduces performance by 1%

of a standard deviation. Column (2) tests whether the result is driven by the correlation between ozone and PM 2.5. Ozone is known to irritate lung airways and increase respiratory problems. It is found in the highest concentrations during the summer months when solar radiation is high. Since fewer stadiums are within a 10 km range of an ozone monitoring station, the sample size is reduced by slightly more than a fifth. The effect of PM 2.5 on performance is qualitatively unchanged, while the effect of ozone is not statistically discernible. Column (3) replaces month fixed effects with a more stringent set of fixed effects for week-of-the-year, mitigating concerns that the main results being driven by the progressive decrease in pollution and improvement in performances as summer approaches.[11]

Overall, results consistently suggest that PM 2.5 decreases performance by 1-1.3% of a standard deviation for a 10 $\mu g/m^3$ increase in concentrations. [12] The results are remarkable if one considers that most competitions occur in warmer months when pollution levels are relatively low. 90% 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 $\mu g/m^3$.

[11] Results are virtually identical when including both ozone and week fixed effects. See Table 7 in Appendix.

[12] The effect size is about one fifth of the marginal effect of a 1°C reduction of the daily maximum temperature (Table 10 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)	(2)	(3)
	Std. Result	Std. Result	Std. Result
PM 2.5	-0.0011***	-0.0013***	-0.0010**
	(0.0004)	(0.0004)	(0.0004)
Ozone		0.0002	
		(0.0002)	
Individual FE	Yes	Yes	Yes
Time	Yes	Yes	Yes
Weather	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes
Week	No	No	Yes
Observations	502529	388169	502529

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.

5.1 Avoidance behavior

Individuals may avoid competing in locations with high pollution levels if they fear their health is at risk. Alternatively, they might choose where to compete depending on weather conditions that correlate with pollution. The inclusion of individual fixed effects should mitigate concerns of bias due to avoidance behavior. Nonetheless, I test whether concentrations of PM 2.5 predict participation in competitions. Table 3 reports the results of a regression of the log number of participants in a given stadium-day on PM 2.5 and weather, time, and city fixed effects. Column (2) includes ozone as a regressor, and Column (3) adds week-of-the-year fixed effects. Results suggest that athletes do not avoid competitions on polluted days.

Table 3: Testing for presence of avoidance behavior.

	(1) Log(Partecipants)	(2) Log(Partecipants)	(3) Log(Partecipants)
PM 2.5	-0.0011	-0.0025	0.0001
	(0.0024)	(0.0029)	(0.0026)
Ozone		0.0006	
		(0.0019)	
Time	Yes	Yes	Yes
Weather	Yes	Yes	Yes
Stadium	Yes	Yes	Yes
Week	No	No	Yes
Observations	3312	2540	3312

Standard errors in parentheses

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

Note. Dependent variable: log number of participants to competitions in a given stadium-day. *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* includes stadium fixed effects. *Week* include week-of-the-year fixed effects. Standard errors are clustered by stadium.

5.2 Heterogeneity by task requirements

As an illustration of how a task framework can contribute to understanding the productivity costs of environmental conditions, I compute heterogeneous effects by the typical duration of a competition. The latter is calculated as the average duration of a given event by year 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, 2020b), rely on energy for movement that is produced in the absence of oxygen. On the other hand, tasks that require dynamic strength, such as those performed by construction laborers, depend on oxygen for the chemical reactions used to produce the energy for movement.[13]

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 consistent across the three main specifications (Table 4). This suggests that longer-lasting tasks that consequently rely on pulmonary capacity bear greater costs of air pollution.

[13] 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". Dynamic strength is defined as "the ability to exert muscle force repeatedly or continuously over time [involving] muscular endurance and resistance to muscle fatigue".

Table 4: The impact of PM 2.5 on physical performance. Heterogeneous effects by task requirements.

	(1) Std. Result	(2) Std. Result	(3) Std. Result
PM 2.5	-0.0008**	-0.0011***	-0.0007*
	(0.0004)	(0.0004)	(0.0004)
Duration	0.0002***	0.0001***	0.0002***
	(0.0000)	(0.0000)	(0.0000)
PM 2.5 $\times$ Duration	-0.0000***	-0.0000**	-0.0000***
	(0.0000)	(0.0000)	(0.0000)
Ozone		0.0002	
		(0.0002)	
Individual FE	Yes	Yes	Yes
Time	Yes	Yes	Yes
Weather	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes
Week	No	No	Yes
Observations	502529	388169	502529

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). *Duration* is the average duration of competitions (in seconds) in groups defined by event, year, and gender. 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.

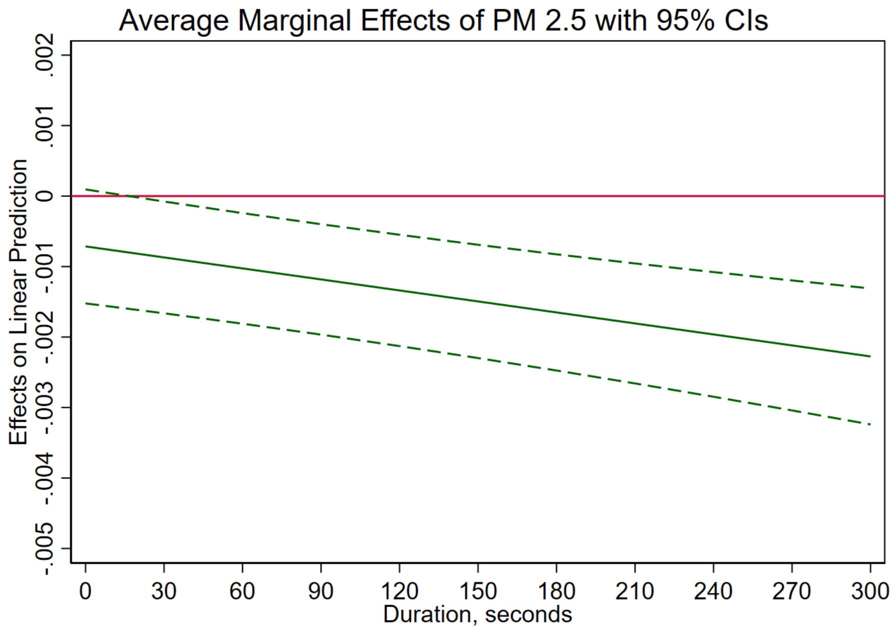

Figure 3: Marginal effect of PM 2.5 on performance by average event duration in groups defined by event, year, and gender.

5.3 Gender, age, and ability effects

Next, Columns (1) through (3) of Table 5 interact PM 2.5 with a female dummy variable. It appears that PM 2.5 has no different impact on the productivity of females and males. Columns (4) through (6) interact PM 2.5 with age; Columns (7) through (9) interact PM 2.5 with am 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 negative productivity effect of PM 2.5 grows larger with age (Columns (4) to (6)).[14] 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, low ability individuals are arguably more likely to drop out of the sport than high ability ones. Columns (7) through (9) suggest that the performance loss caused by PM 2.5 is greater for top athletes, approximately five times as large. At least part of the mediating effect of age should be attributed to increased competition among individuals. One possible explanation is that low ability athletes are more able to compensate for losses from air pollution.

[14]Figure 6 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 15 years of age.

Table 5: The impact of PM 2.5 on physical performance. Heterogeneous effects by gender, age, and ability.

	Gender			Age			High ability		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Std. Result	Std. Result	Std. Result	Std. Result	Std. Result	Std. Result	Std. Result	Std. Result	Std. Result
PM 2.5	-0.0012***	-0.0012***	-0.0011***	0.0023**	0.0010	0.0029***	-0.0008**	-0.0010**	-0.0008*
	(0.0004)	(0.0005)	(0.0004)	(0.0010)	(0.0011)	(0.0010)	(0.0004)	(0.0004)	(0.0004)
Female × PM 2.5	0.0003	-0.0000	0.0002						
	(0.0004)	(0.0005)	(0.0004)						
Ozone		0.0002			0.0002			0.0002	
		(0.0002)			(0.0002)			(0.0002)	
PM 2.5 × Age				-0.0002***	-0.0001**	-0.0003***			
				(0.0001)	(0.0001)	(0.0001)			
PM 2.5 × High ability							-0.0036***	-0.0037***	-0.0038***
							(0.0005)	(0.0005)	(0.0005)
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Week	No	No	Yes	No	No	Yes	No	No	Yes
Observations	502529	388169	502529	502529	388169	502529	502529	388169	502529

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). *High ability* is an indicator for athletes that perform in the top decile at least 50% of the time. 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.

5.4 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, 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 scenario and the ability to outperform competitors in a final sprint. 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 fixed effects are included in the regression. Nonetheless, to address the remaining doubts, I estimate the three main specifications excluding all race competitions of distance over 400 meters and report results in Table 6. Table 9 in Appendix further addresses strategic behavior in multi-stage competitions including qualifiers.

Results are virtually unchanged, confirming that strategic races do not drive the observed impacts of PM 2.5.

Table 6: The impact of PM 2.5 on physical performance. Excluding events where strategic behavior is possible.

	(1) Std. Result	(2) Std. Result	(3) Std. Result
PM 2.5	-0.0011***	-0.0014***	-0.0009**
	(0.0004)	(0.0004)	(0.0004)
Ozone		0.0002	
		(0.0002)	
Individual FE	Yes	Yes	Yes
Time	Yes	Yes	Yes
Weather	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes
Week	No	No	Yes
Observations	418122	321249	418122

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, 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.

6 Conclusions

Despite the growing literature assessing the effect on workers' productivity of environmental conditions such as pollution and temperature, the ability to assess the portability of results remains elusive. I argue that a task framework Autor et al. (2003) that links tasks to skills and ability requirements could help to bridge this gap. A body of studies has already stepped into this direction, estimating the effects of pollution and temperature on cognitive abilities measured through standardized tests. However, in the context of air pollution, equivalent evidence on the productivity effects through primarily physical channels is limited.

This paper offers new evidence on the impacts of PM 2.5 on physical abilities 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 causal 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% of a standard deviation after including a battery of fixed effects, including individual fixed effects and a flexible specification of weather. 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.

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.

Individuals in the data are positively selected on physical capabilities and typically young. However, low entry barriers make track and field competitions widely accessible and equally to males and females. While no claims of representativeness are made, the results speak to the literature on pollution costs. They are especially relevant for developing countries, where large shares of the economy employ manual laborers, and the population is young. Hopefully, future research will deepen our understanding of pollution's heterogeneous impacts across jobs and its distributional consequences.

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A Appendix

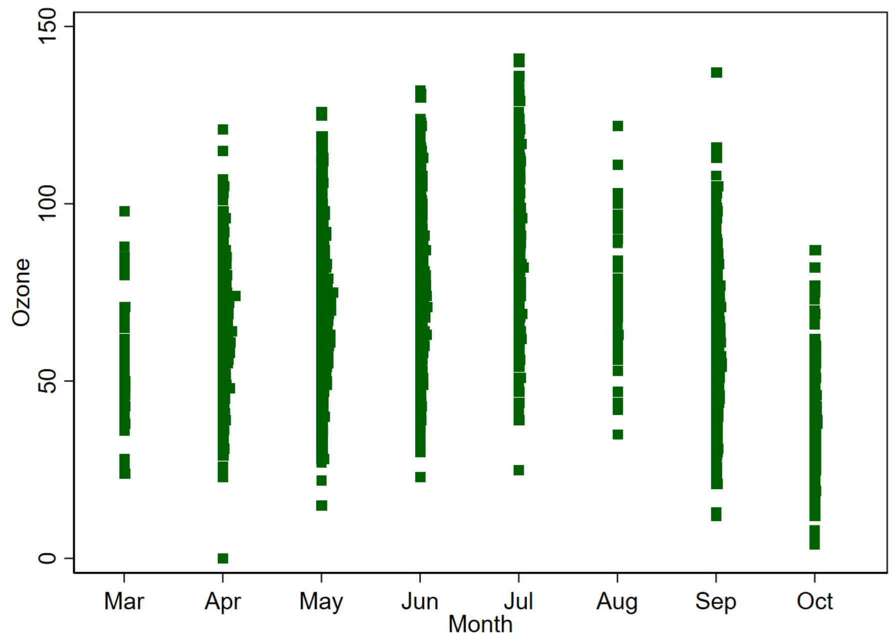

Figure 4: Distribution of ozone by month.

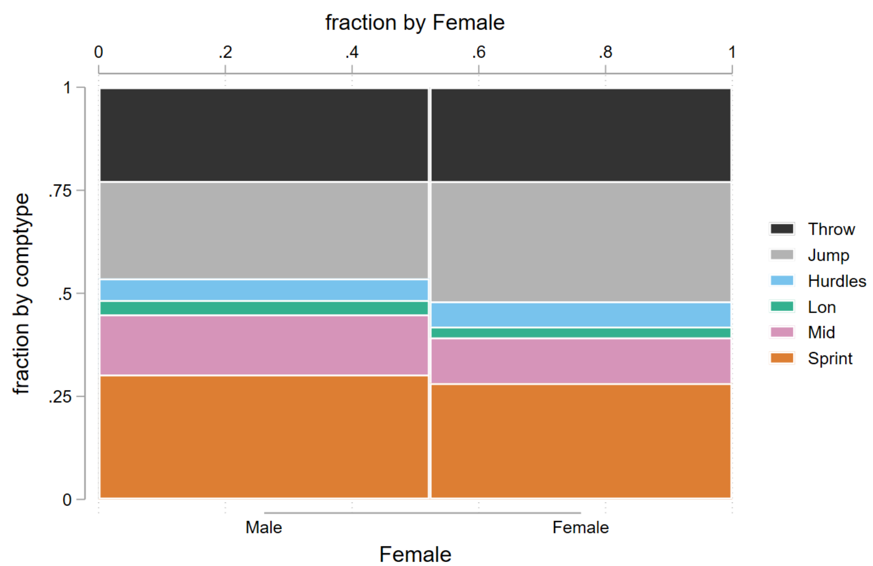

Figure 5: Share of observations by gender and type of event: races (sprints, hurdles, mid and long distance), jumps and throws.

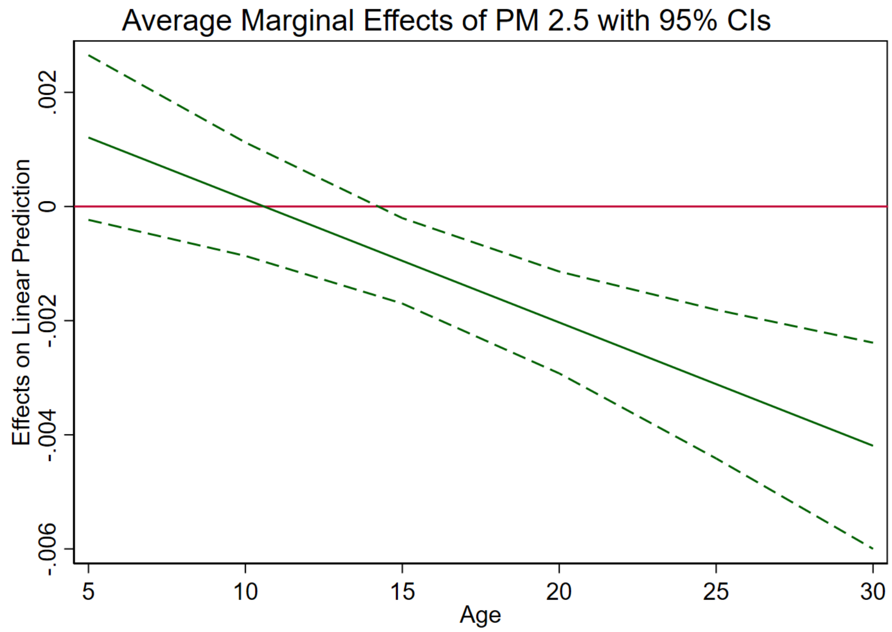

Figure 6: Marginal effect of PM 2.5 on physical performance by age.

Table 7: The impact of PM 2.5 on physical performance. Adjusting for ozone and week fixed effects.

	(1)
	Std. Result
PM 2.5	-0.0010**
	(0.0004)
Ozone	-0.0000
	(0.0002)
Individual FE	Yes
Time	Yes
Weather	Yes
Stadium, Team	Yes
Week	Yes
Observations	388169

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 8: The impact of PM 2.5 on physical performance. Quadratic effects.

	(1) Std. Result	(2) Std. Result	(3) Std. Result
PM 2.5	0.0004	-0.0006	0.0017*
	(0.0009)	(0.0010)	(0.0009)
PM 2.5 × PM 2.5	-0.0000*	-0.0000	-0.0001***
	(0.0000)	(0.0000)	(0.0000)
Ozone		0.0002	
		(0.0002)	
Individual FE	Yes	Yes	Yes
Time	Yes	Yes	Yes
Weather	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes
Week	No	No	Yes
Observations	502529	388169	502529

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.

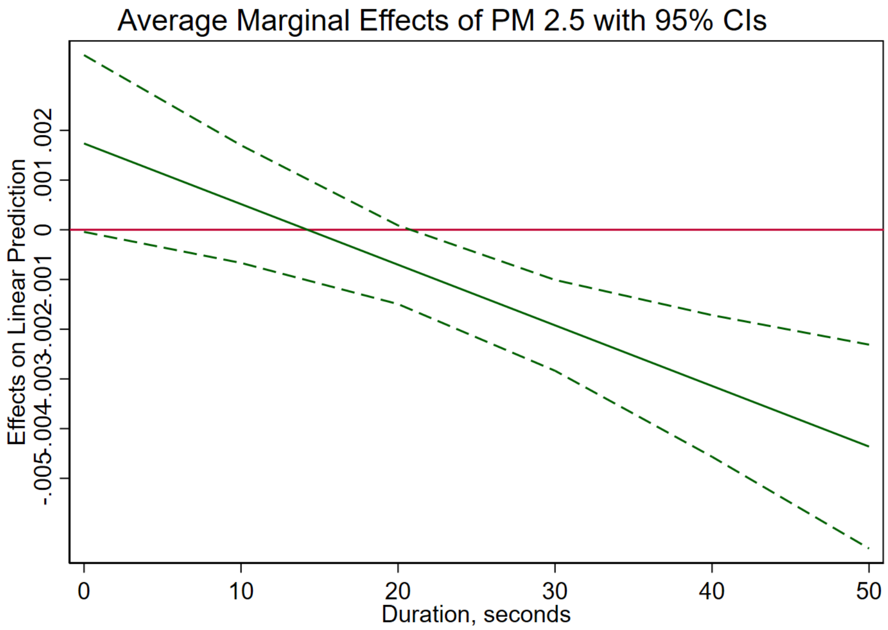

Figure 7: Nonlinear effect of PM 2.5 on physical performance.

Table 9: 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)	(3)
	Std. Result	Std. Result	Std. Result
PM 2.5	-0.0010***	-0.0014***	-0.0009**
	(0.0004)	(0.0004)	(0.0004)
Ozone		0.0002	
		(0.0002)	
Individual FE	Yes	Yes	Yes
Time	Yes	Yes	Yes
Weather	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes
Week	No	No	Yes
Observations	413795	318014	413795

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 10: The impact of PM 2.5 on physical performance. Comparison with the effect of temperature.

	(1)	(2)	(3)
	Std. Result	Std. Result	Std. Result
PM 2.5	-0.0012***	-0.0014***	-0.0011***
	(0.0004)	(0.0004)	(0.0004)
Temp. max	0.0055***	0.0063***	0.0053***
	(0.0009)	(0.0010)	(0.0009)
Ozone		-0.0001	
		(0.0002)	
Individual FE	Yes	Yes	Yes
Time	Yes	Yes	Yes
Wind bins	Yes	Yes	Yes
Precip. bins	Yes	Yes	Yes
Stadium, Team	Yes	Yes	Yes
Week	No	No	Yes
Observations	502529	388169	502529

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.