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Amateur runners more influenced than elite runners by temperature and air pollution during the UK's Great North Run half marathon

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HIGHLIGHTS

- Examination of the impact environmental factors have on half marathon performances.
- Increased air temperatures and O_3 concentrations can both slow half marathon times.
- The slowest participants are impacted the most by these environmental variables.
- Elite athletes show a significant slowing in pace under increased O_3 concentrations.
- Increased exposure time believed to cause the greater impact on slower participants.

GRAPHICAL ABSTRACT

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ABSTRACT

The short- and long-term impacts of air pollution on human health are well documented and include cardiovascular, neurological, immune system and developmental damage. Additionally, the irritant qualities of air pollutants can cause respiratory and cardiovascular distress. This can be heightened during exercise and especially so for those with respiratory conditions such as asthma. Meteorological conditions have also been shown to adversely impact athletic performance; but research has mostly examined the impact of pollution and meteorology on marathon times or running under laboratory settings. This study focuses on the half marathon distance (13.1 miles/21.1 km) and utilises the Great North Run held in Newcastle-upon-Tyne, England, between 2006 and 2019. Local meteorological (temperature, relative humidity, heat index and wind speed) and air quality (ozone, nitrogen dioxide and $PM_{2.5}$) data is used in conjunction with finishing times of the quickest and slowest amateur participants, along with the elite field, to determine the extent to which each group is influenced in real-world conditions. Results show that increased temperatures, heat index and ozone concentrations are significantly detrimental to amateur half marathon performances. The elite field meanwhile is influenced by higher ozone concentrations. It is thought that the increased exposure time to the environmental conditions contributes to this greater decrease in performance for the slowest participants. For elite athletes that are performing closer to their maximal capacity (VO_2 max), the higher ozone concentrations likely results in respiratory irritation and decreased performance. Nitrogen dioxide and $PM_{2.5}$ pollution showed no significant relationship with finishing times. These results provide additional insight into the environmental effects on exercise, which is particularly important under the increasing effects climate change and regional air pollution. This study can be used to inform event organisation and start times for both mass participation and major elite events with the aim to reduce heat- and pollution-related incidents.

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1. Introduction and background

Urban air quality is of wide-reaching concern due to its effects upon human and environmental health (European Commission, 2013; Walton et al., 2015). The World Health Organisation (WHO) provides air quality guidelines (AGQs) for outdoor air pollutants for which there is evidence of an increased risk to health (World Health Organisation, 2021). For the air pollutants of interest to this study, namely: ozone (O_3), nitrogen dioxide (NO_2) and $PM_{2.5}$ (particles with a diameter of <2.5 μm), the short term WHO AQGs are 15 μg m^{-3} for $PM_{2.5}$ averaged over a 24 h mean; 25 μg m^{-3} for $PM_{2.5}$ averaged over a 24 h mean; and 100 μg m^{-3} for O_3 averaged over a 8 h mean, With global physical activity levels being at an all-time low (Hallal et al., 2012; Marmett et al., 2020; Swinburn et al., 2011, 2019), there have been increasing calls for physical activity to be increased to help combat the global obesity crisis and reduce the likelihood of additional social and economic costs by improving mental health and wellbeing, reducing prevalence of health related diseases and improving productivity (Hallal et al., 2012; Marmett et al., 2020; Swinburn et al., 2011; Public Health England, 2016; Swinburn et al., 2019; Stevinson and Hickson, 2014; Grunseit et al., 2018; Hindley, 2020; Stevinson et al., 2015). However, the detrimental health effects of urban air quality need to be considered when exercising, especially when in some cases the pollution risks outweigh the benefits of physical activity (Guo et al., 2020; McCreanor et al., 2007; Pasqua et al., 2018; Strak et al., 2010). These risks include short term cardiorespiratory irritation, reduced lung function and increased likelihood of asthma attacks, whilst long term pollution exposure has been shown to contribute to reduced cognition, cardiovascular and respiratory diseases and ultimately a reduction in life expectancy and premature death (Burnett et al., 2014; Calderon-Garciduenas et al., 2016; Lelieveld et al., 2015; Rajagopalan et al., 2018; World Health Organisation, 2020).

The effect of air pollution (O_3, NO_2 and $PM_{2.5}$) on exercise and athletic performance has been examined in a mixture of 'real world' and laboratory based studies. Most notably, Marr and Ely (2010), Helou et al. (2012) and Guo and Fu (2019) who showed that increased pollution levels were responsible for slower marathon times. Poor air quality has also been shown to reduce VO_2 max (the maximum amount of oxygen a person can utilise during exercise) and maximal exercise performance (Boussetta et al., 2017; Giles et al., 2014; Giles et al., 2018; Morici et al., 2020). This can be coupled with increased perceived exertion levels and respiratory effects such as reduced lung function and irritation (Boussetta et al., 2017; Giles et al., 2014; Giles et al., 2018; Morici et al., 2020).

Meteorological conditions, namely temperature, relative humidity and wind speed, have been shown both in past academic research and recent sporting events to have a significant impact on athletic performance (Bigazzi, 2016). Marathon and laboratory studies indicate that higher temperatures decrease performance due to alterations in the circulatory, endocrine and thermoregulatory systems to maintain a stable core body temperature (Casa, 1999; Ely et al., 2007; Helou et al., 2012; Miller-Rushing et al., 2012; Nadel, 1990; Nybo et al., 2014; Vihma, 2010; Vugts, 1997; Zhao et al., 2013). Increased relative humidity can also be detrimental by reducing heat dissipation, whilst high wind speeds as a head- or cross-wind will also result in slower performances (Casa, 1999; Davies, 1980; Helou et al., 2012; Nadel, 1990; Vihma, 2010). Meteorological conditions have also been shown to seriously affect elite athletes during events, with two UK athletes Jonathon Brownlee and Callum Hawkins collapsing at the 2016 Cozumel World Triathlon Grand Final and 2018 Gold Coast Commonwealth Games marathon respectively and significant proportion of the 2019 Marathon World Championships field failing to finish in Doha (BBC Sport, 2016; BBC Sport, 2018). Amateur exercisers are also at risk with a number of deaths and heat related medical incidents being reported during (BBC Sport, 2018; Carlstrom et al., 2019; Khorram-Manesh et al., 2020; The Guardian, 2018).

Previous research has generally focused on marathon events but Schwabe et al. (2014) found that the risk of serious medical incidents were as common in half marathon events as full- and ultra-marathon events. For example, examination of the Gothenburg half marathon in Sweden showed that as temperatures increase, notably from 15°C and above, the number of medical emergencies and 'did not finish' participants also increased (Carlstrom et al., 2019; Khorram-Manesh et al., 2020; Luning et al., 2019). This is corroborated by Hostler et al. (2014) who found 39 cases of heat-related incidents at the 2011–2013 Pittsburgh combined half and full marathon event. Hostler et al. (2014) noted that more incidents occurred after the half marathon route was changed, which resulted in increased sun exposure. D'ulisse (2019) also reported 24 incidents of heat-related illness during the 2017 Montreal half marathon held under heatwave conditions. Half marathon running pace under hot and humid conditions have also been shown to decrease when core body temperatures reach 39 °C between the 6 and 9 km mark of events (Rodrigues et al., 2020). These factors, coupled with increasing temperatures and concerns regarding the potentially detrimental effects of air quality and meteorology on health and performance mean that further examination of participants responses to such variables is required (Miller-Rushing et al., 2012; Morici et al., 2020).

To further explore the influence of the environmental variables on athletic performance, this paper examines the Great North Run: an annual half marathon (13.1 miles/21.1 km) event held in Newcastle Upon Tyne, UK, during September. The time taken for an elite athlete to complete a half marathon is approximately 1 h, and for amateur runners it takes longer. Hence the effect of, and any association with, environment parameters upon running times is due to short term (acute) physiological effects. Slower runners will experience the environmental conditions for longer. Since its inception in 1981, the Great North Run has become a highly popular event for both recreational and elite male and female athletes, earning the title of the 'largest half marathon' in the world in 2014 (Guinness World Records, 2021). The often (relatively by UK standards) warm weather experienced in September is known to affect athletes. Previous studies of the Great North Run have shown that heat stroke has been commonly reported at the event, with four participants having the condition listed as their suspected cause of death in 2005 (BBC, 2005; Hawes et al., 2010; Yankelson et al., 2014). As has been highlighted, most previous research has either focused separately on either elite or recreational runners over either 5000 m or marathon distances (Helou et al., 2012). Therefore, this examination of the Great North Run provides a novel environment to examine how both elite and recreational athletes respond to variations in air quality and meteorology at the same event.

2. Materials and methods

Finishing times for the Great North Run were extracted for 2006–2019 inclusively from the events data archive. This included the entire male and female elite fields ($n = 668$ and 399 respectively) and the quickest and slowest amateur participants. Elite runners are pre-identified in the finishing list and have gained this status by achieving the qualifying time or standard set by the race organiser. Currently for the Great North Run this has been set at 69:00 and 83:00 min for men and women respectively but may be different in previous and future iterations of the event. The fastest and slowest amateur participants were identified by taking the first 150 and last 150 male and female amateur finisher's times taken from the Great North Run archive available online. This gave three specific groups of finishers to examine and unlike previous studies which have utilised the first or top three finishers only, provides a wider-ranging view as to the potential effects meteorology and air quality may have on participants.

Utilising the quickest finishers in the amateur field will provide a good comparison between elite and amateur athletes and whether there are any differences between their respective finishing times in response to meteorology or air quality. There is also an increased likelihood that these amateurs will have higher volume training regimes compared to the slowest amateur finishers. Increased exercise levels have been shown to increase the minute ventilation rate and pollution exposure compared to more sedentary activities (Giles and Koehle, 2014; Pasqua et al., 2018). Therefore, these 'first' finishers are potentially more likely to be working at a higher percentage of their VO_2 max and consequently have a higher uptake of air and thus pollution which may influence their performance. The slowest finisher's times were examined to explore the hypothesis that meteorology and air quality influences slower participants more. This is most likely due to reduced training and physiological capacity and conditioning, and increased exposure to external variables (Ely et al., 2007; Vihma, 2010).

Air quality data was extracted from the only Department for Environment, Food and Rural Affairs (DEFRA) Automatic Urban and Rural Network (AURN) urban background monitoring station located in Newcastle city centre (Fig. 1). This provided hourly readings for O_3, NO_2 and $PM_{2.5}$. Hourly meteorology data for temperature, relative humidity and wind speed was obtained through the worldmet package in R (Carslaw, 2018) from the site located North West of the city at Newcastle International Airport (Fig. 1). Heat index, which combined the influence of temperature and relative humidity, was calculated using the weathermetrics package in R Studio (Anderson et al., 2013). This uses equations created by the National Weather Service (Eq. (1) – where T = temperature in °F and RH is relative humidity in %). This method of calculation has been shown to provide the most accurate values in a study of 21 algorithms by Anderson et al. (2013).

$$\begin{aligned}\text{Heat Index} = & -42.379 + (2.04901523 \times T) + (10.14333127 \times RH) \\ & - (0.22475541 \times T \times RH) - \left(6.83783 \times 10^{-3} \times T^2\right) \\ & - \left(5.481717 \times 10^{-2} \times RH^2\right) + \left(1.22874 \times 10^{-3} \times T^2 \times RH\right) \\ & + \left(8.5282 \times 10^{-4} \times T \times RH^2\right) - \left(1.99 \times 10^{-6} \times T^2 \times RH^2\right)\end{aligned} \tag{1}$$

The mean finishing time for male and female participants was calculated for the elite and amateur fields, respectively. Consistent age data was not available across the study period so was not included in analyses. The mean air quality and meteorological variables between 10:00 and 12:00 h inclusive and 10:00–15:00 h inclusive was also calculated. These two periods cover the start time for the elite and amateur fields as well as the duration participants would be running for. This was to provide as much explanatory variability as possible during the participant's time on course, something that has been highlighted previously as a limitation in studies which only use a single mean value (Cheuvront and Haymes, 2001; Maughan, 2010).

Prior to analysis, all data was checked for normality and homogeneity through skewness, kurtosis and Shaprio-Wilks and Levene's tests and was logged where necessary due to data not being normally distributed. Outliers exceeding the interquartile range detected by the boxplot "$out" function in R for the elite finishers were also removed. Similarly to Helou et al. (2012), Marr and Ely (2010), Trapasso and Cooper (1989) and Vihma (2010), analysis was performed through correlation, linear regression and two multiple linear regression models, one for the meteorology variables and one for the air quality variables. Meteorology and air quality variables were not included in the same multiple linear regression model due to the risk of multicollinearity, (e.g. between temperature, NO_2 and O_3.) Post-test analysis was performed using diagnostic tests; Quantile-Quantile, Scale-Location, Fitted vs Residuals, Cooks-Distance plots and Variable inflation factors (VIFs) for the multiple linear regression models.

Further correlation and linear regression analyses were also performed between the temperature, heat index, O_3 and NO_2 variables to further determine the relationships between them during the Great North Run and the potential influence they may have on performances. This is because it is inherently difficult to fully extract the influence of one of these variables on participants due

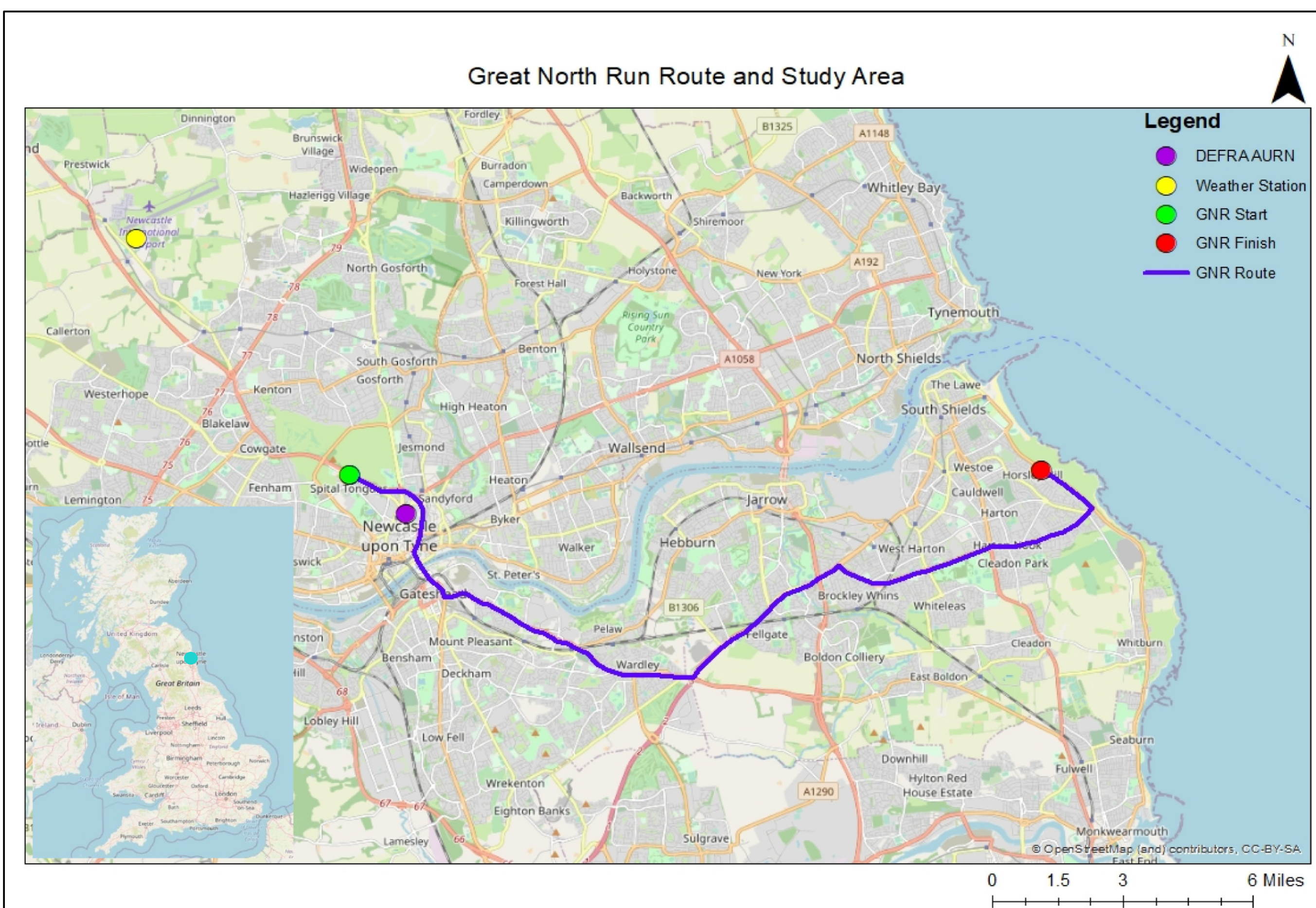

Fig. 1. The Great North Run Route from central Newcastle to the eastern coast. The DEFRA AURN monitoring site is located in the city centre whilst the meteorology monitoring station is in the north west located at Newcastle International Airport.

to their interactions as part of the Leighton reactions (Eqs. (2) and (3), Clapp and Jenkin, 2001; Helou et al., 2012; Leighton, 1961).

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{2}$$

$$NO_2 + h\nu\ (+O_2) \rightarrow NO + O_3 \tag{3}$$

To determine whether there were difference between elite, fastest amateur and slowest amateur finishing times and the associated meteorological and air quality variables the athletes were exposed to, descriptive statistics and a one-way ANOVA with suitable post-hoc tests were performed. This was designed to better account for the increased time the slowest participants took to complete the half marathon in comparison to the elite and quickest amateur participants. Correspondingly, the explanatory variable period used for analysis was increased. This allows for the examination of the debate surrounding whether air pollution and/or meteorology influences the quickest or slowest athletes the most.

3. Results

Descriptive statistics data for the run times split by sex and ability grouping is found in Table 1. For both sexes, there is less variation in running times for the elite athletes compared to the amateur participants, with the quickest amateurs also showing less variation than the slowest amateur grouping.

Table 2 shows the significant results of linear regression analysis, with further discussion of results shown in the following sections.

3.1. Elite athletes

For elite athletes, male finishing times (h:m:s) ranged from 0:59:07 to 1:18:24 across the study period, with female times between 1:04:28 and 1:38:14. Correlation and linear regression analysis (Table 2) between the mean male and female finishing times each year and the corresponding explanatory variables showed that O_3 had a slowing effect for the female elite subset (coefficient $= 470.4$, $R^2 = 0.47$ $p \leq 0.01$).

3.2. Fastest amateurs

For the quickest finishing amateur participants, male finishing times ranged from 1:00:11 to 1:24:21 h:m:s, and female times from 1:16:23 to 1:40:25 h:m:s (thus showing some overlap with the elite athletes). However, the median and mean finishing times of elite athletes is considerably quicker, and was shown to be significant through the use of a Kruskal-Wallace and subsequent Dunn test ($p \leq 0.01$). This same test also confirmed that statistically the slowest amateur finishing times were significantly different to the quickest amateurs and the elite athletes ($p \leq 0.01$).

Similarly, there were no significant results between the quickest amateurs and air quality variables. However, for the male subset significant relationships were highlighted by the multiple linear regression for O_3 ($p \leq 0.01$) and $PM_{2.5}$ ($p = 0.05$). Despite this, upon closer inspection with post-hoc tests, the variable inflation factors (VIFs) were not within the accepted boundaries of 3 and subsequent multiple linear regression tests with O_3 and NO_2, O_3 and $PM_{2.5}$ and NO_2 and $PM_{2.5}$ that did satisfy the VIFs conditions showed no significant relationships. The female subset analysis did not show any significant nor close to significant results, including those for the effect of O_3 and $PM_{2.5}$.

3.3. Slowest amateurs

The slowest finishers, unlike their quicker counterparts, showed a number of significant relationships between finishing times and meteorology and air quality variables. Analysis of the male showed that temperature, heat index and O_3 showing detrimental relationships ($p \leq 0.01$) and quicker times being recorded under higher NO_2 levels for correlation ($p = 0.04$). The same results were shown for the linear regression analysis ($p = 0.01$), although NO_2 was not significant ($p = 0.06$). Temperature and heat index was also significantly related to O_3 levels ($p \leq 0.04$). Multiple linear regression only had one significant result, with temperature being positively related to finishing times (coefficient $= 180.55$, $R^2 = 0.4$, $p = 0.02$). This suggests that temperature is the more influential variable when compared with heat index effects.

Finally, female analysis of the slowest finishers also mirrored that of the male results. Temperature, heat index and O_3 all showed positive correlations and linear relationships with finishing times ($p \leq 0.03$). Multiple linear regression also showed temperature to be detrimental to performance (coefficient $= 222.67$, $R^2 = 0.26$, $p = 0.03$) whilst temperature and heat index were also positively related to O_3 levels ($p \leq 0.05$).

It appears that the slowest female participants may be slightly less influenced by detrimental variables, with temperature and O_3 explaining slightly less of the variance in their finishing times compared to their male counterparts. Fig. 2 below shows the relationships between the slowest male run times, temperature and O_3.

3.4. Finishing 'group' differences

To determine whether the significant results shown by the slowest amateur participants was due to differences in the air quality and meteorological conditions experienced as a consequence of the longer time they spend

Table 1
The minimum, mean, maximum and standard deviation of variables examined at the Great North Run event between 2006 and 2019.

Variable	Minimum	Mean	Maximum	Standard deviation
Finishing time - elite male (s)	3536	4033	4704	253.1
Finishing time - elite female (s)	3868	4670	5894	433.3
Finishing time - fast amateur male (s)	3611	4701	5061	498.9
Finishing time - fast amateur female (s)	4585	5580	6019	502.0
Finishing time - slow amateur male (s)	12,512	14,158	53,974	1362.4
Finishing time - slow amateur female (s)	13,420	14,932	54,789	2049.9
Temperature (elite and fast amateur – °C)	9.7	14.3	17.8	2.0
Temperature (slow amateur - °C)	10.8	15.1	17.8	1.7
Relative humidity (elite and fast amateur - %)	60.0	73.6	97.9	10.3
Relative humidity (slow amateur - %)	55.2	70.3	97.9	10.4
Wind speed (elite and fast amateur – ms^{-1})	0.4	3.8	8.3	2.2
Wind speed (slow amateur – ms^{-1})	0.4	4.2	8.8	2.2
Heat index (elite and fast amateur)	8.0	14.0	18.0	2.4
Heat index (slow amateur)	10.0	14.6	17.0	1.8
O_3 (elite and fast amateur – $\mu g\ m^{-3}$)	20.7	40.3	87.0	11.5
O_3 (slow amateur – $\mu g\ m^{-3}$)	17.0	39.4	87.0	9.9
NO_2 (elite and fast amateur – $\mu g\ m^{-3}$)	15.9	22.4	29.0	3.5
NO_2 (slow amateur – $\mu g\ m^{-3}$)	17.1	27.3	56.2	11.3
$PM_{2.5}$ (elite and fast amateur – $\mu g\ m^{-3}$)	3.5	7.2	11.7	3.3
$PM_{2.5}$ (slow amateur – $\mu g\ m^{-3}$)	2.7	7.8	14.4	4.1

Table 2
Linear regression analysis results. Significant results ($p < 0.5$) are highlighted.

Analysis Group	Variable (vs run time (s))	Intercept (s)	Coefficient (s)	Standard Error	R^2 value	p value
Elite male	Temperature	3934.29	6.22	9.66	0.05	0.53
	Relative Humidity	4911.5	-475.5	322.9	0.08	0.17
	Wind Speed	4064.63	-10.13	8.58	0.03	0.26
	Heat Index	3978.71	3.27	8.27	0.07	0.7
	Ozone	3842.4	113.9	156.0	0.04	0.48
	Nitrogen Dioxide	4134.15	-5.39	5.318	0.01	0.34
	$PM_{2.5}$	3999.96	-2.21	8.4	0.18	0.8
Elite Female	Temperature	4612.49	3.4	12.78	0.08	0.8
	Relative Humidity	5899.0	-663.1	416.0	0.11	0.14
	Wind Speed	4646.76	3.74	11.78	0.07	0.76
	Heat Index	4665.28	-0.26	10.86	0.08	0.98
	Ozone	6421.0	470.4	138.9	0.47	<0.01
	Nitrogen Dioxide	4871.98	-9.56	6.74	0.08	0.19
	$PM_{2.5}$	4741.08	-16.57	7.44	0.4	0.08
Fastest Amateur Male	Temperature	4583.25	8.93	7.88	0.02	0.28
	Relative Humidity	4648.24	0.86	1.67	0.06	0.62
	Wind Speed	4702.73	2.4	7.61	0.07	0.76
	Heat Index	4599.99	8.06	6.63	0.04	0.25
	Ozone	4783.37	-42.87	132.32	0.08	0.75
	Nitrogen Dioxide	4850.01	-6.09	4.95	0.04	0.25
	$PM_{2.5}$	4644.01	7.16	1.41	0.14	0.22
Fastest Amateur Female	Temperature	5626.96	0.78	8.6	0.08	0.93
	Relative Humidity	5731.6	-1.26	1.72	0.04	0.48
	Wind Speed	5657.03	-4.7	7.82	0.05	0.56
	Heat Index	5625.69	0.9	7.29	0.08	0.9
	Ozone	5820.0	-113.9	135.6	0.03	0.42
	Nitrogen Dioxide	5659.63	-1.08	5.52	0.1	0.85
	$PM_{2.5}$	5526.62	14.75	8.51	0.25	0.14
Slowest Amateur Male	Temperature	11225.43	191.77	63.82	0.4	0.01
	Relative Humidity	15020.31	-12.61	12.96	0.004	0.35
	Wind Speed	13942.75	44.88	62.78	0.04	0.49
	Heat Index	11706.02	167.14	59.04	0.37	0.01
	O_3	12747.55	34.63	10.9	0.43	<0.01
	Nitrogen Dioxide	14672.67	-20.61	11.64	0.15	0.1
	$PM_{2.5}$	14181.16	-17.65	54.05	0.18	0.76
Slowest Amateur Female	Temperature	11557.2	221.04	80.01	0.34	0.02
	Relative Humidity	15585.32	-9.76	16.04	0.05	0.55
	Wind Speed	14847.7	12.08	77.47	0.08	0.88
	Heat Index	11932.96	207.80	70.94	0.38	0.01
	Ozone	13346.1	39.7	14.2	0.36	0.02
	Nitrogen Dioxide	15666.39	-27.76	13.9	0.2	0.07
	$PM_{2.5}$	14953.53	-24.6	64.84	0.17	0.72

on the route, analysis between the 10:00–12:00 and 10:00–15:00 data was performed. Despite descriptive statistics showing, on average, slightly warmer, windier and more polluted conditions for the 10:00–15:00 data period, results showed that there were no significant differences between the conditions experienced by the fastest and slowest finishers of the Great North Run ($p \geq 0.05$). As has been previously highlighted, there were significant differences between the finishing times of all three groups ($p \leq 0.01$). This, and the slightly more 'adverse' conditions faced by the slowest amateurs are shown in Fig. 3.

4. Discussion

4.1. Elite and quickest amateurs

This Great North Run provides an excellent opportunity to examine the influence of meteorology and air quality on both amateur and elite participants, who follow the same course at nearly the same time. Results suggest that elite female athletes are detrimentally impacted by increased O_3 levels, whilst male elites are not. This reflects the results of the Diamond League athletics series examined by Hodgson et al. (2021), which showed female athletes to be more susceptible to the effects of air pollution, temperature and wind speeds. The reasons for this are unclear, but have also been previously highlighted by Helou et al. (2012). In contrast, however, the elite male and the quickest amateur participants, both male and female, are not significantly influenced in terms of their finishing time by the meteorological or air quality conditions found on the event day. Despite this, anecdotally and from laboratory tests, the local conditions may have caused an increase in perceived exertion and an irritant response of the eyes and respiratory system, but not to an extent that would be shown in the finishing times (Florida-James et al., 2011; Giles et al., 2014, 2018; Kargarfard et al., 2015). Furthermore, the work of Helou et al. (2012) and Marr and Ely (2010) showed no effects of $PM_{2.5}$ on marathon performances, as was also observed in this study.

Particularly for the elite participants, a lack of significant relationships other than the female elites slowing under elevated ozone concentrations may also be due to them having a higher running economy, which results in reduced energy demands and heat production and enables them to run faster for longer in adverse conditions (Conley and Krahenbuhl, 1980; Maughan, 2010; Noakes et al., 1990). This counters the theory by Gasparetto and Nesseler (2020) that although quicker runners run for the shortest period of time, they are doing so more intensely and closer to their maximal capacity, making them more likely to suffer from overheating and other performance decreases. However, the work of Ely et al. (2007), Montain et al. (2007) and Vihma (2010) all suggest that quicker runners would be influenced less. Similarly, Renberg et al. (2014) showed that temperature ultimately had no influence on running performance despite increased heart rate and blood lactate levels being recorded. However, Gasparetto and Nesseler's (2020) argument can be used to suggest why, despite having physiological, psychological and genetic advantages over amateur runners, elite female athletes saw performance decreases under higher ozone concentrations whilst the fastest amateurs did not. This may be due to elite athletes performing closer to their maximal capacity and thus more likely to be influenced by pollution and other environmental factors (Gasparetto and Nesseler, 2020). As is noted previously, why this has so far only been demonstrated for female athletes underlines a need for further study (Helou et al., 2012; Hodgson et al., 2021).

The influence of improved running economy can also be considered for the quickest amateur finishers, many of whom finished in a similar time to, or even quicker, than some of the elite field, suggesting that they too have a suitably high enough running economy to perform well in unfavourable conditions. It is also likely that the quickest and elite runners will have put in the highest amount of training prior to the event (often 150–260 km per week) which has been shown to significantly influence overall race performances (Billat et al., 2001; Casado et al., 2019; Enoksen et al., 2011; Ferreira and Rolim, 2006; Klemm, 1989; Noakes, 1986; Tjelta et al., 2014; Tjelta, 2016). This results in athlete's being more physiologically and psychologically adapted to perform well, including in warmer conditions (Hargreaves, 2008; Helou et al., 2012; Kenefick et al., 2007; Maughan et al., 2007a, 2007b; Zouhal et al., 2009). Elite athletes will also be well acclimatised to potentially warm conditions with either access to overseas training camps or originating from and training in the heat of Africa: East African athletes in particular are the dominant force in distance running (Baker and Horton, 2003; Hamilton, 2000; Larsen, 2003) and made up 89.5 % of male and 54.5 % of female marathon winners in the study by Helou et al. (2012). This is supported by the close bunching of the elite finishing times compared to the fastest amateurs and then in turn the slowest amateurs. There is less variation between the minimum and maximum finishing times as well as less standard deviation for the quickest groups (Fig. 3, Table 1). This supports research that has shown elite and the quickest amateur runners often pace distance running races better than amateur and the slowest amateur runners respectively (Ely et al., 2008; Santos-Lozano et al., 2014; Trubee et al., 2014).

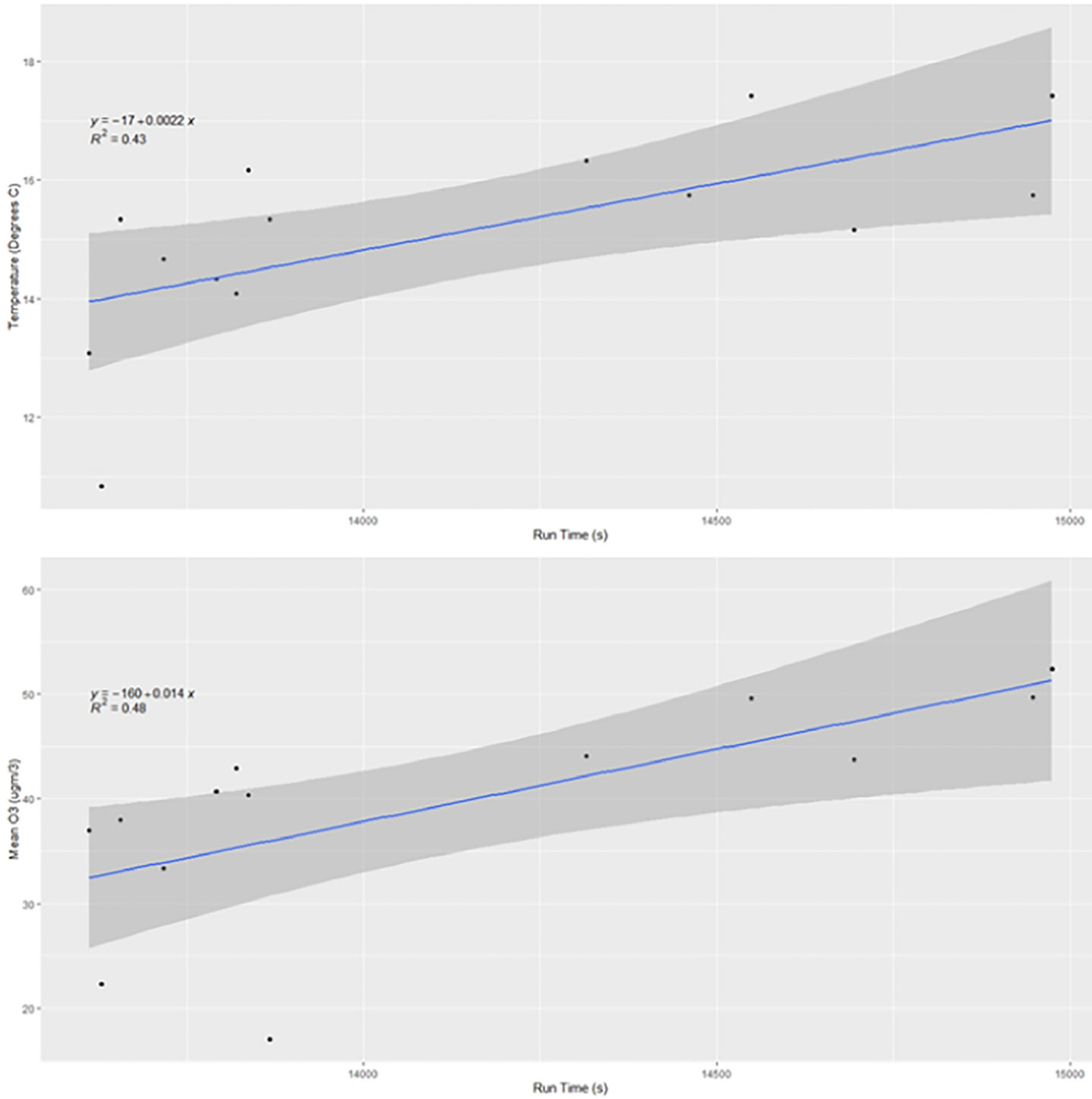

Fig. 2. The influence of temperature (top) and O_3 (bottom) on the slowest amateur male subset.

4.2. Slowest amateurs

For the slowest amateurs, the reasons stated above in Section 4.1. may, in reverse, also be contributing to the significant results shown for them: where relationships between finishing times and temperature, heat index (to a lesser extent) and O_3 levels where $p \leq 0.02$. Fitness differences relative to physiological potential will contribute to finishing time variation and the effect of external variables such as temperature on performance (Helou et al., 2012; Ely et al., 2007; Alvarez-Ramirez and Rodriguez, 2006; Alvarez-Ramirez et al., 2007; Montain et al., 2007). Slower runners are likely to be further away from their physiological potential, thus resulting in a greater influence of temperature and heat index on their performance. Sandsund et al. (2012) also showed that running economy decreases under increased temperatures: consequently, slower runners with reduced running economy will be further influenced as the temperature increases when compared to elite and quicker runners. Additionally, Ely et al. (2007, 2008), Montain et al. (2007) and Vihma (2010) all argued that slower runners are more vulnerable to environmental influences and will have the greatest reduction in performance, especially under high temperatures as they are running for longer periods and therefore are exposed more. This is supported by these findings that show temperature and heat index to be significantly related to decreased performances ($p \leq 0.02$).

It has been shown that O_3 has a significant negative influence on the slowest of participants. Here, increased exposure time would result in increased perceived exertion and cardiorespiratory irritation, especially when exercise causes increased pollution uptake (Bigazzi, 2016; Daigle et al., 2003; Gibbons and Adams, 1984; Giles and Koehle, 2014; Gong et al., 1985). Rundell (2012) suggest that chronic exposure to pollutants would reduce lung function and increase vascular dysfunction, contributing to reduced performance. Helou et al. (2012) showed that ozone was detrimental to marathon performances and both Gibbons and Adams (1984) and Gong et al. (1985) determined that O_3 pollution would reduce workload and time to fatigue by 30 % and 8 %, respectively. Additionally, due to events, including the Great North Run, starting in the morning, the photochemical production of O_3 will not have peaked for the elite and quickest finishers but will be increasing for slower finishers (Chimenti et al., 2009; Helou et al., 2012; Morici et al., 2020).

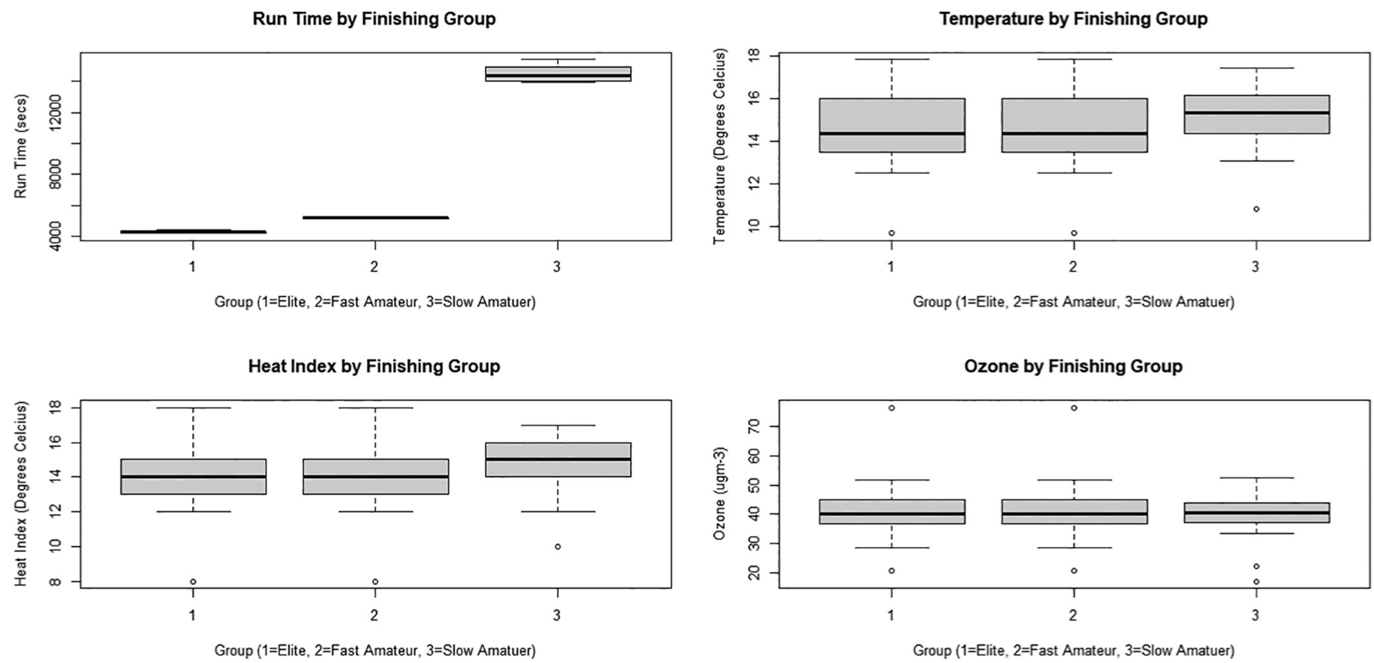

Fig. 3. From left to right, top to bottom: Variations in the mean finishing time, temperature, heat index and O_3 measurements experience by the elite, quickest amateur and slowest amateur participants at the Great North Run across the study period of 2006–2019. The elite and fastest amateur ozone, temperature and heat index measurements are the same as highlighted in the methods section.

The relationship between O_3, NO_2 and temperature as outlined in the methodology could suggest that the effect of O_3 on performance may be related to temperature increases (Chimenti et al., 2009; Helou et al., 2012; Lippi et al., 2008; Shephard, 1984). However, O_3 has been shown to have a detrimental effect on general lung function and athletic performance, even when combined with high temperatures (Gibbons and Adams, 1984; Gong et al., 1985; Rundell, 2012). The linear regression results also suggest that O_3 concentrations explain a similar or even larger proportion of the variance in finishing times than temperature and heat index, indicating that the effect of the pollutant on performances cannot be overlooked and in this case, is most likely to be detrimental to slowest of participants who are exposed for longer periods of time.

The 'beneficial' impact of increased NO_2 levels on the slowest finisher's performances is unexpected but may be due to anticorrelations with other environmental parameters (Fig. 4). The chemical interplay between NO_2 and O_3, as described by the Leighton reactions in Eqs. (2) and (3) and shown in Fig. 4 leads to the anticorrelation between O_3 and NO_2. Furthermore, higher NO_2 levels often correlate with cooler temperatures, which have been shown to improve performance (Helou et al., 2012; Vugts, 1997). Therefore, the lower temperature is more beneficial than the subsequent increase in NO_2 is detrimental to performance (Helou et al., 2012; Vugts, 1997). Furthermore, correlation and linear regression analysis between temperature and NO_2 found that there was a negative relationship between the two variables ($p \leq 0.07$) which suggests that the faster times under higher NO_2 could be attributed to lower temperatures. One final possibility for the apparent performance improving effect of NO_2, is that NO_2 is chemically linked to nitrates and associated species. These species are vasodilators that increase blood flow through reduced arterial pressure, which could be beneficial to performance. However, laboratory examination of this vasodilator theory has not been performed (Cosby et al., 2003; Lim et al., 2005).

Another consideration for the greater influence of temperature and heat index on the slowest finisher's performance is a propensity for slower runner's to run together in larger groups than quicker runners, who may also be solo running (Alvarez-Ramirez and Rodriguez, 2006; Alvarez-Ramirez et al., 2007; De Freitas et al., 1985). In these large group dynamics, convective heat loss is more than halved compared to a solo runner, leading to increased core temperatures, perceived exertion and overall heat stress up to three times higher than a solo runner would experience under the same conditions (De Freitas et al., 1985; Montain et al., 2007).

4.3. Gender effects

Due to physiological differences between male and female participants, male finishing times across the three groups analysed were significantly quicker, as was also found by Helou et al. (2012). Although slight, results for the slowest finishers suggest that male participants are influenced more than female by environmental factors. This is especially so for temperature and O_3, the former of which is supported by Kaciuba-Uscilko and Ryszard (2001). It has been shown that thermal responses to heat and heat loss, including during exercise, differ between the genders, with core temperature control being greater for women due to a larger surface area to mass ratio, higher subcutaneous fat content and potentially lower exercise capacity (Gagnon et al., 2009; Kaciuba-Uscilko and Ryszard, 2001). Furthermore, body mass is generally lower for females compared to males due to physiological differences in stature, musculature and body fat percentages: with lower mass being shown to be advantageous for running under increased temperatures (Marino et al., 2000; Zouhal et al., 2011). Billat et al. (2001) also found that male marathon runners had a lower running economy than their female counterparts, which would lead to increased heat production and more pronounced performance decreases over time.

4.4. Insignificant results and limitations

$PM_{2.5}$ showed no significant results with finishing times, which, given its serious long term health effects, is maybe surprising (Feng et al., 2016). However, previous real-world studies have also shown no relationships between $PM_{2.5}$ and performance. (Helou et al., 2012; Marr and Ely, 2010). A potential explanation of these results is that the resuspension of particulate matter from runners (similar to that from vehicles) is likely to not be quantified in the analysis and be contributing to the insignificant results (Hatzopoulou et al., 2012; Martins and Carrilho de Graca, 2018). Additionally, levels of $PM_{2.5}$ reached during the event may not have been high

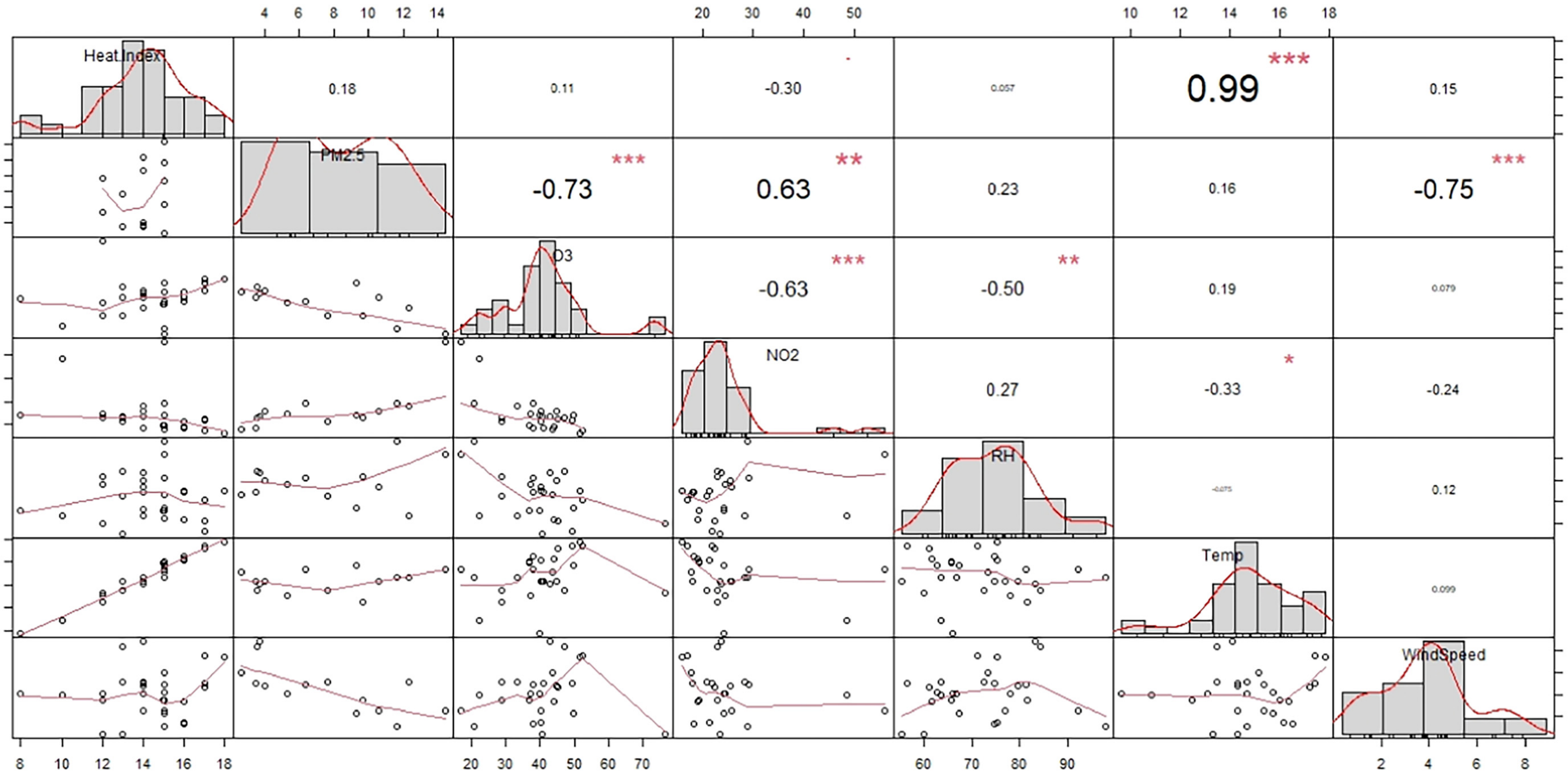

Fig. 4. Correlation matrix of the environmental variables examined in this study.

enough to detrimentally impact participant performances with future studies examining $PM_{2.5s}$ impact under higher concentrations recommended.

Variation in wind speeds in this study did not show any significant relationships. Although some research has suggested that increased wind speeds can slow performance in terms of a head wind and improve performance as a tail wind, its influence is difficult to quantify due to multiple variations in speed and direction during real world events (Davies, 1980; Knechtle et al., 2019; Vihma, 2010). This is especially so for an event such as the Great North Run which over the course of 21.1 km has multiple changes in direction and variability in building density alongside the route. Consequently, there would be variation in wind parameters over the event duration that would not be represented in neither the results nor the data captured for analysis (Cheuvront and Haymes, 2001; Maughan, 2010). Consequently, this could be overcome through the use of additional monitoring sites at strategic locations alongside the route, to better determine wind speed and wind direction variations.

Although identified by Bigazzi (2016) as the second most influential variable that could influence athletic performance due to limited heat dissipation, relationships between relative humidity and finishing times of the Great North Run were not found. This may be due to the amateur group's exercise intensity and/or relative humidity levels (mean 70.3 %) not being consistently high enough to elicit excess heat production and also limit heat dissipation. In contrast, for the overall elite field and female subsets, positive relationships were found at close to significant *p*-values ($p = 0.1$ and $p = 0.07$ respectively). This slightly more detrimental impact on elite female finishing times may be due to their increased exercise intensity and thus higher heat production compared to amateur participants which cannot be dissipated as easily under the higher relative humidity (Casa, 1999; Cheuvront and Haymes, 2001; Gasparetto and Nesseler, 2020; Helou et al., 2012; Nadel, 1990). As the influence is statistically more noticeable for elite women, this is likely because of reduced sweat rates compared to their male counterparts as detailed by Kaciuba-Uscilko and Ryszard (2001).

A potential limitation of this study is the use of a single air quality and meteorology monitoring station respectively, whilst the Great North Run route in Fig. 1 covers a wider spatial area. The run starts in Newcastle city centre and concludes at South Shields on the coast, resulting in potential exposure to different meteorological conditions. For example, studies have shown that the land-sea breeze can influence air quality and meteorology of coastal areas (Bagtasa and Yuan, 2020; Park and Chae, 2018). Thermal contrasts between the land and water temperatures can induce a stronger land-sea breeze that will disperse pollution, particularly $PM_{2.5}$ and PM_{10}, whilst weaker land-sea breezes can result in pollutant accumulation in coastal areas (Bagtasa and Yuan, 2020; Igel et al., 2017; Papanastasiou and Melas, 2008; Rafiq et al., 2020; Tsai et al., 2011). Furthermore, Li et al. (2020), Papanastasiou and Melas (2008) and Zhang et al. (2020) also showed that O_3 concentrations can be greatly increased along coastal areas by sea breezes. In addition to these pollution effects, land-sea breezes can lower land surface temperatures and increase the recorded wind speeds on land (Bauer, 2020; Park and Chae, 2018; Yamamoto and Ishikawa, 2020). However, previous research has also adopted this single measurement site for data acquisition; and although air pollution and meteorology are spatially variable, the measurements utilised will be indicative of local values and conditions faced by participants during the race (Helou et al., 2012; Marr and Ely, 2010; Vihma, 2010). This is enhanced by the fact that the monitoring locations and Great North Run route is consistent across the study period. Other confounding factors that are harder to account for include individual athlete's training state and acclimatisation to environmental conditions may influence performances, as would damp underfoot conditions and shoe wear choices as carbon-plated shoes become more prevalent outside of elite fields (Joubert and Jones, 2022; Senefeld et al., 2021). To provide greater spatial resolution of the environmental conditions faced by participants at the Great North Run or other mass participation events where comprehensive monitoring is not available the use of urban air quality modelling is recommended.

Finally, the influence of wind direction needs to be taken into account due to the start and finish points of the event being located in different places. The dominant wind directions were between south-southwest and west-northwest (Table 3). Due to the shallow ‘v’ shape of the course these winds would be slight tail or cross-tail winds. There are no dominant easterly winds that would be a headwind and potentially slow events. Consequently, as all wind directions during the study period would show some form of benefit and no real hindrance like an easterly wind, analysing them together and not in smaller groups was considered of limited additional benefit.

5. Conclusions

The effect of urban air quality on human health is a major concern, and with the need to increase global activity levels, the effect of pollution on the growing number of athletic event entrants needs to be examined. This is also required for elite athletes with concerns over their safety being raised at previous and future Olympic venues, and several notable medical incidents in recent years being attributed to adverse meteorological conditions (BBC Sport, 2016, 2018, 2019; Bloom, 2019; De La Cruz et al., 2019; Donnelly et al., 2016; Florida-James et al., 2011; Kosaka et al., 2018; Wang et al., 2009). With climate change predictions suggesting that mean and extreme temperatures will increase, this will have a knock-on effect on physical activity in general, event performances and increase the risk of heat stress related medical incidents (Hawes et al., 2010; Maloney and Forbes, 2011; Miller-Rushing et al., 2012; Yankelson et al., 2014).

This study has built on previous research examining the effect of meteorology and air quality on marathon and 5000 m athletic performances, highlighting the difference in effect the two variable groups have on elite, first amateur finishers and the last amateur finishers. Most notably and like previous research, increased temperatures and heat index slow the performance of the slowest finishers. Similarly, increased O_3 levels are detrimental to the slowest participant group and the elite female athletes, although it is important to note that O_3 concentrations are correlated with temperature – as shown in previous studies. However, results and previous research suggest that O_3 cannot be discounted as an influencing variable on Great North Run performances (Gibbons and Adams, 1984; Gong et al., 1985; Rundell, 2012). NO_2 has been linked to improved performances, although again this is likely in relation to lower air temperatures. Finally, no significant relationships were found between finishing times, relative humidity and wind speed. Despite expectations of $PM_{2.5}$ also

Table 3
Wind direction during Great North Run events. Direction is in degrees.

Event year / Time	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
10:00	190	No data	280	280	190	290	225	205	295	170	215	199	246	265
11:00	227	180	306	285	180	306	220	215	315	177	220	190	260	280
12:00	178	200	360	270	330	331	225	210	330	180	190	210	260	260
13:00	174	No data	5	275	275	4	220	195	313	175	200	205	255	248
14:00	176	293	20	275	270	350	220	233	340	184	210	200	245	300
15:00	140	280	40	275	260	345	260	270	5	170	205	205	260	274
Main wind directions	SSW	S-WNW	W-NNE	W	S-NNW	WNW-N	SW	SW	NW	S	SSW	SSW	WSW	W

reducing performance, this was not shown and may be partially attributed to a limitation of monitoring around the Great North Run.

This research has also provided additional insight into half marathon studies, which have included the Great North Run, and other endurance events which have reported increased heat stress incidents for participants by detailing the effect of increased temperatures and heat index on the slowest participants in particular due to increased exposure times (Ely et al., 2007; Ely et al., 2008; Montain et al., 2007; Vihma, 2010). This will prove highly beneficial to future event organisers when planning event start times, as has been seen with the Rio and Tokyo Olympics, as well as 'do not start' temperatures and highlighting which participants may be more likely to require medical aid (Kosaka et al., 2018; William, 2007; William, 2010). It also highlights the utility, or even need, for additional meteorological and air quality monitoring in urban and rural areas: where events move between urban, rural and coastal locations extra monitoring sites will be needed to capture variation between these areas.

CRediT authorship contribution statement

JRH—conception and design of work. Data acquisition and analysis. Data interpretation. Write up and submission process. Approval of final work.

LC—conception and design of work. Data interpretation. Write up editing and approval of final work.

FDP—conception and design of work. Data interpretation. Write up editing and approval of final work.

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Declaration of competing interest

The authors declare that they have no competing interests.

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