Effect of Ambient Temperature on Marathon Pacing Is Dependent on Runner Ability

MATTHEW R. ELY[1], DAVID E. MARTIN[2], SAMUEL N. CHEUVRONT[1], and SCOTT J. MONTAIN[1]

[1]U.S. Army Research Institute of Environmental Medicine, Natick, MA; [2]Laboratory for Elite Athlete Performance, Georgia State University, Atlanta, GA

ABSTRACT

ELY, M. R., D. E. MARTIN, S. N. CHEUVRONT, and S. J. MONTAIN. Effect of Ambient Temperature on Marathon Pacing Is Dependent on Runner Ability. *Med. Sci. Sports Exerc.*, Vol. 40, No. 9, pp. 1675–1680, 2008. Warmer weather negatively impacts the finishing time of slower marathon (42.2 km) runners more than faster runners. How warmer weather impacts runners' regulation of effort (pacing) leading to the decreased performance is poorly understood. **Purpose:** To determine the influence of air temperature on pacing of runners with differing abilities throughout the marathon. **Methods:** Race results were obtained from three Japanese Women's championship marathons that included 5 km times, finishing time, and corresponding weather conditions. A total of 62 race years' outcomes were analyzed using the race winner and 25th, 50th, and 100th place finishers. **Results:** The fastest marathoners (winners) ran an even pace throughout the race while runners of lesser ability slowed as the race progressed, particularly after 20–25 km. The difference between the first (0–5 km) and last (35–40 km) 5-km split times (pace differential) for the 100th place finishers was the same in cool (C = 5–10°C) as warm (W = 15.1–21°C) conditions (C = 199 ± 45 s; W = 198 ± 40 s). The pace differential for the 50th place finisher tended to increase with increasing air temperature (C = 115 ± 16 s; W = 16 3± 27 s) but was not significantly different. In contrast, warmer weather resulted in a slowing ($P < 0.05$) of pace for the 25th place finisher (C = 90 ± 25 s; W = 191 ± 20 s) and race winners (C = −22 ± 14 s; W = 24 ± 13 s). **Conclusions:** Increasing air temperatures slow pace more in faster runners (winner, 25th) than slower runners (50th, 100th). These results suggest that the negative effect of warmer weather on the finishing times of slower runners is due to slower running velocities from start to finish, rather than a greater deceleration in pace which is exhibited by faster runners. **Key Words:** ENVIRONMENT, ENDURANCE EXERCISE, END SPURT, DISTANCE RUNNING, RACING

The marathon foot race (42.2 km) is considered by many to be one of the most challenging endurance competitions. Given the popularity of the event and the recent "2006 World Congress on the Science and Medicine of the Marathon," it is surprising that little information is available on pacing (regulation of effort) over the 42.2-km distance (2). While pacing strategies for optimal performance have been gleaned from articles addressing the thermoregulatory responses (19), metabolism (2), and uneven terrains (21) found in marathon running, most analyses did not directly measure runner pacing (21) or included very small sample sizes (2,19).

A constant running velocity (even pace) or a moderately fast early running velocity before slowing to desired sustainable velocity are generally recommended for fast race performances (10,13). Whether these recommendations reflect pacing in a marathon is unclear, as most have investigated much shorter endurance events (1,10,13,16,20,22). Additionally, the observational studies examining marathon runner pacing included limited comparisons between the faster and slower runners and did not investigate the impact of weather on pacing (2,19).

Fast marathon times are typically achieved in cool environmental temperatures (T_{db} = ~10°C) (9,11). As weather warms, performances slow in a predictable and quantifiable manner (8,18), independent of gender (8). In a recent investigation, it was documented that slower runners were more negatively impacted by increasing heat stress than those who finished faster (8). Unfortunately, only finishing times were available for analysis and any impact of weather on pacing between faster and slower runners could not be determined.

There exist three women's championship marathons in Japan that have been run consistently for many years (Tokyo, Osaka, and Nagoya). The courses have similar flat topography, are at or near sea level, and are run on excellent-quality macadam. These three races require runners to meet a qualifying time to participate and thus

---

Address for correspondence: Matthew R. Ely, M.S., U.S. Army Research Institute of Environmental Medicine, Kansas St, Bdg 42, Natick, MA 01760–5007; E-mail: matthew.ely@us.army.mil.

Submitted for publication December 2007.
Accepted for publication April 2008.

0195-9131/08/4009-1675/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3181788da9

ensure that all competitors are experienced. The course records have decreased an average of 45, 26, and 26 s per year for Tokyo, Osaka, and Nagoya respectively, over the past 16, 26, and 20 yr. This record progression is similar to that of the world record which has decreased an average of 21 s per year since 1983 (14). Additionally, the runner field has been stable throughout the years with an average of 2600 s separating the race winner from the 100th place finisher. Two unique features of these races are that race organizers are meticulous in capturing 5-km times, so that coaches can monitor their athletes' pace dynamics and obtain an appreciation for when fatigue starts to influence performance, and weather conditions are measured at regular intervals throughout the race. The homogeneity of these three races enable them to be combined to examine (1) race pacing of groups that differ in ability within competitive race fields and (2) the interaction of weather on the pacing of these groups.

PURPOSE

The purpose of this investigation was to examine the overall pacing of competitive women marathoners of different abilities over the 42.2-km distance, and to determine whether increasing ambient temperature alters pacing differently depending on running ability. It was hypothesized that all runners would maintain running velocity similarly, but that slower finishers would have more difficulty sustaining a constant running velocity in warmer weather (8) and thus would decelerate more during latter half of a marathon race compared to faster finishing runners.

METHODS

The weather data of the Tokyo, Osaka, and Nagoya marathons included ambient temperature, relative humidity, wind speed, and cloud cover. Because the wet bulb globe temperature could not be reliably calculated, only ambient temperature was included in this study analysis. Ambient temperature was stable over the length of all marathons examined; thus, the average ambient temperatures are reported.

To examine runners of multiple abilities, the race winner, as well as the 25th, 50th, and 100th place finishers results were extracted from each year of race results. These data are in the public domain, therefore written and informed consent was not required from individual athletes. Initially, runner performances were compared by normalizing each runner's measured 5-km times in relation to the arithmetic mean of 5-km times calculated from the initial 40 km. Briefly, each runners average 5-km pace was calculated by taking their race time for the initial 40-km and dividing this by 8 (40 km/8). The time to complete each measured (true) 5-km race interval was then compared to the average 5-km time (true 5-km time – average 5-km time), so that if the difference was negative, the runner ran their respective 5-km faster than average pace; if positive, that 5-km interval was slower than average. Additionally, individual runner performances were assessed by comparison to the current course record within each race. A percentage off the course record was calculated at each 5 km from 5 to 40 km by the equation [(individual 5-km time − course record 5-km time/course record 5-km time) × 100]. To remove any bias associated with improving records over time, the course record used for reference was always the current course record for the year under study.

The last 2.2 km was analyzed separately based on research identifying that an "end spurt" occurs when a task is ~90% complete, irrespective of length of task (1,3,5,20). To examine the end spurt, 1-km race pace of the last 2.2 km (last 5.2% of the race) was compared to the average 1-km race pace over the initial 40 km and to the average 1-km race pace from the true 35 to 40 km.

To examine how pacing over the initial 40 km is affected by ambient temperature, races were binned by 5° increments in ambient temperature into cool (C), temperate (T), and warm (W) conditions (C = 5.1–10°C, T = 10.1–15°C, and W = 15.1–21°C) and also separated by ability (1st, 25th, 50th and, 100th). The same binning method was used to examine the interaction of weather on the end spurt.

The 5-km differences in runner average pace and pace compared to the current course record over the initial 40 km were averaged for each 5-km split (5, 10, 15, 20, 25, 30, 35, and 40 km) by finishing place (1st, 25th, 50th and 100th). Five-kilometer differences in average pace were additionally separated by finishing place (ability) and temperature condition (C, T, and W).

Statistics. A mixed model ANOVA (4 groups × 8 repeated measures) was performed to compare pacing (5-km splits from 5 to 40 km) of the four different place finishers (1st, 25th, 50th, and 100th) collapsed across all temperature conditions. This was done with runners' 5-km split normalized to their average pace as well as to the current course record. To compare overall pacing strategy between the four different place finishers, lines of best fit (goodness of fit) were calculated for each different place finisher then the regression lines were compared among all place finishers. The effect of ambient temperature (C = 5–10°C, T = 10.1–15°C, and W = 15.1–21°C) on early, mid and late pacing (0–5 km, 20–25 km and 35–40 km) was examined using a similar ANOVA analysis (3 temperature conditions × 3 repeated measures) within each group of finishers. One-way repeated-measures ANOVA were used to examine if change in pace over the initial 40 km differed across weather conditions within each finishing group, as well as to assess the effect of temperature within each group on ability to accelerate over final portion of the race, i.e., 1-km pace over the last 2.2 km of the race relative to the initial 40-km average pace and 1-km pace between 35 and 40 km. *F* values were adjusted (Greenhouse–Geisser) if the assumption of sphericity was not met. If data failed assumption of normality, one-way ANOVA analysis on rank was used to test for differences. Tukey HSD procedure was used to identify differences among means if significant main and/or interaction effects were present. Data are presented as Mean ± SE to characterize the precision of the population performance. Significance was accepted at $P < 0.05$. All analyses were conducted using SPSS (Rel. 13.0.1 2004; SPSS Inc, Chicago).

RESULTS

In total, 62 race years were available for analysis, which compared 16 yr of the Tokyo (1984–1999), 26 yr of the Osaka (1982–2007), and 20 yr of the Nagoya (1987–2007) marathons. No race results could be obtained for the 1988 and 2004 Nagoya marathons or the 1995 Osaka Marathon (canceled due to earthquake). Race results were only available for 59 race years for race winners while 58, 57, and 45 race years were available for the 25th, 50th, and 100th place finishers, respectively. In all, the race results of 219 different accomplished women runners were examined.

As illustrated in Figure 1A and B, the runners exhibited two distinctly different pacing profiles. The race winners exhibited a linear pacing profile ($r^2 = 0.15$) in that they ran close to an even velocity throughout 40 km (Fig. 1A; dotted line represents even velocity throughout the initial 40 km) and close to the current course record (Fig. 1B). The 25th, 50th, and 100th place finishers showed a nonlinear pace profile over the first 40 km (cubic fit: $r^2 = 0.98, 0.98, 0.96$, respectively). That is, their initial 5 km was their fastest. The 50th and 100th place finishers then slowed to a pace which was maintained from 10 to 20 km while the 25th place finisher maintained pace from 10 to 25 km, after which all populations progressively decelerated until 40 km (Fig. 1A). Another pattern difference between 25th, 50th, and 100th place finishers was that the 100th place finishers slowed even more from their average pace than the other groups during the latter phases of the race (Fig. 1A). The pacing profiles of the 25th, 50th and 100th place finishers was a consistent pattern, as only 5%, 4%, and 1% of the runners in the 25th, 50th, and 100th place groups, respectively, ran evenly throughout the race.

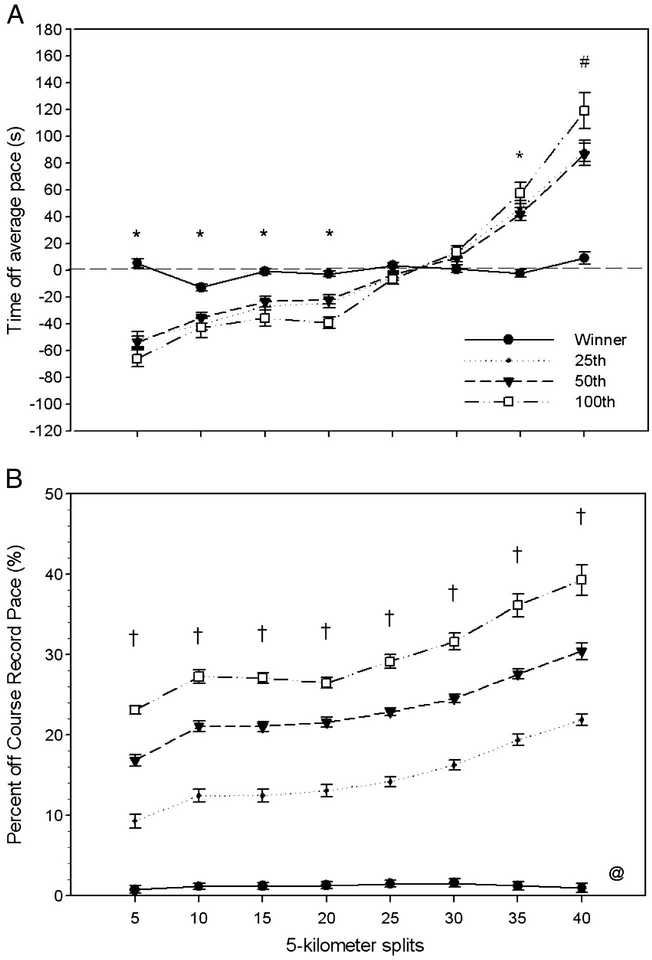

FIGURE 1—Comparison of the pacing of runners with differing performance ability over the initial 40 km of the marathon. (A) Absolute time difference between observed 5-km pace and average 5-km pace over first 40-km. * Winner pacing significantly different that the 25th, 50th and 100th place finishers. # Winner pacing significantly different from the 25th, 50th and 100th place finisher and 100th place significantly different from the 25th and 50th place finishers. (B) Percent off 5-km pace of the existing course record at the time the race was run. † All ability groups are significantly different ($P < 0.05$). @ Winner pacing follows a linear pacing profile ($r^2 = 0.15$) while the 25th, 50th and 100th place finishers pacing fits a cubic curve profile ($r^2 = 0.98$, 0.98, and 0.96 respectively).

Weather impacted pacing, but the impact was dependent on finishing position. First place finishers in the cool temperature condition (5–10°C) started out relatively slow compared to their average running velocity and accelerated such that their time to run the 5-km distance between 35 and 40 km was faster than their average velocity over first 40 km. In contrast, first place finishers in the warm condition (15–21°C) started out at a pace similar to their average running velocity and slowed ($P < 0.05$) during latter stages of the race. In contrast, the running velocities over the first 5 km for the 25th, 50th, and 100th place finishers were all faster than their velocities between 35 and 40 km, regardless of the temperature condition and the difference between the two times increased as the temperature warmed (Table 1). Numerically, the time difference between the initial 5 km and 35–40 km (pace differential) of the race winner increased as the weather warmed from −22 ± 14 s to 7 ± 9 s and 24 ± 13 s (mean ± SE; $P < 0.05$) in the C, T, and W conditions, respectively. Following a similar slowing pattern as the temperature increased, the pace differential of the 25th place finishers was 90 ± 25 s, 143 ± 16 s, and 191 ± 20 s for the three temperature conditions. In contrast to the slowing of running velocity exhibited by the race winner and 25th place finishers, the pace differential of the 100th place finishers was similar regardless of temperature condition (C = 199 ± 45 s, T = 166 ± 18 s, and W = 198 ± 40 s). The 50th place finishers seemed to fill a pattern intermediate between the top finishers (first, 25th) and 100th place runners as pace differential increased from 115 ± 16 s to 154 ± 27 s and

TABLE 1. Time off average 40-km pace(s).

Place	Split	Temperature 5–10°C	 10.1–15°C	 15.1–20.8°C
1st	5 km	20.2 (8.7)	1.9 (3.4)*	−3.9 (6.4)*
	20–25 km	3.1 (4.9)	5.4 (3.0)	1.0 (4.4)
	35–40 km	−1.4 (7.4)**	9.0 (6.8)	20.3 (8.2)***
25th	5 km	−27.0 (10.8)	−49.8 (7.6)	−80.7 (9.5)*
	20–25 km	−0.2 (2.8)	−3.4 (3.5)**	−11.6 (8.2)**
	35–40 km	63.2 (14.8)***	92.7 (10.4)***	110.4 (16.4)****
50th	5 km	−40.0 (9.3)	−60.3 (8.6)	−69.7 (10.4)*
	20–25 km	−2.9 (3.7)	−2.9 (3.7)**	−3.4 (5.4)**
	35–40 km	75.2 (18.7)***	103.7 (19.3)***	93.8 (17.3)***
100th	5 km	−67.6 (14.8)	−57.7 (7.3)	−76.9 (12.0)
	20–25 km	−13.3 (8.5)**	−8.5 (4.0)**	4.2 (7.4)**
	35–40 km	131.5 (32.5)***	107.9 (12.5)***	121.6 (29.1)***

Mean (SE).

(−) value indicates the runners ran faster than average pace over 40 km.

* Significantly different ($P < 0.05$) from 5 to 10°C.

** Significantly different ($P < 0.05$) from 5 km.

*** Significantly different ($P < 0.05$) from 5 km and 20–25 km.

163 ± 27 s for C, T, and W, respectively, but these did not reach statistical significance.

An end spurt was exhibited by the race winners, 25th and 50th place finishers as these runners increased their running velocity over the last 2.2 km compared to their velocity between 35 and 40 km ($P < 0.05$). The magnitude of acceleration appeared to differ between finishing groups as first place finishers were able to accelerate to their average velocity for the initial 40 km, whereas the 25th and 50th place finishers could not ($P < 0.05$). An end spurt was not observed in the 100th place finishers (Fig. 2D). End spurts were also examined separately by temperature condition. For the race winner, the end spurt was only present in the W condition when end spurt velocity was faster ($P < 0.05$) than the runners velocity between 35 and 40 km and statistically similar to their average running velocity over the initial 40-km (Fig. 2C). The 25th and 50th place finishers also exhibited an end spurt only in the W condition where running velocity was significantly increased over 35–40 km but slower ($P < 0.05$) than the average running velocity over the initial 40 km (Fig. 2C).

DISCUSSION

An outcome of this observational study is that the pacing of the race winners was distinctly different than that of competitive slower runners over the marathon distance and is consistent with the observation of Maughan et al. (19) in a smaller group of runners at a single race. Whereas winners ran an even velocity over the 42.2-km distance, slower runners started out relatively faster than their average velocity for the initial 5 km before settling into a pace that they could maintain for 20 km (50th and 100th) or 25 km (25th) before decelerating for the remainder of the race until

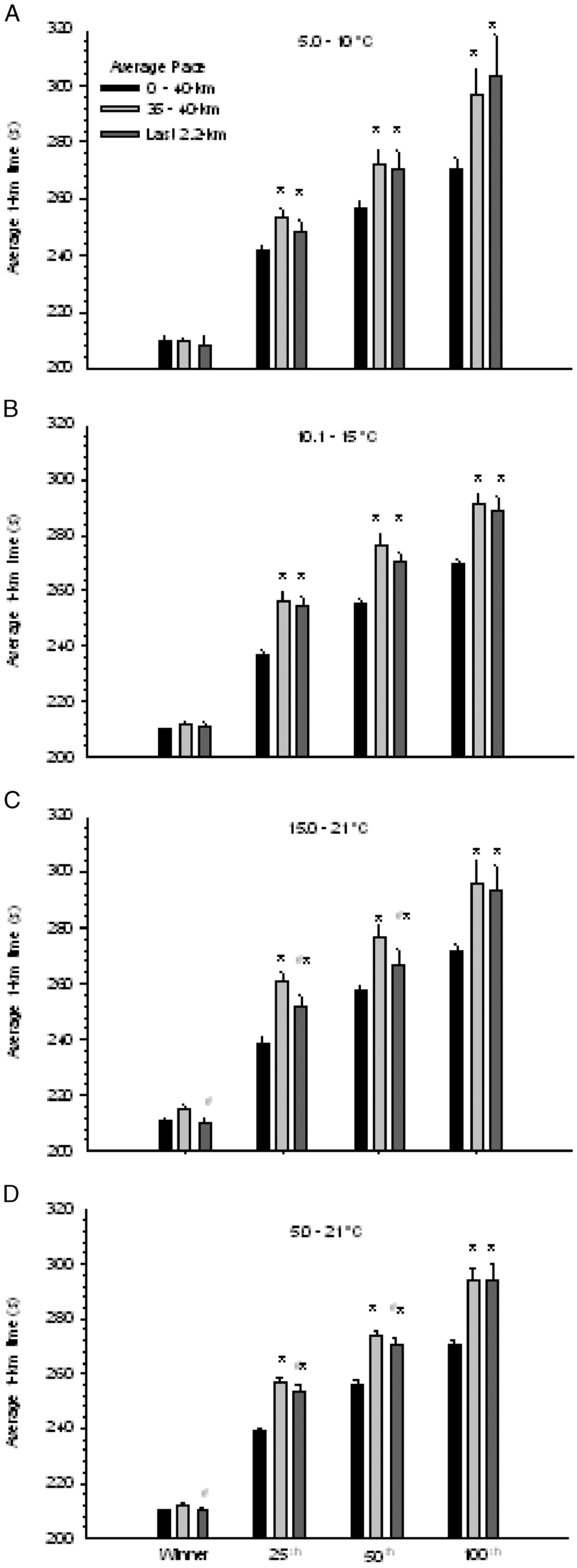

FIGURE 2—Comparison of the 1-km race pace over the initial 40 km (*black bar*) to the pace between 35 and 40 km (*Light grey bar*) and the last 2.2 km (*End spurt; dark grey bar*) for A: 5–10°C, B: 10.1–15°C, C: 15.1–21°C, and D: 5–21°C ambient temperature conditions. # Significantly different ($P < 0.05$) from 35 to 40 km. * Significantly different ($P < 0.05$) from initial 40 km.

the end spurt. The consistency of this pacing pattern between finishing groups suggests that the winner and slower runners represent two unique populations with respect to pacing.

Running at an even velocity is generally recommended for fast race performance (10,19,20) as uneven distribution of effort has been associated with greater physiological demand and reduced performance (21) in faster and slower runners. Yet, a nonlinear slowing of running velocity has been observed in other studies of long-distance running (2,19). Like Buoncristiani and Martin (2), in this study running pace slowed as a cubic function of distance for the 25th, 50th and 100th place finishers who consistently chose an early running velocity that could not be sustained and began running slower than average pace between 25 and 30 km (59–71% of total race distance) (Fig. 1A). Similarly, Noakes (20) reported that running velocity fell markedly 40–50% into 100-km races.

The different pacing of runners in the current data set might be explained by different *a priori* goals. It is conceivable that race winners run to win/place and, therefore, are less concerned about early race running velocity as long as they are positioned at/near the race leaders. The 25th and 50th place runners know that it is unlikely that they will win/place, and their primary objective was more likely to set a personal record time. To achieve that goal, these runners select an early running velocity that is faster than the average running velocity of their current personal best marathon time. More often than not, however, that running velocity cannot be sustained, and velocity decelerates progressively during the second half of the race. Whether they actually set a personal record time depends on whether the early running velocity put them far enough ahead of their objective time to compensate for the slowing late in the race.

We hypothesized that warm weather would have a greater effect on pacing of slower finishers (8). Contrary to our hypothesis, weather affected pacing in the faster runners and appeared to have little or no effect on the slower runners (Table 1). In cool weather, the winners started the marathon at a velocity slower than their average race velocity and were able to sustain the velocity for the duration of the run; in warm weather, the winners started out closer to their average velocity but decelerated during the second half of the race. Likewise, warmer weather resulted in the 25th place finishers slowing more over 42.2 km than in cool weather. In contrast, the 100th place finishers followed similar decelerating pacing patterns regardless of air temperature (Table 1). Thus, if the 100th place finishers represent the same population previously shown to slow absolutely more as weather warms (8), they evidently run slower over the entire distance rather than by implementing greater pace changes as the race progresses.

Slowing of running velocity with increasing air temperature has been observed previously. Tucker (23) reported that the power output of cyclists performing a 20-km effort (27–28 min) in a cool (15°C), temperate (25°C), and hot (35°C) environment at a constant perceived exertion (RPE) decreased over time in all trials, but the rates of power decline were steepest in the hot trial, followed by the temperate and then cool. A similar decrease in power output of cyclists was documented between a 23°C and 32°C environment (22) where power output was significantly reduced within the first 15 min of a 30-min time trial and remained lower throughout the trial. In a separate study, subjects running (~27 min) in the heat (35°C) modified their pacing during the trial so that they finished the exercise bout, albeit slower compared to when the trial was performed in cooler temperature conditions (15°C) (17).

One explanation for the compromised pacing of winner and 25th place finisher in warmer weather is that their pace and heat production were outside the "prescriptive zone," that is, the range of temperatures where core temperature responses to a given metabolic rate are independent of ambient temperature (15). When heat production exceeds loss, core temperature rises and exercise hyperthermia ensues, which is one factor implicated in endurance fatigue (12). If the runners were competing in climatic conditions that sufficiently narrowed the prescriptive zone, they would be expected to be competing with relatively greater hyperthermia compared to running the same velocity in cooler conditions. The greater hyperthermia, in turn, may have affected central motor drive and motivation to sustain race running velocity. To compensate, the runners slowed late in exercise. In addition, warmer weather increases the requirement for evaporative heat loss, thus increasing the likelihood that dehydration will play a role in fatigue (6).

The capability and magnitude of end spurt were dependent on both finishing position and weather conditions. When groups were collapsed to investigate the effect of ability, independent of weather, the winner, 25th, and 50th place finishers exhibited an end spurt (increase in running velocity) over the final 2.2 km that was significantly faster than their average running velocity between 35 and 40 km, whereas 100th place finishers did not accelerate over final 2.2 km of the race. The likelihood of an end spurt, however, appeared dependent on weather, as it was only in the warm weather condition (15.1–21°C) that the winner, 25th and 50th place finishers accelerated sufficiently to run faster than their average running velocity over the previous 5 km. Of particular interest, is that even when the end-spurt was present, it was only the winner who was able to accelerate sufficiently to run at a velocity equal to their average race velocity over the initial 40 km. Even though the 25th and 50th place finishers accelerated during final portions of the race relative to their running velocity over the previous 5 km, the faster running velocity was still slower than their average running velocity over first 40 km of the race.

End spurts commonly occur in perceptual and simple motor tasks when the task is perceived to be ~90%

complete (3–5) and occur in runners participating in 8- to 10-km races (17,20). The dependant effect of weather in the current study might be explained by the relatively slower running velocity during the 5-km preceding initiation of the end-spurt when runners competed in the W condition compared to the cooler conditions (C, T), as the runners may have overcompensated their running velocity and slowed enough to a point where they could produce an end spurt, whereas this was not possible in cooler conditions (Fig. 2A, B).

A limitation of the present study is the relatively narrow range of ambient temperatures within the dataset (5–21°C). This may have compromised our ability to distinguish the effects of weather and/or differences between runners. The warmest temperature in this dataset was well below what would be considered hot (>30°C) in a laboratory setting and lower than three studies examining interaction of pacing and ambient temperature (17,22,23). Regardless, changes in running velocity with increasing temperatures were still identified and weather conditions beyond the range studied are uncommon (6,8) except in Summer Olympic contests (9). Another limitation of this data set is that the data are from championship marathons restricted to women only. Although previous research reported men and women marathoners respond similarly to warm weather (6,8,9), some caution should be used in extrapolating to wider population(s).

CONCLUSIONS

The pacing of marathon winners and slower finishers are distinctively different. Marathon winners maintain a relatively constant running velocity throughout the race, while still accomplished marathon runners of lesser ability set an initially fast first 5-km pace before selecting a pace they can maintain until 20–25 km; after which, they progressively slow for the remainder of the race. Cooler weather (5–10°C) is associated with an improved ability to maintain running velocity compared to warmer conditions; particularly by faster runners. Additionally, if athletes are able to maintain running velocity, it is less likely that they will generate an end spurt in the last 2.2 km of the marathon.

REFERENCES

1. Ansley A, Schabort E, Gibson A, Lambert M, Noaks TD. Regulation of pacing strategies during successive 4-km time trials. *Med Sci Sports Exerc*. 2004;36(10):1819–25.
2. Buoncristiani JF, Martin DE. Factors affecting runners' marathon performance. *Chance*. 1983;6(4):24–30.
3. Catelano JF. Effect of perceived proximity to end of task upon end-spurt. *Percept Mot Skills*. 1973;36:363–77.
4. Catelano JF. End-spurt in addition of numbers. *Percept Mot Skills*. 1974;39:121–2.
5. Catelano JF. End-spurt following simple repetitive muscular movements. *Percept Mot Skills*. 1974;39:763–6.
6. Cheuvront SN, Haymes EM. Thermoregulation and marathon running: biological and environmental influences. *Sports Med*. 2001;31(10):743–62.
7. Cheuvront SN, Carter R, Sawka MN. Fluid balance and endurance exercise performance. *Curr Sports Med Rep*. 2003; 2(4):202–8.
8. Ely MR, Cheuvront SN, Roberts WO, Montain SJ. Impact of weather on marathon running performance. *Med Sci Sports Exerc*. 2007;39(3):487–93.
9. Ely MR, Cheuvront SN, Montain SJ. Neither cloud cover nor low solar loads are associated with fast marathon performance. *Med Sci Sports Exerc*. 2007;39(11):2029–35.
10. Foster C, Snyder AC, Thompson NN, Green MA, Foley M, Schrager M. Effect of pacing strategy on cycle time trial performance. *Sports Med*. 1994;14:77–85.
11. Frederick EC. Hot times. *Running*. 1983;9:51–3.
12. Gonzales-Alonzo J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol*. 1999;86(3):1032–9.
13. Gosztyla AE, Edwards DG, Quinn TJ, Kenefick RW. The impact of different pacing strategies on five-kilometer running time trial performance. *J Strength Cond Res*. 2006;20(4):882–6.
14. Hymans R. Progression of world best performances and IAAF official world records 5th ed. Monaco (Fr): International Association of Athletics Federations, 2003, pp. 106–10, 276–8.
15. Lind AR. A physiological criterion for setting thermal environmental limits for everyday work. *J Appl Physiol*. 1963;18(1): 51–6.
16. Marino FE. Anticipatory regulation and avoidance of catastrophe during exercise-induced hyperthermia. *Comp Biochem Physiol, B*. 2004;139:561–9.
17. Marino FE, Lambert MI, Noakes TD. Superior performance of African runners in warm humid but not cool conditions. *J Appl Physiol*. 2004;96:124–30.
18. Martin DE, Buoncristiani JF. The effects of temperature on marathon runners' performance. *Chance*. 1999;12(4):20–5.
19. Maughan RJ, Leiper JB, Thompson J. Rectal temperature after marathon running. *Br J Sports Med*. 1985;19(4):192–5.
20. Noakes TD. Lore of running, 4th edition, Champaign, IL: Human Kinetics, 2001, pp. 637–8.
21. Staab JS, Agnew JW, Siconolfi SF. Metabolic and performance responses to uphill and downhill running in distance runners. *Med Sci Sports Exerc*. 1992;24(1):124–7.
22. Tatterson AJ, Hahn AG, Martin DT, Febbraio MA. Effects of heat stress on physiological responses and exercise performance in elite cyclists. *J Sci Med Sport*. 2000;3(2):186–93.
23. Tucker R, Marle T, Lambert EV, Noakes TD. The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. *J Physiology*. 2006;574(3):905–15.