The threshold ambient temperature for the use of pre-cooling to improve cycling time trial performance

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Abstract

Purpose. Cycling time trial performance can be compromised by moderate to high ambient temperatures. It has become commonplace to implement pre-cooling prior to competition to alleviate this performance decline. However, little is known about the ambient temperature threshold above which pre-cooling becomes an effective strategy for enhancing endurance performance. It was the aim of this study to investigate the effect of pre-cooling in different environmental temperatures on time trial performance. **Methods.** Trained cyclists completed two time trials with (COLD) and without (CON) pre-cooling using an ice-vest and sleeves ensemble in ambient temperatures of 24˚C, 27˚C and 35˚C. **Results.** Time trial performance faster following COLD in both 35˚C (6.2%) and 27˚C (2.6%; both $P<0.05$) but not 24˚C (1.2%). Magnitude based inferential statistics indicate that COLD was *very likely beneficial* to performance in 35˚C and *likely beneficial* in 27˚C and *possibly beneficial* in 24°C. Mean power was 2.4%, 2.5% and 5.6% higher following COLD and considered to be *likely beneficial* in 24°C and *very likely beneficial* in 27˚C and 35˚C. COLD reduced mean skin temperature throughout the warm-up and into the time trial in all ambient temperatures ($P<0.05$). Sweat loss was lower following COLD in 24˚C and 27˚C but not 35˚C. There was no effect of COLD on gastrointestinal temperature at any point. **Conclusions.** Pre-cooling with an ice-vest and sleeves is likely to have a positive effect on time trial performance at temperatures above 24˚C, with a clear relationship between ambient temperature and the magnitude of effect of pre-cooling

Keywords

Cycling, ice-vest, skin temperature, sweat, core temperature

Introduction

Endurance exercise performance progressively deteriorates as the surrounding ambient temperature increases,[1,2] which is exacerbated when combined with increasing humidity[3] and solar radiation.[4] Importantly comparable negative effects of the heat, albeit with a smaller magnitude, have been shown in more ecologically valid measures of performance, such as cycling time trials.[1] It is clear that there is a strong link between increases in thermoregulatory strain, due to elevations in both metabolic and ambient heat, and impaired endurance performance.[5]

In order to compete at the highest level possible during competitions in the heat, the practice of pre-cooling has spread in many sports, with ~50% of athletes having a defined strategy prior to competing in elevated ambient temperatures.[6] Importantly, there is mounting evidence to support that cooling the body prior to performance in the heat can have an ergogenic effect.[7,8] This is thought to be due to a decrease in skin and/or core temperature before exercise starts, which increases the capacity for heat storage during exercise and therefore exercise is expected to be possible for a longer duration compared to no pre-cooling. Pre-cooling can be applied via a variety of methods, some of which are more applicable in the field than others. Two of the most common methods include the use of cooling vests,[9] orice slurries,[10] or via a combination of internal methods.[11] Tyler *et al*., provide an excellent overview of the most common pre-cooling methodologies and their respective physiological and perceptual effects,[8] and the reader is directed there for further details. A recent meta-analysis supports the beneficial effect of ice-vest use on time trial performance, where a mean improvement in performance of ~5% is reported.[12] Furthermore, a second meta-analysis including 28 investigations of pre-cooling, and its effect on performance, reports a moderate to large beneficial effect of these interventions prior to endurance performance.[8] However, the authors highlight that the optimal cooling strategies for a range of sporting scenarios are yet to be determined owing to the wide range of experimental protocols and cooling strategies currently employed within the available literature. Thus, it appears that pre-cooling with the use of an ice-vest presents an effective method by which time trial performance in the heat may be improved.

One factor that remains unknown is whether there is an ambient threshold above which pre-cooling may become effective at improving time trial performance. It has been demonstrated that ambient temperatures in excess of 11˚C have the ability to negatively impact on cycling performance.[13] However, no study has yet investigated the existence of a lower threshold above which pre-cooling becomes effective. With most studies to date focusing on a single ambient temperature, typically above 30˚C or a Wet Globe Bulb Temperature (WGBT) of 26 ˚C.[8] Therefore, the aim of the present study was to investigate the use of pre-cooling using an ice-vest in different environmental temperatures on cycling time trial performance as well as physiological and perceptual responses. Pooling these data with our previous time trial data collected at 35˚C[9] provides an ambient temperature range of 24˚C, 27˚C and 35˚C. It was hypothesized that our pre-cooling intervention, comprising a cooling vest and sleeves, would improve self-paced time trial performance in all environmental temperatures, with the magnitude of effect dependent on environmental temperature.

Method

Participants

The present study employed an independent groups design, where trials were completed in ambient temperatures of 24°C, 27°C and 35°C and includes a cohort from our previous study.[9] All participants were endurance trained, competitive male cyclists and triathletes, training in excess of three times per week and were familiar with competing in time trials. The performance level of the participants was determined based on their relative VO_{2max}.[14]

Participant data are presented in table 1. All participants were free from injury and not taking any medication. The Loughborough University ethical advisory committee approved all experimental procedures and confirmed adherence to the Declaration of Helsinki, with all participants providing their written informed consent.

Table 1: Participant characteristics

T_{amb} (°C)	N	Age (yr)	Height (cm)	Mass (Kg)	VO_{2max} ($mL \cdot kg \cdot min^{-1}$)	Training frequency/wk	Performance Level*
24	9	23.6 ± 2.0	180.4 ± 3.2	72.6 ± 2.2	62.0 ± 5.3	≥3	3
27	9	24.2 ± 7.2	177.8 ± 5.0	72.4 ± 6.4	60.6 ± 6.2	≥3	3
35	8	25.1 ± 6.1	178.9 ±.6.1	72.5 ± 5.1	61.3 ± 4.3	≥3	3

*Performance indicator level from[14]

Experimental Design

Participants visited the laboratory on four occasions. Visit 1 consisted of body composition measurement and an incremental exercise test to exhaustion to determine $\dot{V}O_{2\max}$ and maximal power output (W_{max}). Visits 2 to 4 were simulated cycling time trials in which participants were instructed to complete a set amount of work in as short a time as possible. Visit 2 served as a familiarization trial to ensure that participants were able to complete the required exercise and to minimise any potential learning effect on time trial performance. Visits 3 and 4 constituted the experimental visits where participants underwent i) pre-cooling using a cooling garment frozen overnight (COLD) or ii) a no cooling control (CON). Each group completed CON and COLD in either 24°C, 27°C and 35°C. Trials were conducted in a counterbalanced order, with each visit separated by a minimum of 7 days to minimise acclimation effects.

Visit 1

Participants first had their height (Seca, Birmingham, UK) and mass (ID1 Multi Range, Sartorius, Goettingen, DE) recorded. Body composition was determined using skinfold callipers (Harpenden, HaB Intl Ltd, Warwickshire, UK) weighted for the athletic population.[15] The $\dot{V}O_{2\max}$ test was conducted on an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands), and consisted of 3 minutes at 95W, followed by 35W increments every 3 minutes until the participant reached volitional fatigue.

Visits 2-4

Participants reported to the laboratory at the same time of day on each occasion, having abstained from caffeine and alcohol ingestion or any strenuous exercise in the preceding 24 hours.

Prior to each experimental visit, participants were given an ingestible temperature pill (VitalSense, Mini Mitter, Oregon, USA) to measure gastrointestinal temperature (T_{gi}) and instructed to take it 8-10 hours prior to reporting to the laboratory. On arrival, the pill was located using a receiver to confirm that it was functioning correctly. Participants then had their nude weight recorded (ID1 Sartorius, Goettingen, DE) and were then instrumented with wireless temperature sensors (iButton, DS1922, Sunnyvale, CA, USA) at eight locations to allow for the calculation of mean skin temperature.[16] Heart rate was recorded continuously throughout the trials (RS800, Polar, Finland). In order to minimise differences in clothing insulation, all participants wore a standard athletic shirt during the stabilisation, cooling and warm up periods along with their own cycling shorts. The shirt was removed on completion of the warm up prior to the start of the time trial.

Following instrumentation, participants remained in a temperate climate (21.2 ± 0.8˚C) prior to the collection of baseline measures after 30 minutes. Participants were then moved to an environmental chamber maintained at 24.0 ± 0.1°C & 49.5 ± 1.4% relative humidity (WBGT 19.2°C), 27.2 ± 0.3°C & 50.7 ± 5.3% relative humidity (WBGT 22.1°C) or 35.0 ± 0.4°C & 50.6% ± 1.3% relative humidity (29.2°C) where they donned the cooling garments for the experimental condition (COLD) or remained seated in cycling clothing for a further 30 minutes (CON). On completion of the pre-cooling phase, participants then mounted the cycle ergometer to complete a standardised 9-minute warm up that consisted of 3-minute stages of 150W, 200W and 250W. If worn, the cooling garments were removed on completion of the warm up. Participants then had 5 minutes to stretch and prepare for the start of the time trial.

During the time trial, participants were given a set amount of work to complete in as fast a time as possible, equivalent to cycling for 1 hour at 75% W_{max} (902.9 ± 127.6 kJ) The ergometer was set in linear mode so that 75% W_{max} was obtained when participants cycled at their preferred cadence. Participants exercised separately with no performance feedback other than the accumulated work done, target workload and a graphical representation of fluctuations in power output. Participants were allowed to drink water *ad libitum*, with the total volume consumed recorded to allow for calculation of sweat loss. During the warm up and time trial phases, airflow was fixed at 3 $m \cdot s^{-1}$, provided by a vertical array of three fans. At 10% intervals of total work done, T_{gi} was recorded. At 20% intervals RPE,[17] thermal sensation,[18] and thermal comfort[19] were recorded. 20% intervals were chosen to minimize participant/investigator interaction. On completion of the time trial, participants were re-weighed and sweat rate calculated as the change in body mass corrected for fluid intake over time.

Cooling Garments

The cooling ensemble consisted of vest and sleeves that were constructed of a breathable mesh fabric and pockets of hydrophilic silica gel saturated with water and frozen, as described previously.[9] The cooling power of the vest, was calculated using a thermal manikin (NEWTON, Measurement Technology Northwest, USA) with a surface temperature of 34°C to mimic skin temperature and a wet surface to represent sweat production.[20] The garments remained in place on the manikin for 60 minutes, with power recorded every 30s. The overall cooling power of the garments was 190 $W \cdot m^{-2}$.

Statistics

All data were pooled to include the data previously reported at 35°C[9] and analysed accordingly. Normal distribution of data was assessed by the Shapiro-Wilk test. A nested design mixed model General Linear Model analysis was performed with temperature as between groups and Cooling as within participant factors (SPSS, version 23, IBM, Armonk, NY). Where significant differences were identified, *post-hoc* pairwise comparisons were conducted. Based on recent meta-analyses,[8,12] a clear unidirectional hypothesis is stated for the impact of cooling on time trial performance, therefore a one-tailed, paired samples t-test was used to determine the effect of cooling on performance within each environmental condition. The strength of relationships between variables was assessed using Pearson's product-moment correlation coefficient. The accepted level of significance was $p<0.05$. Magnitude-based inferences about the true (population) effect of pre-cooling on performance variables at each ambient temperature were calculated. The uncertainty in the effect was expressed as 90% confidence limits (CI) and as the likelihood that the true value of the effect represents substantial change; harm or benefit.[21] The smallest meaningful change (SMC) in time trial performance was assumed to be a change in performance time of 1.0%. Effect sizes were calculated for time trial completion time and mean power output, with effect sizes of < 0.2

classified as small, 0.4–0.6 as medium, and > 0.8 as large[22]. All data are presented as mean ± SD unless otherwise stated.

Results

Participants

There were no differences in participant characteristics between experimental groups and data are presented in table 1. Groups were closely matched for their characteristics, especially $\dot{V}O_{2\max}$ and also had similar variances within the groups.

Table 1 near here

Time Trial Performance

Overall main effects of both Cooling (P<0.01) and of Temperature (P<0.01) were observed, but no interaction (P=0.23). Finish times at 34ºC were longer than at both 24ºC and 27ºC, but the latter two did not differ. Time trial performance was faster following COLD at 35°C (4141±448s vs. 3901±260s, P=0.05, ES = 0.80) and 27°C (3804±197 s vs. 3709 ± 128s; P<0.05, ES = 0.43) but not at 24°C (3677±216s vs. 3635±279s, P=0.29, ES = 0.17, figure 1A). This equated to performance differences of 6.2, 2.6% and 1.2% following COLD compared to CON at 35°C, 27°C and 24°C respectively (figure 2B). Individual performance effects are presented in figure 3. When considered relative to the smallest worthwhile change in performance, qualitative inference indicates that the effect of COLD was *very likely beneficial* at 35°C (SMC = 41s, CI = 59.5 to 420.5, with chances of a beneficial/trivial/harmful effect being 96.4%, 2.5% and 1.1%; figure 2C), *likely beneficial* for 27°C (SMC = 38s, CI = 24.8 to 165.2, with chances of a beneficial/trivial/harmful effect being 91.5%, 8.1% and 0.4%, figure 2C) and *possibly trivial* at 24°C (SMC = 37s, CI = -20 to 84, with chances of a beneficial/trivial/harmful effect being 43.1%, 54.9% and 1.9%, figure 2C). COLD was *very* *unlikely* to have a detrimental effect on performance in 35°C and 24°C, and *most unlikely* to detrimentally impact on performance in 27°C.

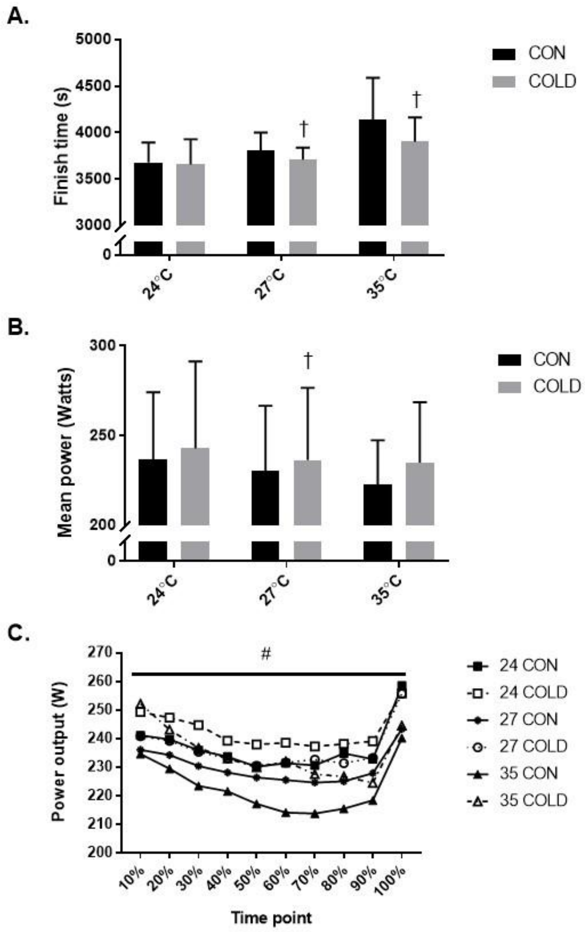

Figure 1: Performance data showing A) time trial completion times, B) mean power output throughout the duration of each time trial and C) pacing profile throughout the time trial. † denotes a significant difference from CON (P<0.05). # denote a significant effect of time (P<0.05). Data presented as mean ± SD

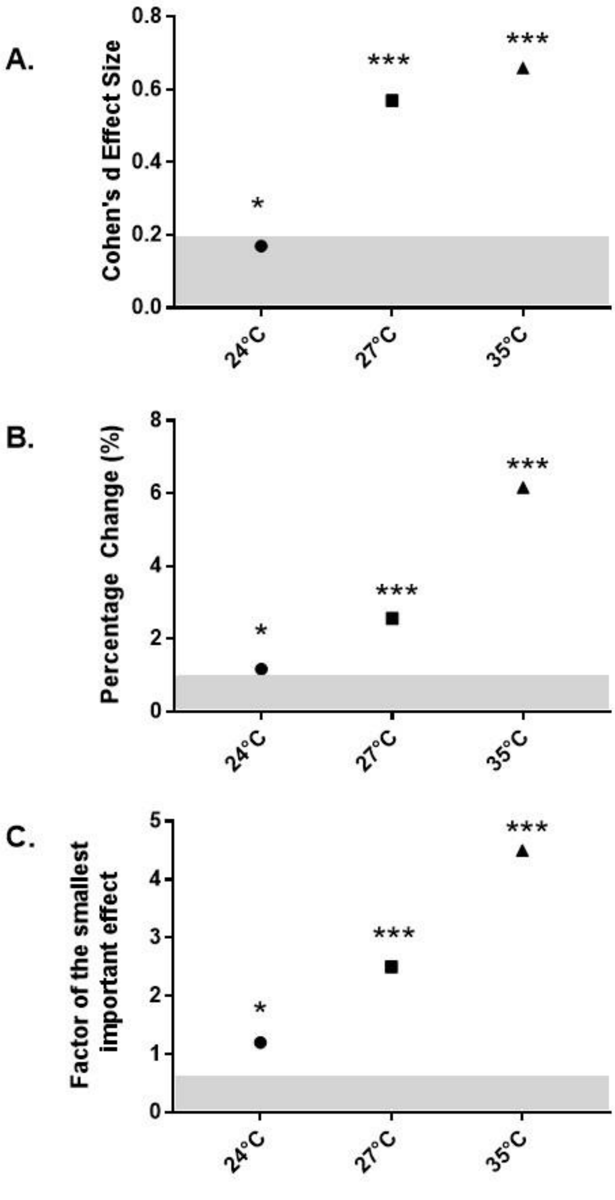

Figure 2: Differences in finish time with the use of pre-cooling compared to no pre-cooling when expressed as A) Cohen's d effect size, B) percentage change and C) the smallest important effect. The numbers of asterisks (*) indicate the likelihood for the between-groups differences to be substantial, with 1 symbol referring to possible difference, 2 to likely, 3 to very likely differences. The shaded area reflects the threshold for the smallest worthwhile change.

Mean Power

Overall main effects of Cooling ($P<0.01$) but not of Temperature ($P=0.8$) were observed, nor was there an interaction ($P=0.62$). Mean power output was higher following COLD in 27˚C (220±6 W vs. 231± at 6 W, $P<0.05$, ES = 0.62, figure 1B), but not in 35˚C (223±25 W vs. 235±33 W, $P=0.54$, ES = 0.30) or 24 ˚C (237±37 W vs. 242±49, $P=0.15$, ES=0.22). This equated to differences in power output equivalent to 5.2%, 2.6% and 2.4% following COLD compared to CON at 35°C, 27°C and 24°C respectively (figure 4B). When considered relative to the smallest worthwhile change in performance, qualitative inference indicates that the effect of COLD on power output was *likely beneficial* in 35˚C (SMC = 2.2W, CI = 2.2 to 21.8, with chances of a beneficial/trivial/harmful effect being 95.3%, 3.2% and 1.5%, figure 4C), *very likely beneficial* in 27˚C (SMC = 2.3W, CI = 3.6 to 18.4, with chances of a beneficial/trivial/harmful effect being 97.4%, 2.1% and 0.6%, figure 4C) and *likely beneficial* in 24˚C (SMC = 2.4W, CI = -0.8 to 10.8, with chances of a beneficial/trivial/harmful effect being 81.8%, 15.5% and 2.8%, figure 4C), and. In all cases, COLD was *very unlikely* to have a detrimental impact on mean power output throughout the course of the time trial. On an individual level, the number of riders displaying a higher mean power output following COLD by more than the smallest meaningful change calculated for each ambient temperature was: 24°C n=8; 27°C n=7 and 35°C n=6. There was no difference in pacing strategy between cooling conditions ($P = 0.92$, figure 1C).

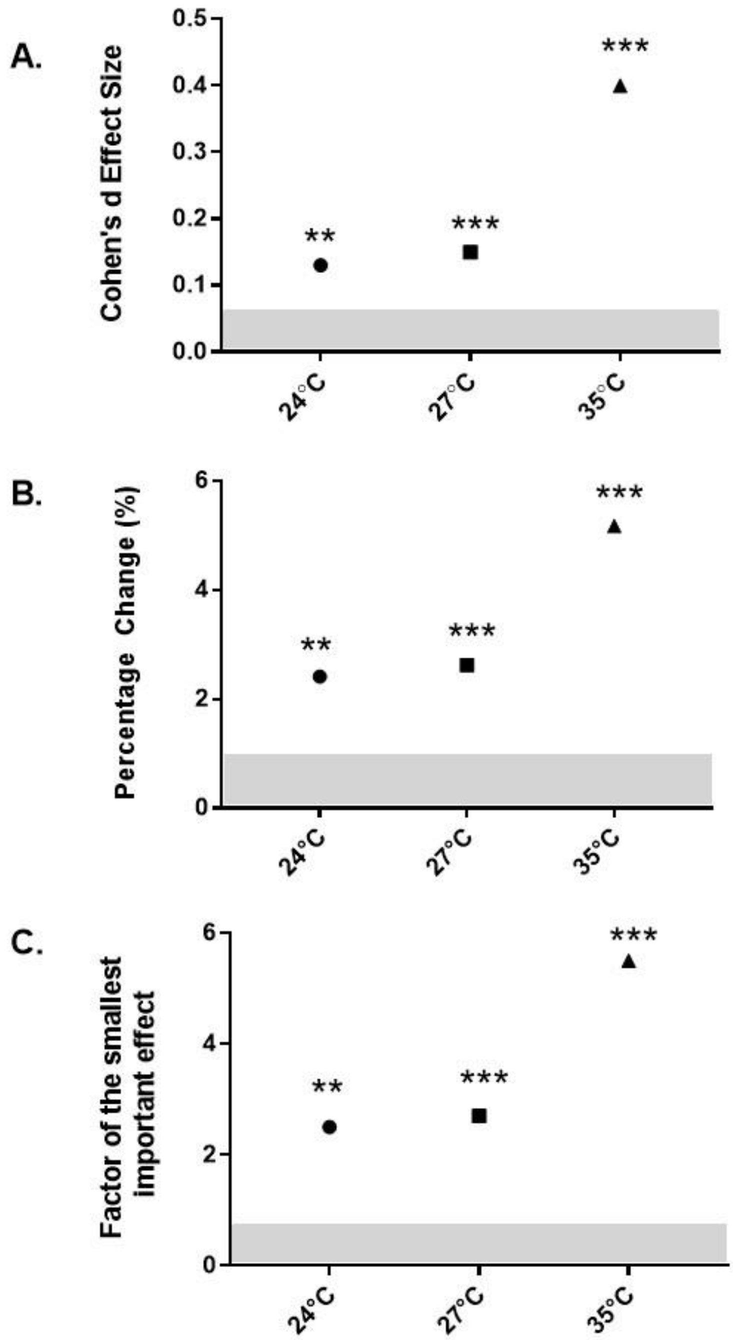

Figure 3: Differences in mean power output with the use of pre-cooling compared to no pre-cooling when expressed as A) Cohen's d effect size, B) percentage change and C) the smallest important effect. The numbers of asterisks (*) indicate the likelihood for the between-groups differences to be substantial, with 1 symbol referring to possible difference, 2 to likely, 3 to very likely differences. The shaded area reflects the threshold for the smallest worthwhile change.

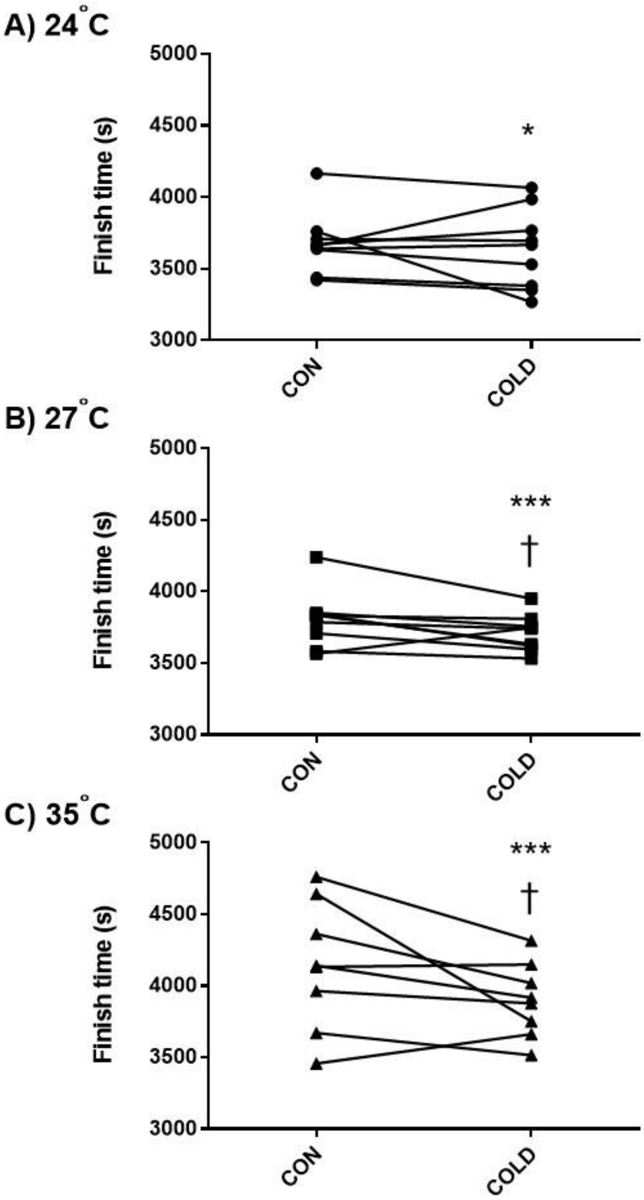

Figure 4: Individual performance responses to the use of pre-cooling (COLD) in A) 24°C, B) 27°C and C) 35°C. † denotes significantly different to no pre-cooling (CON). The numbers of asterisks (*) indicate the likelihood for the between-groups differences to be substantial, with 1 symbol referring to possible difference, 2 to likely, 3 to very likely differences.

Skin temperature, gastrointestinal temperature and heart rate

There were main effects of time, cooling condition and an interaction effect (all $P<0.001$) on mean skin temperature. In both 24˚C and 35˚C, $\bar{T}_{sk}$ was lower following COLD throughout the warm up (all $P<0.0001$) and for the first 10% of the time trial ($P<0.05$). At

27˚C this effect was evident until 20% time trial completion ($P<0.05$). There was only a main effect of time ($P<0.0001$) but not cooling condition on T_{gi} ($P=0.64$). Consequently, mean body temperature reflected these data with main effects for both time and cooling condition (both $P<0.0001$) and an interaction effect ($P<0.0001$; figure 5A). There was a main effect of time ($P<0.0001$) but not condition ($P=0.88$) on heart rate during the time trial.

Sweating

There were main effects for pre-cooling ($P<0.01$) and environmental temperature ($P<0.05$), although there was no significant interaction ($P=0.21$, figure 5B). Sweat loss was lower following COLD in 24°C (1417.2±315 mL vs. 1288±176 mL, $P<0.05$) and 27°C (1677±314 mL vs. 1545±347 mL, $P<0.05$) but there was no difference at 35°C (1276±244 mL vs. 1265±339 mL, $P=0.86$)

Perceptual Measures

Main effects of both time and condition and an interaction effect were evident for thermal sensation (all $P<0.0001$). Thermal sensation was reported as feeling cooler throughout the warm up following COLD in all environmental conditions (all $P<0.005$). At the end of the recovery period, thermal sensation remained lower following COLD across all temperatures ($P<0.05$). There were no differences to thermal sensation throughout the time trial between conditions. Thermal sensation was positively correlated to finish time from T0 ($r=0.362$, $P<0.01$) through to 60% of workload completion ($r=0.282$, $P<0.05$) with the strongest correlation occurring at REC ($r=0.395$, $P<0.005$, figure 5C). There were main effects of time ($P<0.0001$) and condition ($P<0.01$) and an interaction effect ($P<0.0001$) for thermal comfort. Thermal comfort did not correlate to finish time at any stage (all $P>0.165$). Participants reported that they were more uncomfortable in COLD in 27˚C throughout first 40% of the time trial (all $P<0.01$). There were no differences in thermal comfort between cooling conditions in

24˚C or 35 ˚C. Lastly, a main effect of time was found for RPE (P<0.0001), but no significant effects of COLD (P=0.77) were evident.

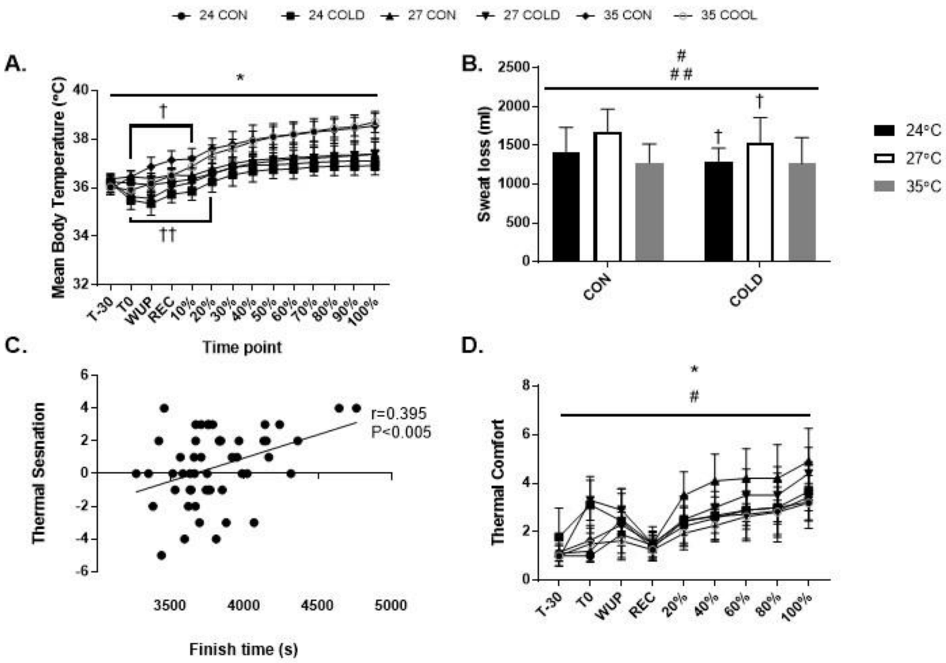

Figure 5: Physiological and perceptual effects of pre-cooling before and during a self-paced time trial in different ambient temperatures. A) mean body temperature, B) sweat loss, C) thermal sensation following warm up and the relationship to finish time, D) thermal comfort. * denotes a main effect of time. # and ## denote main effects of cooling and temperature respectively. † denotes a difference between no cooling (CON) and pre-cooling (COOL) at †† denotes a difference between CON and COOL at 24 and 35°C. Data presented as mean± SD

Discussion

The aim of the present investigation was to establish the existence of an environmental threshold above which pre-cooling has an ergogenic effect for cycling time trial performance when using an ice-vest. Our data are consistent with the previously observed negative effect of increasing temperature on time trial performance, for both the cooling and control data. More importantly, our data show that pre-cooling has a significant ergogenic effect on time trial performance completed in 35˚C and 27˚C but not in 24˚C, resulting in performance changes of 6.2%, 2.6%, and 1.2% respectively. The effect of pre-cooling was *very likely beneficial* to performance in 35˚C, *likely beneficial* at 27˚C and *possibly beneficial* in 24˚C. These results indicate that cyclists should start to consider implementing a pre-cooling procedure prior to racing a time-trial in environmental temperatures of above 24˚C. Furthermore, in cooler temperatures, pre-cooling may have some benefit, although our data cannot conclusively support this. However, utilising pre-cooling in lower ambient temperatures is unlikely to have a detrimental effect on performance at the cooling intensities used here

A previous meta-analysis supports an environmental effect on the magnitude of pre-cooling benefit,[12] similar to that reported here. They report a clear difference in performance improvement in temperatures above 26˚C, where there was a mean improvement of 6.6% compared to 1.4% below this temperature, which still represents a meaningful effect,[23] and could yield a performance benefit. However, as those values included data on both time to fatigue protocols and time-trial tests, the magnitude of any potential benefit was likely over-estimated, given that the authors report the largest performance effect was evident in the open-ended trials (8.6%) compared to time trials (4.2%). In addition, the data from Tyler et al., included a WBGT threshold of 26˚C for inclusion in their analysis.[8] As the equivalent WGBT in the present study at ambient temperatures of 24˚C and 27˚C was 19.2˚C and 22.1˚C respectively, this indicates that the effective WGBT threshold above which pre-cooling becomes effective at improving endurance performance is ~19˚C. Therefore, Tyler et al. may have been overly restrictive in their study inclusion criteria, further highlighting the lack of understanding of the existence of a threshold temperature above which pre-cooling becomes effective. Therefore, further investigation is warranted to establish the exact environmental temperature threshold above which pre-cooling using a variety of techniques becomes a beneficial strategy, as currently this is equivocal in the available literature.

The present study demonstrates a clear reduction in sweat loss in response to COLD in both 24˚C and 27˚C compared to CON. Although we did not directly measure hydration, it is possible that this reduction in sweat loss contributes to a better maintenance of hydration. However, the effect of dehydration on performance is equivocal. [24,25],[26,27]

Sparing sweat loss (and maintaining hydration) through the increase in evaporative cooling potential, owing to the moisture released from the cooling garments, will likely contribute to improving endurance performance in the heat. Mechanistically, apart from the cooling power delivered by the phase change of ice to water in the vest, the moisture released from the vest will further reduce the requirement of sweat to dissipate heat. Evaporation of moisture from the vest will contribute to evaporative heat loss, without requiring an increase in sweat production, therefore helping to moderate body temperature and maintain hydration.

The performance effect reported here occurred following a clear reduction in $\bar{T}_{sk}$, which was independent of a reduction in T_{gi}. This finding is in-line with that of Schlader et al., [28,29] and our previous work[9] suggesting that $\bar{T}_{sk}$ has a key role in the modulation of exercise intensity independently of core temperature. It is likely that elevations in $\bar{T}_{sk}$ result in behavioural alterations, which will manifest in changes to intensity selection during exercise.[28,29] Therefore, future research into cooling techniques aimed at improving endurance performance should focus on lowering $\bar{T}_{sk}$ at the onset of exercise and its effect on thermal perception. This may help alleviate some of the discomfort associated with the implementation of many whole-body cooling interventions that are used prior to performance, in order to lower T_{gi} before the onset of exercise.

Compared to 24˚C and 27˚C, where peak $\bar{T}_{sk}$ during the time trials was ~32˚C, the performance effect of a reduction in $\bar{T}_{sk}$ following COLD was likely exacerbated in 35˚C where $\bar{T}_{sk}$ exceeded 35˚C. This is important as a $\bar{T}_{sk}$ of >35˚C has previously been shown to limit aerobic performance in hot conditions.[30] Whilst a benefit of COLD on performance is observed at 27˚C and a $\bar{T}_{sk}$ of ~32˚C, it is smaller than that which is evident at 35˚C and may be linked to a lower $\bar{T}_{sk}$. Furthermore, as this study reports a higher mean power output at 27˚C and above, it may be that a $\bar{T}_{sk}$ of 31-32˚C represents a lower $\bar{T}_{sk}$ threshold, above which detrimental performance effects become evident. Coupled with the fact that there is no performance effect at 24˚C where $\bar{T}_{sk}$ reaches ~30˚C, it appears that ambient conditions of less than ~27˚C do not provide sufficient thermoregulatory challenge to elevate $\bar{T}_{sk}$ to a degree that would severely hinder time trial performance due to a modulation in intensity selection.

Reductions in $\bar{T}_{sk}$ in response to COLD are reflected in the change to thermal sensation, particularly during the warm up phase, where there is a clear shift in thermal sensation towards feeling cool/cold. Although this effect does not last beyond the warm up phase, it is possible that the reduction in thermal sensation contributes to perceptually driven changes to performance.[28,29] Moreover, the present data show identical reductions in thermal sensation following COLD in 24˚C, 27˚C, and 35˚C yet improvements in finish time and mean power were only clearly evident at 27˚C and 35˚C. Therefore, it is possible that alterations to thermal perception only have a significant performance effect where environmental heat stress is relatively high. We suggest that in temperatures above 24˚C, thermal perception begins to play a more important role in time trial performance, and may represent a greater reliance on peripheral feedback in formulating pacing strategies for competition in the heat. However, the significance of central versus peripheral feedback in the regulation of exercise perception and exercise performance remain a contentious area for debate.[31,32]

Practical Applications

The present data indicate a threshold ambient temperature above 24˚C before pre-cooling has a performance benefit to cycling time trials. It is suggested that this is at least in part due to reductions in $\bar{T}_{sk}$, which plays an important role in the modulation of self-paced exercise intensity. Therefore, in competition where environmental temperature exceeds 24˚C or a WBGT of 19˚C, athletes and coaches should consider the implementation of a pre-cooling strategy aimed at reducing $\bar{T}_{sk}$ prior to endurance performance. However, any such strategy should be used in practice in order to allow the athlete to moderate their pacing strategy to prevent them from selecting an unsustainably high intensity in the early phases of the time trial, which could accelerate the onset of fatigue. Future work should investigate how such habituation to pre-cooling can further improve performance in the heat.

Conclusion

These data show that the use of pre-cooling has a beneficial effect on cycling time trial performance when environmental temperature is in excess of 24˚C. These data indicate that the performance benefit appears driven by the alteration to skin temperature and perceptual variables in the initial phases of the warm up and time trial.

References

1. Tatterson AJ, Hahn AG, Martini DT, Febbraio MA. Effects of heat stress on physiological responses and exercise performance in elite cyclists. *J Sci Med Sport*. 2000;3(2):186-193. doi:10.1016/S1440-2440(00)80080-8.
2. Tucker R, Marle T, Lambert E V., Noakes TD. The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. *J Physiol*. 2006;574(3):905-915. doi:10.1113/jphysiol.2005.101733.
3. Maughan RJ, Otani H, Watson P. Influence of relative humidity on prolonged exercise capacity in a warm environment. *Eur J Appl Physiol*. 2012;112(6):2313-2321. doi:10.1007/s00421-011-2206-7.
4. Otani H, Kaya M, Tamaki A, Watson P, Maughan RJ. Effects of solar radiation on endurance exercise capacity in a hot environment. *Eur J Appl Physiol*. 2016;116(4):769-779. doi:10.1007/s00421-016-3335-9.
5. Havenith G, Fiala D. Thermal Indices and Thermophysiological Modeling for Heat Stress. *Compr Physiol*. 2015;6(January):255-302. doi:10.1002/cphy.c140051.
6. Périard JD, Racinais S, Timpka T, et al. Strategies and factors associated with preparing for competing in the heat: a cohort study at the 2015 IAAF World Athletics Championships. *Br J Sports Med*. 2017;51(4):264 LP-270.
7. Bongers CCWG, Thijssen DHJ, Veltmeijer MTW, Hopman MTE, Eijsvogels TMH. Precooling and percooling (cooling during exercise) both improve performance in the heat: a meta-analytical review. *Br J Sports Med*. 2015;49(6):377 LP-384.
8. Tyler CJ, Sunderland C, Cheung SS. The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis. *Br J Sports Med*. 2015;49(1):7-13. doi:10.1136/bjsports-2012-091739.
9. Faulkner SH, Hupperets M, Hodder SG, Havenith G. Conductive and evaporative

precooling lowers mean skin temperature and improves time trial performance in the heat. *Scand J Med Sci Sports*. 2015;25 Suppl 1(S1):183-189. doi:10.1111/sms.12373.

10. Siegel R, Maté J, Watson G, Nosaka K, Laursen PB. The influence of ice slurry ingestion on maximal voluntary contraction following exercise-induced hyperthermia. *Eur J Appl Physiol*. 2011;111(10):2517-2524. doi:10.1007/s00421-011-1876-5.
11. Ross MLR, Garvican LA, Jeacocke NA, et al. Novel precooling strategy enhances time trial cycling in the heat. *Med Sci Sports Exerc*. 2011;43(1):123-133. doi:10.1249/MSS.0b013e3181e93210.
12. Wegmann M, Faude O, Poppendieck W, Hecksteden A, Fröhlich M, Meyer T. Pre-Cooling and Sports Performance. *Sport Med*. 2012;42(7):545-564. doi:10.2165/11630550-000000000-00000.
13. Galloway SDR, Maughan RJ, Laursen PB, et al. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Med Sci Sport Exerc*. 1997;29(9):1240-1249. doi:10.1097/00005768-199709000-00018.
14. Pauw K De, Roelands B, Geus B De, Meeusen R. Guidelines to classify subject groups in sport- science research. *Int J Sports Physiol Perform*. 2013;8:111-122. doi:10.1123/ijspp.8.2.111.
15. Jackson AS, Pollock ML. Generalized equations for predicting body density of men. *Br J Nutr*. 1978;40(03):497. doi:10.1079/BJN19780152.
16. ISO; International Organization for Standardization. *Ergonomics - Evaluation of Thermal Strain by Physiological Measurements*. Geneva: International Organization for Standardization; 2004.
17. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377-381.
18. ASHRAE. Thermal comfort. ASHRAE handbook of fundamentals. In: Atlanta, USA;

1997:8.1-8.26.

19. Griffiths ID, Boyce PR. Performance and Thermal Comfort. *Ergonomics*. 1971;14(4):457-468. doi:10.1080/00140137108931266.

20. Faulkner SH, Ferguson RA, Hodder SG, Havenith G. External muscle heating during warm-up does not provide added performance benefit above external heating in the recovery period alone. *Eur J Appl Physiol*. 2013;113(11):2713-2721. doi:10.1007/s00421-013-2708-6.

21. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports Physiol Perform*. 2006;1(1):50-57.

22. Cohen JW. *Statistical Power Analysis for the Behavioural Sciences*. 2nd ed. Hillside, NJ: Lawrence Erlbaum Associates; 1988.

23. Hopkins WG, Hawley JA, Burke LM. Design and analysis of research on sport performance enhancement. *Med Sci Sport Exerc*. 1999;31(3):472-485.

24. Cheuvront SN, Carter RIII, Sawka MN. Fluid Balance and Endurance Exercise Performance. *Curr Sports Med Rep*. 2003;2(4):202-208.

25. Walsh R, Noakes T, Hawley J, Dennis S. Impaired High-Intensity Cycling Performance Time at Low Levels of Dehydration. *Int J Sports Med*. 1994;15(07):392-398. doi:10.1055/s-2007-1021076.

26. Cheung SS, Mcgarr GW, Mallette MM, et al. Separate and combined effects of dehydration and thirst sensation on exercise performance in the heat. *Scand J Med Sci Sport*. 2015;25(S1):104-111. doi:10.1111/sms.12343.

27. Berkulo MAR, Bol S, Levels K, Lamberts RP, Daanen HAM, Noakes TD. Ad-libitum drinking and performance during a 40-km cycling time trial in the heat. *Eur J Sport Sci*. 2016;16(2):213-220. doi:10.1080/17461391.2015.1009495.

28. Schlader ZJ, Simmons SE, Stannard SR, Mündel T. Skin temperature as a thermal

controller of exercise intensity. *Eur J Appl Physiol*. 2011;111(8):1631-1639. doi:10.1007/s00421-010-1791-1.

29. Schlader ZJ, Prange HD, Mickleborough TD, Stager JM. Characteristics of the control of human thermoregulatory behavior. *Physiol Behav*. 2009;98(5):557-562. doi:10.1016/j.physbeh.2009.09.002.

30. Sawka MN, Cheuvront SN, Kenefick RW. High skin temperature and hypohydration impair aerobic performance. *Exp Physiol*. 2012;97(3):327-332. doi:10.1113/expphysiol.2011.061002.

31. Marcora S, Perrey S, Smirmaul BPC, et al. Counterpoint: Afferent feedback from fatigued locomotor muscles is not an important determinant of endurance exercise performance. *J Appl Physiol*. 2010;108(2):454-457. doi:10.1152/japplphysiol.01388.2009.

32. Perrey S, Smirmaul B de PC, Bosio A, et al. Comments on Point:Counterpoint: Afferent feedback from fatigued locomotor muscles is/is not an important determinant of endurance exercise performance. *J Appl Physiol*. 2010;108(2):458 LP-468.