Title of the article: The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: A meta-analysis

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ABSTRACT

Exercise is impaired in hot, compared to moderate, conditions. The development of hyperthermia is strongly linked to the impairment and as a result, many different strategies have been investigated to combat this. This meta-analysis focused on one of the most popular strategies: cooling. Pre-cooling has received the most attention but more recently cooling applied during the bout of exercise has also been investigated and both were reviewed. We conducted a literature search and retrieved twenty-eight articles which investigated the effect of cooling administered either prior to (n = 23) or during (n = 5) an exercise test in hot (WBGT > 26°C) conditions. Mean and weighted effect sizes (Cohen's *d*) were calculated. Overall, pre-cooling has a moderate (*d* = 0.73) effect on subsequent performance but the magnitude of the effect is dependent upon the nature of the test. Sprint performance is impaired (*d* = -0.26) but intermittent performance and prolonged exercise are both improved following cooling (*d* = 0.47 and *d* = 1.91 respectively). Cooling during exercise also has a positive effect on performance and capacity (*d* = 0.76). Improvements were observed in studies with and without cooling-induced physiological alterations and the literature supports the suggestion of a dose-response relationship between cooling, thermal strain and improvements in performance and capacity. In summary, pre-cooling can improve subsequent intermittent and prolonged exercise performance and capacity in a hot environment but sprint performance is impaired. Cooling during exercise also has a positive effect on exercise performance and capacity in a hot environment.

SUMMARY: WHAT ARE THE NEW FINDINGS?

- There are limited data regarding pre-cooling prior to sprint exercise in the heat but it appears that pre-cooling impairs such performance, particularly when the active muscles are directly cooled.
- Cooling administered before or during intermittent-sprint and endurance performance in the heat has a performance benefit, but the effectiveness of the cooling intervention appears to be dependent upon the magnitude of thermal strain experienced and the volume of the cooling applied.
- Exercise performance and capacity can be improved by cooling prior to or during the bout with and without cooling-induced alterations in physiological variables.
- Optimal cooling strategies are yet to be identified for a range of sporting settings due to marked differences in the cooling protocols and performance and capacity assessments investigated to date.

INTRODUCTION

Exercise in the heat

The detrimental effect of hot environmental conditions on exercise performance and capacity are well documented.[1-5] Cycling capacity is reduced in a dose-response fashion in temperatures which exceed 11°C,[1] running time-trial performance is impaired by ~10% when performed in temperatures of 30°C compared to 14°C[2] and acclimated African runners outperform non-acclimated Caucasian runners in hot (35°C) though not cool (15°C) conditions.[4]

Despite the well-documented impairments in capacity and performance, the exact mechanisms which limit exercise in hot environments are still not fully understood. During open-looped, fixed-intensity protocols exercise is voluntarily terminated at a core temperature of ~40°C in both human and animal studies,[6,7] and animal data suggests that it may be the obtainment of a high brain, rather than body, temperature that causes the termination.[6] In closed-loop, performance studies self-selected workloads are reduced in hot conditions prior to the attainment of high internal temperatures suggesting an anticipatory down-regulation which allows for the task to be completed within homeostatic limits.[3] Central levels of a variety of neurotransmitters have been implicated in the onset of fatigue during exercise, and recent data suggest that cerebral dopamine concentrations play a dominant role in the regulation of exercise performance and adherence in hot environmental conditions.[8]

Although the exact mechanisms remain unclear, the development of hyperthermia is integral to all of the proposed theories and so a number of strategies have been investigated in an attempt to attenuate the rate at which hyperthermia develops during exercise in a hot environment. These interventions include acclimation programmes,[9] hydration strategies[10] and cooling interventions. A variety of cooling methods have been investigated differing in the duration, method and site of application and this review will focus on the effect that external, cooling interventions administered prior to, or during, exercise have on subsequent exercise performance and capacity in a hot environment.

Pre-cooling

To date, pre-cooling is the intervention which has received the greatest level of attention. Many different methods of pre-cooling have been investigated prior to exercise in a hot environment and these include water-immersion;[7,11-16] the application of ice packs onto the skin;[12,17] the wearing of ice-cooling garments;[12,18-24] cold air exposure[25] and a combination of these approaches.[21,23,26-31] It has been postulated that pre-cooling may benefit subsequent exercise performance or capacity in hot environments both directly and indirectly. Firstly, if the magnitude of the cooling is sufficient, it can directly affect the physiological state of the body and enhance subsequent performance by lowering the level of thermal strain experienced.[7,16] It is worth noting however, that pre-cooling may also induce physiological alterations such as extreme vasoconstriction and/or decreases in muscular temperature[31] which may impair subsequent performance. Secondly, if the magnitude of cooling is insufficient to have a direct effect upon the physiological state of the body, performance benefits may still occur without physiological adjustment, seemingly due to an alteration in the level of perceived strain experienced by the exercising individual.[32]

Cooling during exercise

It is not uncommon for the desired physiological alterations (e.g. reduced core temperature) induced by pre-cooling to be lost during exercise and for the individual to end the exercise bout under the same level of thermal strain as they experienced during control trials.[11,13,14,18,23,33] As a result, there has been recent interest in cooling during exercise investigating the effect of head cooling using cold air exposure,[34] torso cooling using an ice vest[35] and neck cooling using a cooling collar.[36-38] Cooling during exercise may have issues regarding practicality (e.g. excess weight and skin irritation[39] and sporting regulations) and such issues may account for the relative lack of interest in this area to date. There has been increased interest in the design of practical devices in recent years from exercise and occupational physiologists, the military, fire-fighters and sporting institutes[40] and it is worth noting that five of the six studies investigating cooling during exercise have used practical garments and all six have been published in the last 2 years. With this in mind, if cooling during exercise is shown to offer a benefit to performance or capacity in a hot environment (and technological advances continue to minimise the practical concerns) cooling during exercise might be an area which receives more attention in the near future.

Aim of the review

There is an increasing level of interest in the effect of cooling interventions administered both pre- and during- exercise due to the scheduling of major competitions in thermally challenging environments. For example, the 2022 FIFA World Cup will be held in Qatar where the temperatures are expected to exceed 40°C, and optimising cooling strategies has been highlighted as a research priority by a FIFA-endorsed panel of experts in a recent review.[41] Marino [42] conducted a review of the pre-cooling literature 10 years ago, at a time when there were only a few studies in the area and so the review combined investigations conducted in temperate conditions with those conducted in the heat (only 5 manuscripts focused on pre-cooling prior to exercise in hot conditions). In the decade since this review there has been an exponential increase in the number of publications investigating the effect of cooling prior to, and during exercise in hot conditions and a wide-range of techniques have been investigated. Many of these more recent interventions have used practical cooling methods and more representative exercise modalities in an attempt to improve the ecological validity of the research. The increase in the number of cooling investigations allows for a meta-analysis to be conducted in order to obtain more reliable information about the effect of the intervention.[43] The aim of this meta-analysis is to review and synthesise the current literature with regards to the effect that pre-cooling and cooling administered during exercise has on exercise performance and capacity in hot environments.

METHODS

Literature search parameters used

A search using the PubMed database was conducted on the 11th April 2012. The search terms used were 'pre cooling' (874 results), 'pre-cooling' (81 results), 'pre cooling exercise' (66 results), 'cooling' (23,949 results), 'cooling exercise' (723 results), 'exercise performance in the heat' (790 articles), 'exercise capacity in the heat' (391 results), 'practical pre cooling' (17 results), 'practical pre-cooling' (2 results), 'cooling jackets' (7 results), 'cooling vests' (18 results), 'forearm cooling' (235 results), 'leg cooling' (269 results), 'neck cooling' (212 results) and 'head cooling' (921 results). Subsequent manual searches were performed using the reference lists from the recovered articles.

Inclusion/exclusion criteria

The analysis was limited to articles using human participants published in English language peer-reviewed journals in which there were a cooling and a control group. Abstracts and unpublished theses were not included. English language manuscripts were selected due to the native language of the authors. Although this may have resulted in some articles which met the other criteria being excluded, it has been reported that language-inclusive meta-analyses do not differ when estimating the effectiveness of an intervention compared to language-exclusive versions.[44] Cooling must have been administered prior to, or during, exercise in a hot environment (WBGT > 26°C). A number of cooling studies have investigated cooling administered prior to exercise in temperate conditions; however, the effect of cooling on performance or capacity is likely to be artificially reduced in such conditions. Due to an increase in the level of interest in, and usage of, practical cooling devices this review focused on cooling which was external in nature. To avoid duplication, fluids (e.g. ice slurries) were not considered, and interested readers are directed to the recent review of such interventions by Siegel and Laursen.[45] Investigations solely focussing on the thermoregulatory responses to cooling were excluded. We used the four-stage (Identification; Screening, Eligibility and Inclusion) process identified in the PRISMA statement[46] to reduce the number of initial search results to the twenty-eight manuscripts reviewed in this article (Summarised in Table 1 (supplementary/online only) and Table 2).

Data grouping

The reviewed manuscripts were divided into two groups depending on whether the cooling was administered prior to or during exercise and analysed as sub-groups. Subsequent analysis was performed on the pre-cooling data by dividing the data set into three groups 1) cooling prior to a single sprint of < 70 s (primarily anaerobic in nature[47]); 2) cooling prior to a test using intermittent sprints (mixed energy system); and 3) cooling prior to prolonged (> 6 minute), primarily aerobic[47], exercise.

Data analyses

Mean values and standard deviations (SD) for cooling and control trials were obtained from data within the manuscripts. Where values were not stated, the data were estimated from the figures within the manuscript. Effect sizes (Cohen's *d*[48]) were calculated for each study. Weighted-mean estimate of the effect sizes were calculated to account for sample size differences. A mean un-weighted effect size and associated 95% confidence intervals were also calculated. Cohen's classification of effect size magnitude was used whereby $d < 0.19$ = negligible effect; $d = 0.20 – 0.49$ = small effect, $d = 0.50 – 0.79$ = moderate effect and $d > 0.8$ = large effect.[48] A sample size versus effect size funnel plot was produced to evaluate possible publication bias.

RESULTS

Data screening

Cooling data were visually analysed using a funnel plot (Figure 1). Pre-cooling and cooling during studies were looked at collectively due to the low number of investigations reviewed (N = 28). The funnel plot indicates that there may be a problem associated with publication bias as highlighted by the three studies to the lower right-hand side of the figure. The three investigations in question[7,13,22] all used open-loop capacity tests, which have a higher coefficient of variation than closed-loop performance alternatives;[2,38] however, other investigations using open-loop capacity tests reported lower effect sizes. It should also be noted that the homogeneity of the distribution will be somewhat artificially enhanced due to the small number of papers reviewed of which a number involved multiple performance measures.

Pre-cooling

The overall weighted-mean estimate of the effect size for the effect of pre-cooling on subsequent exercise performance calculated from the twenty-three original investigations was *d* = 0.73. The un-weighted-mean estimate of the effect size was *d* = 0.77 (95% CI: 0.65 – 0.89) (Figure 2). Manuscripts such as the one by Castle et al.[12] compared more than one cooling intervention and/or reported more than one performance measure in their manuscript so the twenty-three investigations resulted in a combined total of sixty cooling intervention/performance measure combinations. The individual effect sizes are shown in Table 1 (Supplementary/online only).

Pre-cooling prior to single and intermittent sprint exercise

Two investigations[15,31] reported the effect of pre-cooling on the performance of a single sprint performance but one of the manuscripts[31] had two cooling interventions and two performance measures, so a total of five data sets were analysed. The weighted-mean estimate of the effect size for the effect of pre-cooling on subsequent sprint exercise performance calculated was *d* = -0.26 and the un-weighted-mean effect size was *d* = -0.32 (95% CI: -0.18 – -0.45) (Figure 2). The overall weighted-mean estimate of the effect size for the effect of pre-cooling on subsequent intermittent sprint exercise performance calculated from the eight investigations,[12,17,20,21,27-30] involving a total of twenty-six cooling interventions/performance measure combinations, was *d* = 0.47. The un-weighted-mean effect size was *d* = 0.47 (95% CI: 0.40 – 0.53) (Figure 2). For investigations which had exercise bouts of various intensities[27-30] the effect size was calculated for the ‘high intensity’, ‘very high intensity’ and ‘hard’ data sets only.

Pre-cooling prior to prolonged exercise

The overall weighted-mean estimate of the effect size for the effect of pre-cooling on subsequent endurance exercise performance or capacity calculated from the thirteen investigations,[7,11,13,14,16,18,19,22-26,33] involving a total of sixteen cooling interventions/performance/capacity measure combinations, was d = 1.91. The un-weighted-mean effect size was d = 2.04 (95% CI: 1.53 – 2.36) (Figure 2).

Exercise capacity tests are more variable and less valid than exercise performance tests [49] and so analysis was also performed separately on the seven investigations involving performance tests [11,14,16,18,23,26,33] and on the six involving capacity tests.[7,13,19,22,24,25] The weighted- and un-weighted-mean estimate of the effect sizes for the effect of pre-cooling on subsequent endurance exercise performance were d = 1.06 and d = 1.13 (95% CI: 1.00 – 1.25) respectively compared to d = 2.88 and d = 2.89 (95% CI: 2.02 – 3.76) for capacity tests (Figure 2).

Cooling during exercise

The overall weighted-mean estimate of the effect size for the effect of cooling during exercise on exercise performance and capacity calculated from the five investigations[34-38] was d = 0.76. The un-weighted-mean effect size was d = 0.72 (95% CI: 0.58 – 0.94) (Figure 2). The largest individual effect size was observed in the only investigation in which participants were subjected to uncompensable heat stress[35] (d = 2.26). When removing this investigation from analysis the overall weighted-mean estimate of the effect size for cooling during exercise in compensable heat stress[34,36-38] was reduced to d = 0.45 and the un-weighted effect size was reduced to d = 0.46 (95% CI: 0.40 – 0.50). The individual effect sizes are shown in Table 2.

Table 2: A summary of the main study design details and data from the articles included in the meta-analysis which used cooling during exercise

Ref	Subjects	Protocol	Ambient conditions	Cooling intervention	Effect size (d)	Main effect for physiological and perceptual variables during exercise						
						Area Cooled	Core temp	Skin temp	Heart rate	RPE	TS	Sweat rate
Ansley et al. [34]	N = 9 males	CE T_{exh} @ 75% $\dot{V}O_{2max}$	T_{amb} = 27 - 29°C rh = 40 – 60% WBGT = 27°C	Head. Fan cooling with water misting	Cap: 0.51	↓*	↔	-	↔	↓*	-	-
Kenny et al. [35]	N = 10 males	TR T_{exh} (or 120 min) @ $3 m \cdot hr^{-1}$ wearing NBC suit	T_{amb} = 35°C rh =65% WBGT = 38°C	Torso. Ice vest worn under the NBC suit	Cap: 2.26	-	↓*	↓*	↓*	↓*	↓*	-
Tyler et al. [36] (A)	N = 9 males	90 min TR TT_{pre}	T_{amb} = 30°C rh = 50% WBGT = 29°C	Neck. Cooling collar	Perf: 0.29	↓***	↔	-	↔	↔	↓*	↔
Tyler et al. [36] (B)	N = 8 males	15 min TR TT_{pre}	T_{amb} = 30°C rh = 50% WBGT = 29°C	Neck. Cooling collar	Perf: 0.23	↓***	↔	-	↔	↔	↓*	↔
Tyler & Sunderland [38]	N = 8 males	TR T_{exh} @ 70% $\dot{V}O_{2max}$	T_{amb} = 32°C rh = 50% WBGT = 31°C	Neck. Cooling collar	Cap: 0.43	↓***	↑*	-	↑*	↔	↔	↔
Tyler & Sunderland [37]	N = 7 males	90 min TR TT_{pre}	T_{amb} = 30°C rh = 50% WBGT = 29°C	Neck. Cooling collar	Perf: 0.67	↓***	↔	-	↔	↔	↔	↔
Tyler & Sunderland [37]	N = 7 males	90 min TR TT_{pre}	T_{amb} = 30°C rh = 50% WBGT = 29°C	Neck. Cooling collar (replaced at 30 and 60 min)	Perf: 0.62	↓***	↔	-	↔	↔	↔	↔

↑ increased compared to control; ↓ decreased compared to control; ↔ no change compared to control; - not measured; * P=<0.05; **P=<0.01; ***P<0.001; WBGT = estimated wet bulb globe temperature; TT = time-trial; TT_{pre} = preloaded time-trial; T_{exh} = test to exhaustion; TR = treadmill test; CE = cycle ergometer test; temp = temperature; RPE = rating of perceived exertion; TS = thermal sensation; cap = capacity; perf = performance. N = 6 rather than 5 because the manuscript by Tyler and Sunderland [36] contains two separate investigations (A and B)

DISCUSSION

The current meta-analysis shows that pre-cooling has an overall positive, but moderate, effect on subsequent exercise performed in a hot environment (overall weighted-mean estimate of the effect size: *d* = 0.73). The effect is dependent upon the task being performed following cooling, as sprint performance is impaired (weighted-mean estimate of the effect size *d* = -0.26) but intermittent and prolonged activity are both enhanced (weighted-mean estimate of the effect size, *d* = 0.47 and *d* = 1.91 respectively). This review also highlights that cooling during exercise has a moderate, positive effect on exercise performance and capacity in the heat (weighted-mean estimate of the effect size; *d* = 0.76).

The effect of pre-cooling on sprint performance

Although pre-cooling has been substantially investigated over the last few decades, little work has investigated the effect of pre-cooling on subsequent short-duration, high-intensity exercise and we suggest two main reasons for this. Firstly, much of the literature has attempted to offset the well-documented impairments in performance or capacity observed in high ambient temperatures[1,2] caused by the onset of hyperthermia[50] and the magnitude by which body temperature will increase would be less of a concern in short-duration bouts of exercise. Secondly, a moderate elevation in body temperature may expedite mechanical and metabolic processes and so be advantageous for high-intensity exercise.[51]

Marsh and Sleivert[15] reported a small positive effect (*d* = 0.39) of pre-cooling prior to a 70 s sprint in elevated temperatures; however, Sleivert et al.[31] reported a small to large negative effect (*d* = -0.21 – -0.88) on 45 s performance, reductions similar to those observed in temperate conditions.[52] Interestingly, unlike Sleivert et al.[31], Marsh and Sleivert[15] did not cool the thigh muscles directly and so the tissue temperature may have been warmer in this study. Sleivert et al.[31] had a number of conditions and reported significantly lower muscle temperatures (34.5 ± 1.9°C) in the thigh-cooling trials without a warm-up, which was the trial with the greatest level of impairment (*d* = -0.67 - -0.88). Due to the short duration of a sprint, performance is influenced by muscle temperature, contractile function and/or anaerobic metabolism efficiency rather than cardiovascular or thermoregulatory factors. Cooler muscles have an increased time-to-peak tension and decreased voluntary power output [53] and may have a decreased rate of anaerobic metabolism during high-intensity exercise [31,54] while surface cooling the legs reduces the mean power frequency of the EMG signal [55] which could reflect a reduction in the recruitment of fast twitch motor units or a slowing of muscle fibre conduction velocity.[56] Hyperthermia appears to have a direct effect upon the central nervous system [57-60] resulting in a reduced drive to the motorneuron pool.[61] Morrison et al.[60] reported that maximal voluntary isometric force and volitional activation progressively decreases when performed at 0.5°C core temperature increments between 37.5°C and 39.5°C regardless of skin temperature but returns to baseline levels in a dose-response fashion with reductions in core temperature. In contrast, it has been shown that lowering skin temperature during isokinetic contractions decreases the maximal voluntary contraction independent of core temperature.[62] Any impairment at the muscular level would be expected to affect whole-body performance and so it is possible that sprint performance was unaffected in the investigation of Marsh and Sleivert[15] due to minimal alterations in core or skin temperature but that a performance impairment was observed in the investigation by Sleivert et al.[31] due to direct cooling of the skin superior to the working muscles (Table 1; supplementary/online only).

Unlike isolated sprint performance the data shows that pre-cooling offers a small beneficial effect (d = 0.44) to intermittent sprint performance[12,17,20,21,27-30] and it is likely that this difference is due to differences in the demands of the protocols. The intermittent protocols were longer in duration than the acute sprint test (32 – 80 min v. 45 – 70 s) and involved a greater total volume of work being undertaken. In the sprint investigation by Marsh and Sleivert[15] rectal temperature increased by <0.75°C (Sleivert et al.[31] did not report the change in rectal temperature); however, the increases in the longer sprint protocols was ~1.2 - 2°C.[20,21,27-30] There is a well-documented dose-response effect of cooling related to the magnitude of thermal strain experienced[28,29,63] and the intermittent sprint-protocols provide a greater thermal stress than the shorter-duration sprint versions (Table 1; supplementary/online only). Despite this, not all intermittent tests were improved following pre-cooling. Minett et al.[28,29] reported a dose-response relationship between pre-cooling volume and duration and subsequent improvements in physiological, perceptual and performance outcomes (d = 0.00 – 2.14) but subsequently reported no improvements in performance, despite physiological and perceptual improvements, using the same pre-cooling method[30] (Table 1; supplementary/online only). Minett et al.[30] reported that the distance covered in a simulated cricket bowling test was not altered by pre-cooling but that the distance covered in a longer-duration, intermittent protocol in which higher core temperatures were observed was increased[29] adding further support to the notion that the effectiveness of cooling intervention for the enhancement of performance or capacity in a hot environment is dependent upon the thermal strain experienced and the magnitude of cooling applied.

The effect of pre-cooling on prolonged exercise

Prolonged exercise in the heat poses a greater threat to thermal homeostasis than shorter bouts of exercise and therefore it is unsurprising that greater effect sizes are observed in performance and capacity tests of longer duration (Figure 2). It is not uncommon for core temperatures in excess of 40°C to be recorded following prolonged exercise in hot conditions in sufficiently motivated individuals;[64] however in the manuscripts reviewed, core temperatures at the end of the bout of exercise ranged from ~37.5 – 40.1°C[7,11,13,14,16,18,19,22-26,33] demonstrating that participants experience thermal strain ranging from mild[16,25] to extreme.[7] A major justification for pre-cooling is to allow the participant to commence exercise at a lower core temperature and/or to attenuate the rate at which core temperature increases during the subsequent bout of exercise. All of the investigations which cooled prior to prolonged exercise were successful in reducing core temperature although in some cases the temperature reduction was not present at the commencement of the exercise bout but occurred during the early stages of the exercise,[13,14,19,23,33] (Table 1; supplementary/online only) possibly as a result of the after-drop phenomenon caused by the initial vasoconstriction of the peripheral blood vessels and redistribution of the blood to the core.[64] Four of the interventions were sufficient to have a prolonged effect on core temperature and result in the participant finishing the trial with a lower core temperature in the cooling trial than the control;[16,23,25,26] however, subsequent performance or capacity was also enhanced in investigations in which the effect of the cooling failed to last the duration of the test. On occasions, the lack of difference may be attributed to the type of test used. Similar, or higher, core temperatures at the termination of an open-loop (i.e. capacity) test may represent a cooling-induced dampening of thermal perceptions and an ability to tolerate higher internal temperatures due to the volitional nature of termination point in such tests[38] i.e. participants have exercised for longer and have produced more heat as a result but have not terminated the bout at comparative internal temperatures. Similar, or higher, core temperatures during a closed-loop (i.e. performance) test in which performance was improved following cooling may be due to an increased level of metabolic heat production as a result of the greater amount of work completed in the task.

Improvements in prolonged exercise performance or capacity in hot conditions were observed in all but one of the investigations reviewed.[25] Mitchell et al.[25] reported that exercise capacity at 100% $\dot{V}_{O_{2max}}$ (6 – 7 min) was impaired by pre-cooling using fans and mist spray (*d* = -0.59) despite the intervention reducing peak core temperature by ~1.5°C. The authors proposed that the impairment may have been due to the relatively short duration of the test (large improvements have been observed in capacity tests of shorter duration (e.g. *d* = 4.71 [13] and *d* = 8.14 [22] since the investigation by Mitchell et al.[25]) and to discomfort associated with the cooling procedure used. The authors noted that participants reported lower levels of thermal comfort following the cooling intervention and when asked reported a "lack of spring" and a feeling of "heaviness" in the cooling trials (p. 123). Some investigations which report an enhanced performance in the heat do so with associated beneficial alterations in the participants' perceptions of comfort and thermal strain (e.g. the dampening in thermal strain reported following the alteration of neurotransmitter concentrations [8]). Mitchell et al.[25] suggested that the negative perceptions may contribute to explaining the reduction in performance observed but this is speculation.

The effect of cooling during exercise on longer-duration performance

Five manuscripts investigated the effect of cooling during exercise.[34-38] There was a moderate, positive effect of cooling during exercise (weighted-mean estimate of the effect size, *d* = 0.76); however, further scrutiny suggests that the effectiveness may also be dependent upon the level of thermal strain experienced.[35,36] Cooling during exercise performed in compensable heat stress conditions appears to have a smaller effect on the performance or capacity than in uncompensable heat stress (weighted-mean estimate of the effect size, *d* = 0.45 v effect size, *d* = 2.26). Kenny et al.[35] cooled the torso using an ice vest under nuclear, biological and chemical protective clothing and reported that the vest was effective at reducing the thermal strain experienced, reducing both core and skin temperatures. Uncompensable heat stress places a high thermal load on the body and so it is unsurprising that an effective cooling intervention has more of a pronounced effect of subsequent performance in such conditions compared to compensable heat stress situations. All of the investigations conducted in compensable heat stress conditions cooled the head and/or neck region which is in contrast to most cooling interventions used prior to and during exercise. Most investigations have attempted to reduce the core temperature and so have cooled the torso and/or lower limbs because there is a larger surface area and therefore greater potential for heat exchange. It has been demonstrated that a high hypothalamic temperature is the main factor that limits motor activity[6] and that the head and face are sites of high alliesthesial thermosensitivity[65] so cooling the head may represent a greater thermoregulatory advantage compared to cooling other parts of the body.[66] Table 2 summarises the physiological responses to cooling during exercise. Improvements in capacity and performance are observed in the absence of reductions in heart rate or core temperature [34,36-38] although the greatest improvement was observed when core temperature and heart rate were both reduced by the cooling.[35] Core temperature and heart rate were only reduced in one investigation and this was the only investigation to record skin temperature which was also reduced.[35] The effectiveness of cooling has been linked to the magnitude of the thermal strain experienced with head cooling shown to have no effect on physiological responses until the ambient temperatures reach ~40°C.[63] Kenny et al.[35] investigated the effect of cooling during uncompensable heat stress and so, along with the data from Nunneley et al.[63], it appears that cooling during exercise may only elicit physiological alterations if the thermal strain experienced is severe. An improvement in the perceived difficulty/discomfort of a task has been linked to improved exercise performance/capacity in the heat [67] but the perceptual data obtained while cooling during such exercise is mixed. Improvements in performance and capacity were observed in all trials but the rating of perceived exertion was reduced in only two of the seven trials and thermal sensation was improved in only three of the six in which it was recorded. It appears that physiological and perceptual changes are not required to improve performance/capacity in the heat with cooling during exercise, although beneficial changes may maximise the improvements observed,[35] and so further research is required to ascertain the mechanisms which explain the improvements observed.

Conclusions

Pre-cooling can improve subsequent intermittent-sprint performance and prolonged performance and capacity in a hot environment; however, sprint performance is impaired, especially when the active muscles are directly cooled. Cooling interventions adopted during exercise improve performance and capacity in hot environments. The effectiveness of the cooling intervention used either prior to or during exercise is dependent upon the volume of cooling and the extent of the thermal strain experienced although the intervention does not need to induce alterations in physiological or perceptual variables to have a beneficial effect on performance or capacity.

Practical application

As mentioned earlier, exercise capacity tests are more variable and less valid than exercise performance tests [49] and so the performance test data may be more useful in an athletic setting. Pre-cooling had a lesser effect on performance trials than capacity tests (d = 1.06 v. 2.88 (weighted-mean estimate of the effect size)); however, the effect size was still large.[47] The London 2012 Olympic Games' Men's 10,000 m final was won in a time of 27.51 min (27:30.42). If an intervention with an effect size of d = 1.06 was used in this race (the standard deviation of the 26 finishing times was ± 0.62 min) it would equate to an improvement in performance of 0.66 min (~40 s). If any of the runners finishing 2nd – 17th had ran 40 s faster they would have won the gold medal. In the Women's 10,000 m race (winning time = 30.35 min; finishers = 21; standard deviation = ± 0.62 min (coincidently the same as the men)) a 40 s improvement would have resulted in any of the top 9 finishers winning the race. Another way to view the performance improvements achievable by pre-cooling is to say that there was a mean improvement of 6.9 ± 5.7% (range = 1.1 – 17.1%) which would reduce the winning 2012 Olympic Men's 10,000 m time to 25.61 min. It is worth noting that all of the investigations used trained, rather than elite, athletes and so the performance improvements here are likely to larger than those observed in elite cohorts but performance gains of ~7% would be highly desirable in races at all levels.

Recommendations for future research

There has been a sizable amount of research investigating the effects of pre-cooling on subsequent performance and capacity in a hot environment but methodological differences regarding the interventions and tests used mean that further research is required to identify optimal cooling strategies for different events taking into account the level of thermal strain experienced. The dose-response effect of pre-cooling on subsequent performance has already been discussed[28,30] and so investigating the effect of cooling during exercise with or without prior cooling is an area that merits future research. The authors would also like to make the recommendation that site-specific temperature is recorded in all cooling studies. A number of articles reviewed for this manuscript failed to report the skin temperature at the site of cooling (Table 1; supplementary/online only and Table 2) and in such circumstances it is difficult to fully elucidate the effectiveness of the cooling intervention - this is particularly important when using practical cooling devices because the magnitude of their cooling can be quite localised and transient.[37]

Contributions

All authors contributed to the conception and planning of the review. CT was the author primarily responsible for the initial writing of the manuscript and the data analyses and is identified as the guarantor for the overall content. All authors reviewed and revised the initial submission and approved the final version.

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Competing Interests

None of the authors have any commercial interests or other conflicts of interest to declare.

FIGURES

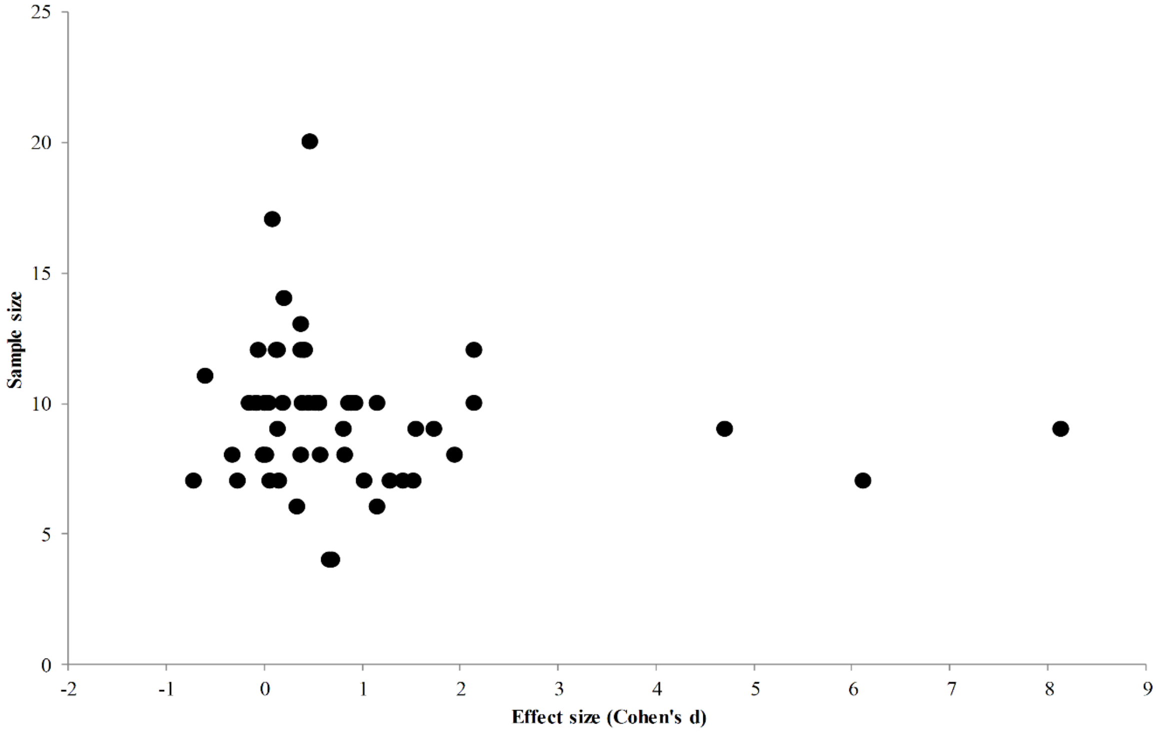

Figure 1: Funnel plot suggesting potential positive, publication bias. Dashed, vertical line marks the weighted-mean estimate of the effect size of all reviewed studies (*d* = 0.73).

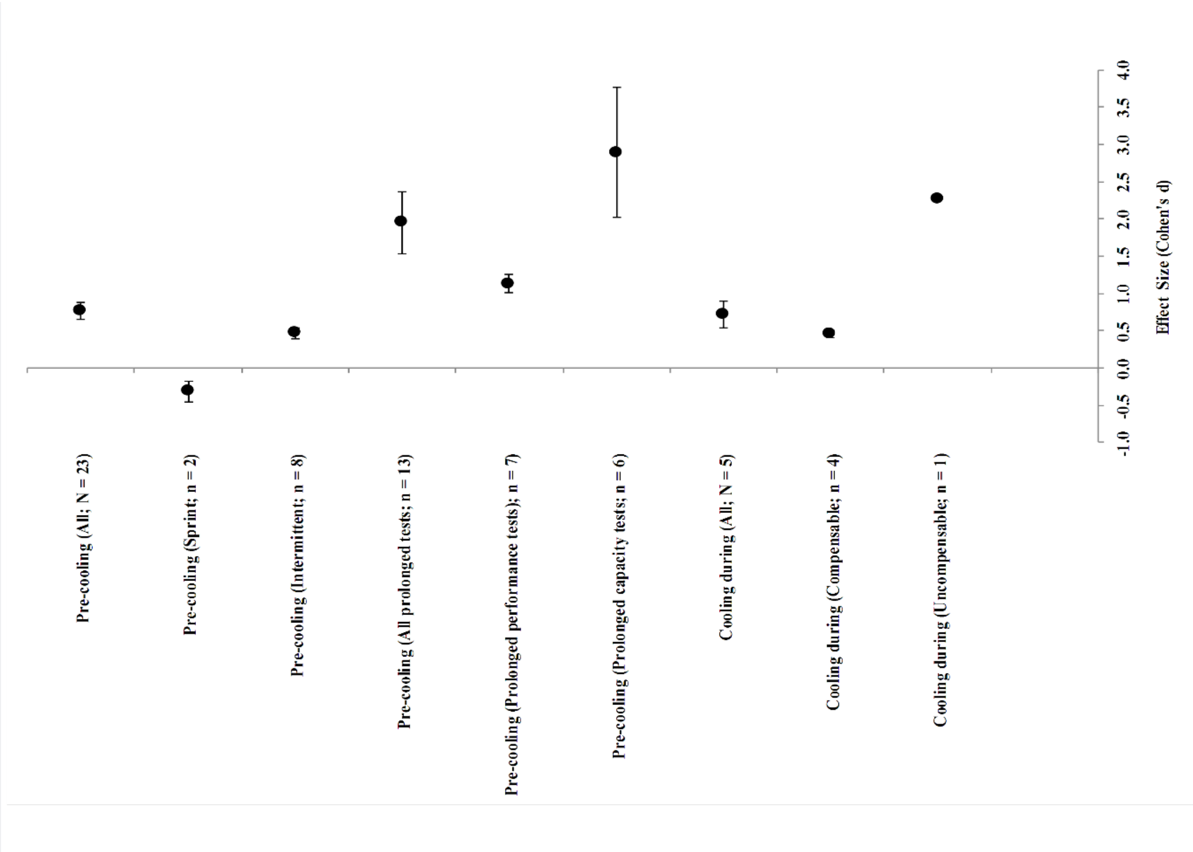

Figure 2: The mean (± 95% confidence intervals) un-weighted effect of pre-cooling and cooling during exercise on exercise performance and capacity in a hot environment related to sub-groups based upon test type. $d < 0$ = impairment; $d > 0$ = improvement. $d = 0 – 0.19$ = negligible effect; $d = 0.20 – 0.49$ = small effect, $d = 0.50 – 0.79$ = moderate effect and $d > 0.8$ = large effect.[48]

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