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ORIGINAL ARTICLE

One night of sleep deprivation decreases treadmill endurance performance

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Abstract The aim was to test the hypothesis that one night of sleep deprivation will impair pre-loaded 30 min endurance performance and alter the cardio-respiratory, thermoregulatory and perceptual responses to exercise. Eleven males completed two randomised trials separated by 7 days: once after normal sleep (496 (18) min: CON) and once following 30 h without sleep (SDEP). After 30 h participants performed a 30 min pre-load at 60% $\dot{V}O_{2\,max}$ followed by a 30 min self-paced treadmill distance test. Speed, RPE, core temperature (T_{re}), mean skin temperature (T_{sk}), heart rate (HR) and respiratory parameters ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$, RER pre-load only) were measured. Less distance ($P = 0.016$, $d = 0.23$) was covered in the distance test after SDEP (6037 (759) 95%CI 5527 to 6547 m) compared with CON (6224 (818) 95%CI 5674 to 6773 m). SDEP did not significantly alter T_{re} at rest or thermoregulatory responses during the pre-load including heat storage (0.8°C) and T_{sk}. With the exception of raised $\dot{V}O_2$ at 30 min on the pre-load, cardio-respiratory parameters, RPE and speed were not different between trials during the pre-load or distance test (distance test mean HR, CON 174 (12), SDEP 170 (13) beats min^{-1}: mean RPE, CON 14.8 (2.7), SDEP 14.9 (2.6)). In conclusion, one night of sleep deprivation decreased endurance performance with limited effect on pacing, cardio-respiratory or thermoregulatory function. Despite running less distance after sleep deprivation compared with control, participants' perception of effort was similar indicating that altered perception of effort may account for decreased endurance performance after a night without sleep.

Keywords Exercise · Pacing · Thermoregulation · RPE · Cardio-respiratory

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Introduction

A number of both occupational and athletic populations may be exposed to short-term sleep loss or deprivation. These may include military personnel on sustained operations, workers on rotational shift patterns and athletes that travel across time zones. Further, those travelling to high altitude and athletes using hypoxic tent facilities report poorer sleep quality with increased number of waking periods (Weil et al. 1978). Despite the anecdotal claims from coaches and athletes that an adequate night's sleep is essential for peak performance; few experimental investigations have examined the effect of sleep deprivation on exercise performance. In fact, the three investigations to examine the effect of one night of sleep deprivation on exercise performance report contradictory findings.

Pickett and Morris (1975) reported time to exhaustion (TTE) was unaltered following 30 h of sleep deprivation, whereas, Martin (1981) reported a marginally ($P = 0.05$) significant decrease in TTE following 36 h of sleep deprivation. Moreover, Chen (Chen 1991) reported one night's sleep deprivation significantly reduced TTE on an incremental protocol but did not significantly reduce TTE at a constant workload equal to 75% of peak power output within the same study. A striking feature of the latter two investigations, which led Martin to report that exercise performance was either resistant or susceptible to sleep loss, was the individual variability in altered TTE following sleep deprivation. For example, in Martin's study, compared with TTE under control conditions, individuals TTE following sleep deprivation ranged from a 5% improvement to a 42% decrement. The equivocal findings of these investigations may result from experimental limitations which include: uncontrolled dietary intakes including caffeine and unknown sleep times on the control trial and evening prior to each trial (Martin 1981; Pickett and Morris 1975). Furthermore, the effect of sleep deprivation on pacing is unknown as these previous studies all used TTE tests. Time to exhaustion tests require individuals to exercise at a constant workload until they become exhausted. The open end point of TTE means these types of tests do not resemble most real-life athletic events which have known end points and require knowledge of pacing. Alternately, endurance performance can be assessed by distance or time trial type endurance tests which are inherently more ecologically valid for real-life athletic performance as they have known-end points and require knowledge of pacing.

The mechanism by which short term sleep deprivation (<36 h) may affect exercise performance is unclear as previous investigations have reported limited alterations during exercise in cardio-respiratory factors (i.e. oxygen uptake, respiratory exchange ratio, heart rate (Martin and Haney 1982; Martin 1981; Martin and Gaddis 1981). In fact, heart rate was actually shown to be reduced after sleep deprivation during sub-maximal exercise (Martin and Haney 1982; Martin and Gaddis 1981). Sleep deprivation has been shown to reduce evaporative cooling and dry heat loss in warm environments (Dewasmes et al. 1993; Sawka et al. 1984). Endurance performance was however not assessed in these investigations and therefore it is unclear whether the impaired heat dissipation mechanisms reported effect endurance performance. Previous literature does suggest that short term sleep loss increases perception of effort (RPE) when exercising at constant workloads, and that this may account for subsequent decrease in TTE (Martin 1981; Martin and Gaddis 1981).

The primary aim of this investigation was to examine the effect of one night of sleep deprivation on pre-loaded 30 min self-paced endurance performance. It was hypothesised that endurance performance would be the decreased following 30 h of sleep deprivation. A secondary aim of this investigation was to examine the effect of 30 h sleep deprivation on pacing, cardio-respiratory, thermoregulatory and perceptual factors during a pre-loaded sub-maximal exercise and a 30 min distance endurance test.

Methods

Participants

Eleven recreationally active healthy males volunteered to participate in the study (Mean (SD): age 20 (3) years; body mass 77.6 (7.8) kg; body fat 13 (5) %; $\dot{V}O_{2\,max}$ 55.5 (5.6) mL kg^{-1} min^{-1}). All participants gave written informed consent before the study, which received local Ethics Committee approval.

Preliminary measurements

Seven to ten days prior to beginning the experimental trials, $\dot{V}O_{2\,max}$ was measured by means of a continuous incremental exercise test on a motorised treadmill (Woodway GmbH, D-79576, Weil am Rhein, Germany) as described previously (Oliver et al. 2007). After a 15 min rest the treadmill speed which elicited 60% $\dot{V}O_{2\,max}$ on a 1% gradient was determined. This treadmill speed was used for the subsequent sub-maximal pre-load. On a separate day participants returned to the laboratory for individual energy requirement estimation and pre-loaded distance test familiarisation. Participants arrived rested and euhydrated at 08:00 h after an overnight fast, having performed no exercise and consuming water equal to 35 ml kg^{-1} of body mass the previous day. Euhydration was verified by ensuring participants urine specific gravity was less than 1.020 g ml^{-1} (Sawka et al. 2007). On arrival and after voiding, anthropometric measurements of height and nude body mass were collected. Following these measures, body composition was estimated by dual energy x-ray absorptiometry (DXA: Hologic, QDR1500, software version V5.72, Bedford, USA). Using the fat free mass determined by DXA resting metabolic rate was estimated (Cunningham 1980). The resting metabolic rate was multiplied by 1.7 to determine energy intake for each participant (Grandjean et al. 2000). Prior to leaving the laboratory participants performed a complete familiarisation of the experimental exercise protocol (i.e. 30 min preload at 60% $\dot{V}O_{2\,max}$ followed by a 30 min maximal distance test).

Experimental procedures

Using randomised cross-over design participants completed two experimental trials separated by seven days. These trials were a control trial (CON) where participants were allowed normal nocturnal sleep and a sleep deprivation trial (SDEP) where participants went without sleep for one night. On the day prior and during each experimental trial, to control nutritional and hydration status, participants were provided with their estimated energy requirements (3280 (209) kcal d^{-1}) and water equal to 35 ml kg^{-1} of body mass. Participants were instructed to consume only the food and water provided. Caffeine intake was prohibited during this time. On the day prior to each trial participants were asked to refrain from exercise and were instructed to sleep for approximately 8 h. Nocturnal activity was measured by an accelerometer (GT1 M, ActiGraph LLC, Florida, USA).

On day one of each experimental trial participants woke at 06:00 h and arrived at the laboratory where they resided in prepared accommodation under supervision for the remainder of the trial. During periods of sleep deprivation, this supervision ensured participants remained awake at all times. After 30 h (day two, 12:00 h) subjects performed a 30 min pre-load treadmill run at 60% $\dot{V}O_{2\,max}$ followed by a 30 min self-paced distance test. Each pre-load and distance test was performed in a quiet laboratory under standardised conditions (19.7 (0.6)°C, 59 (7)% RH) with two fans placed in front of the treadmill with the wind speed set at 2.3 m s^{-1}. No fluids were consumed during the pre-load or distance test. Between the pre-load and distance test subjects were removed from the treadmill for 15 min to allow for blood and saliva to be collected (data presented elsewhere (Ricardo et al. 2009). Prior to the distance test participants were instructed to run as far as possible in 30 min and to control the speed of the treadmill (gradient set at 1%) as and when they felt appropriate. During the distance test participants only had information about elapsed time. Total distance was recorded and participants were provided with this information on completion of the study. This distance test has previously been shown to be highly reproducible (CV 1.6%: (Oliver et al. 2007)).

During the pre-load, minute ventilation, O_2 uptake ($\dot{V}O_2$), CO_2 production ($\dot{V}CO_2$), respiratory exchange ratio (RER) (Cortex Metalyser 3B, Biophysik, Leipzig, Germany), heart rate (HR), core temperature (T_{re}) (YSI 4000A, Daytona, USA), skin temperature by chest, upper arm, thigh, and calf thermistor probes were measured continuously whilst ratings of perceived exertion (RPE, (Borg 1982)) were obtained at 5 min intervals. Mean weighted skin temperature (T_{sk}) was calculated as ((chest + upper arm) × 0.3) + (thigh + calf × 0.2)) (Ramanathan 1964). During the distance test, T_{re}, skin temperature and HR were measured continuously whilst participants indicated RPE at 5 min intervals. In addition, speed was recorded at 5 min intervals.

Statistical analysis

A one tailed paired *t*-test was used to determine the effect of sleep deprivation on time trial performance and resting core temperature. One tailed *t*-tests were selected due to expected differences between sleep deprivation and control conditions (i.e. sleep deprivation was expected to reduce distance completed and resting core temperature in comparison to control). Fully repeated measures ANOVA (trial × time) with Post hoc Tukey's HSD or Bonferroni adjusted *t*-tests were used, where appropriate, to determine the effect of sleep deprivation on physiological and perceptual responses during the pre-load and distance test. Appropriate adjustments to the degrees of freedom were made in cases where the assumptions of sphericity were violated. Significance was accepted as $P < 0.05$. Data are presented as mean ± (SD).

Results

No differences were reported in the amount of sleep participants obtained prior to starting each experimental trial (CON: 517 (19) and SDEP: 513 (21) min: $P = 0.718$). On CON participants slept for average of 496 (18) min whereas participants remained awake throughout SDEP. Urine specific gravity was not significantly different between CON and SDEP at 0 h (CON: 1.017 (0.002) and SDEP: 1.014 (0.001) g ml^{-1}: $P = 0.137$) or 30 h (CON: 1.009 (0.003) and SDEP: 1.005 (0.004) g ml^{-1}: $P = 0.112$). Resting T_{re} was also not different at 30 h between CON and SDEP (CON: 37.27 (0.23) and SDEP: 37.18 (0.25)°C: $P = 0.115$).

Endurance performance

Less distance was covered on the distance test after SDEP (6037 (759) m, 95% confidence intervals 5527 to 6547 m) compared with CON (6224 (818) m, 95% confidence intervals 5527 to 6547 m, $t_{(10)} = 2.5$, $P = 0.016$, Cohen's $d = 0.23$). The mean percentage change in distance completed compared with CON was −2.9% (95% confidence intervals −0.24 to −5.51%). The addition of the 95% confidence limits to the mean identifies the likely range of true differences between the SDEP and CON. Individual assessment revealed nine of eleven participants completed less distance on SDEP compared with CON of which seven exceeded two times the coefficient of variation of the distance test (Fig. 1). Of the two participants that completed greater distances on SDEP compared with CON only one exceeded two times the coefficient of variation of the distance test.

Pre-load physiological and perceptual responses

There were no trial by time interactions during pre-load for HR ($F_{(5.0,\ 50.0)} = 0.46$, $P = 0.805$), min ventilation ($F_{(5.0,45.0)} = 0.53$, $P = 0.753$), $\dot{V}CO_2$ ($F_{(5.0,45.0)} = 1.32$, $P = 0.274$), RER ($F_{(2.0,17.8)} = 0.71$, $P = 0.506$), T_{re} ($F_{(2.1,21.0)} = 0.85$ $P = 0.444$), T_{sk} ($F_{(2.1,19.0)} = 1.710$, $P = 0.207$) and RPE ($F_{(5.0,50.0)} = 1.32$, $P = 0.271$). However,

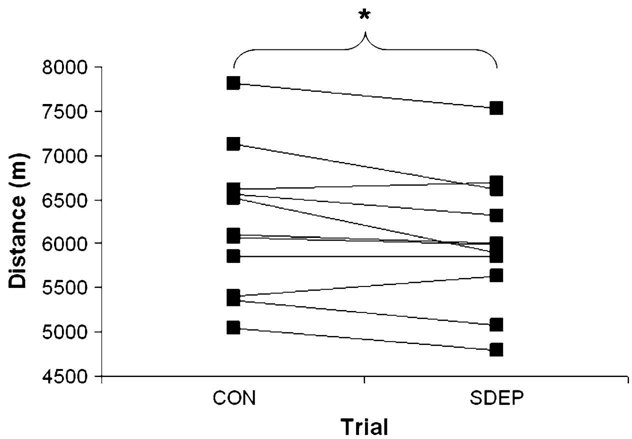

Fig. 1 Individual distance completed (m) in a 30 min pre-loaded distance test after normal sleep (CON) and 30 h of sleep deprivation (SDEP). * indicates a significant ($P = 0.016$) group mean difference between CON and SDEP

there was a significant interaction ($F_{(5.0,\ 45.0)} = 2.9$, $P = 0.025$) for $\dot{V}O_2$ where $\dot{V}O_2$ was significantly greater at 30 min compared with 5 min on SDEP trial only during the pre-load. There were also significant main effects for time for HR ($F_{(1.9,18.9)} = 33.0$, $P = 0.000$), minute ventilation ($F_{(5.0,45.0)} = 11.7$, $P = 0.000$), $\dot{V}CO_2$ ($F_{(2.5,22.6)} = 4.1$, $P = 0.004$), RER ($F_{(5.0,45.0)} = 9.5$, $P = 0.000$), T_{re} ($F_{(1.3,21.0)} = 125.2$, $P = 0.000$), T_{sk} ($F_{(1.4,12.1)} = 42.4$, $P = 0.000$) and RPE ($F_{(1.5,15.1)} = 27.5$, $P = 0.000$) where by they increased during the 30 min pre-load (Table 1). Although there was no interaction for T_{re}, a main effect of condition was revealed where T_{re} was significantly lower on SDEP compared with CON during the pre-load ($F_{(1.0,\ 10.0)} = 8.7$, $P = 0.015$). There were no main effects of condition for HR ($F_{(1.0,10.0)} = 0.22$, $P = 0.647$), min ventilation ($F_{(1.0,\ 9.0)} = 1.76$, $P = 0.217$), $\dot{V}O_2$ ($F_{(1.0,\ 9.0)} = 0.22$, $P = 0.647$), $\dot{V}CO_2$ ($F_{(1.0,\ 9.0)} = 0.37$, $P = 0.557$), RER ($F_{(1.0,\ 9.0)} = 0.05$, $P = 0.824$), T_{sk} ($F_{(1.0,\ 9.0)} = 3.16$, $P = 0.109$) and RPE ($F_{(1.0,\ 10.0)} = 0.35$, $P = 0.854$).

Distance test physiological and perceptual responses

There were no trial by time interactions during the distance test for HR ($F_{(5.0,\ 45.0)} = 1.48$, $P = 0.214$), T_{re} ($F_{(5.0,\ 45.0)} = 0.916$, $P = 0.404$), T_{sk} ($F_{(1.3,\ 6.5)} = 0.77$, $P = 0.448$), RPE ($F_{(5.0,\ 50.0)} = 1.37$, $P = 0.250$) and speed ($F_{(1.7,\ 17.2)} = 0.96$, $P = 0.392$: Table 2). However, there were significant main effects for time where HR ($F_{(5.0,\ 50.0)} = 21.3$, $P = 0.000$), T_{re} ($F_{(1.7,\ 15.1)} = 71.1$, $P = 0.000$), T_{sk} ($F_{(5.0,\ 25.0)} = 6.5$, $P = 0.001$), RPE ($F_{(1.5,\ 15.3)} = 73.5$, $P = 0.000$) and speed ($F_{(1.9,\ 19.2)} = 14.1$, $P = 0.000$) increased during the distance test. Further, there were significant main effects of condition for HR and T_{re} where HR ($F_{(1.0,\ 10.0)} = 6.0$, $P = 0.030$) and T_{re} ($F_{(1.0,\ 9.0)} = 6.6$, $P = 0.030$) were lower on SDEP compared with CON throughout the distance test. There were no main effects of condition during the distance test for T_{sk} ($F_{(1.0,\ 6.0)} = 0.07$, $P = 0.938$), RPE ($F_{(1.0,\ 10.0)} = 0.35$, $P = 0.854$) and speed ($F_{(1.0,\ 10.0)} = 1.71$, $P = 0.221$).

Discussion

The primary aim of the present study was to investigate the effect of one night of sleep deprivation on endurance running performance. Our primary hypothesis is supported as 30 h of sleep deprivation was shown to have a detrimental effect on pre-loaded endurance performance. Despite running less distance after sleep deprivation compared with control, participants' perception of effort was similar indicating that altered perception of effort may account for the decrease in endurance performance after a night without sleep. Further the absence of significant interaction during the distance test for speed suggests that sleep deprivation has a limited effect on pacing. A secondary aim was to examine the effect of sleep deprivation on cardio-respiratory, thermoregulatory and perceptual responses during 30 min of modest intensity exercise. The present results suggest that 30 h of sleep deprivation has a limited effect on cardio-respiratory, thermoregulatory and perception of effort responses during sub-maximal exercise.

These findings are in contrast to a study where 30 h of sleep deprivation was shown to have no effect on TTE (Chen 1991; Pickett and Morris 1975) but are consistent with the other published studies that report a decrease in TTE (Chen 1991; Martin 1981). Given the previous equivocal findings this study provides important strength to the notion that short-term sleep loss is debilitating for endurance performance. The calculated effect size for difference in TTE between the sleep deprivation and control conditions in one previous investigation was 0.19 (Martin 1981) which is very similar to the present investigation ($d = 0.23$); therefore, the marginal significance previously reported is most likely attributable to the smaller sample size in that study ($n = 8$). Previous literature has suggested that alterations in exercise performance following sleep deprivation are highly individual ranging from a 5% improvement to a 45% decrease in TTE after 36 h of sleep deprivation compared with a control (Martin 1981). Moreover, TTE was not decreased by sleep deprivation in three of eight individuals. In the present investigation the difference in distance completed compared with control ranged from a 4% improvement to a 9% impairment, with nine of eleven participants completing less distance after sleep deprivation compared with control. The

Table 1 Cardio-respiratory, thermoregulatory and perceptual responses to a 30 min steady state pre-load exercise at 60% $\dot{V}O_{2\,max}$ after normal sleep (CON) and after 30 h of sleep deprivation (SDEP)

	Time (min)	5	10	15	20	25	30
Heart rate (beats min^{-1})†	CON	124 (13)	130 (16)	135 (15)	139 (18)	139 (17)	143 (15)
	SDEP	122 (12)	129 (13)	135 (14)	136 (16)	139 (19)	143 (15)
$\dot{V}E$(L min^{-1})†	CON	60.6 (7.8)	63.6 (6.2)	64.7 (5.0)	66.1 (7.1)	66.1 (7.9)	66.3 (6.9)
	SDEP	58.7 (7.7)	61.5 (5.4)	64.7 (8.3)	64.1 (8.4)	64.4 (8.5)	65.4 (7.7)
$\dot{V}O_2$(L min^{-1})	CON	2.5 (0.2)	2.5 (0.1)	2.4 (0.2)	2.5 (0.1)	2.5 (0.1)	2.5 (0.2)
	SDEP	2.4 (0.2)	2.4 (0.2)	2.5 (0.23)	2.5 (0.3)	2.5 (0.2)	2.6 (0.3)§
$\dot{V}CO_2$(L min^{-1})†	CON	2.2 (0.2)	2.3 (0.2)	2.3 (0.2)	2.3 (0.2)	2.3 (0.2)	2.3 (0.2)
	SDEP	2.2 (0.2)	2.3 (0.2)	2.4 (0.3)	2.3 (0.3)	2.3 (0.3)	2.4 (0.3)
RER†	CON	0.90 (0.04)	0.93 (0.03)	0.94 (0.04)	0.93 (0.04)	0.92 (0.04)	0.93 (0.03)
	SDEP	0.90 (0.06)	0.94 (0.06)	0.94 (0.05)	0.93 (0.05)	0.92 (0.03)	0.93 (0.03)
T_{re} (°C)†‡	CON	37.4 (0.3)	37.5 (0.2)	37.7 (0.2)	37.9 (0.2)	38.1 (0.2)	38.2 (0.3)
	SDEP	37.2 (0.3)	37.4 (0.3)	37.6 (0.0)	37.7 (0.3)	37.9 (0.3)	38.0 (0.3)
T_{sk} (°C)†	CON	29.0 (1.0)	29.5 (0.9)	30.1 (0.8)	30.5 (1.0)	30.7 (1.2)	30.9 (1.3)
	SDEP	29.7 (0.4)	30.1 (0.5)	30.6 (0.7)	31.0 (0.8)	31.3 (0.9)	31.5 (0.9)
RPE†	CON	8.3 (1.6)	9.5 (1.7)	10.2 (1.8)	10.9 (1.7)	11.3 (1.7)	11.3 (1.8)
	SDEP	8.5 (1.8)	9.1 (1.5)	10.2 (1.5)	10.8 (1.4)	11.5 (1.8)	11.5 (1.6)

Values are mean ± (SD), $n = 11$ for heart rate, rating of perceived exertion (RPE), core temperature (T_{re}), $n = 10$ for mean skin temperature (T_{sk}), minute ventilation ($\dot{V}E$), O_2 production ($\dot{V}O_2$), CO_2 production ($\dot{V}CO_2$), and respiratory exchange ratio (RER) Main effect of time † $P < 0.05$. Main effect of condition ‡ $P < 0.05$. Significant interaction versus 5 min on SDEP only § $P < 0.05$

Table 2 Heart rate, core temperature (T_{re}), skin temperature (T_{sk}), perception of effort (RPE) and speed during a 30 min treadmill distance test after normal sleep (CON) and after 30 h of sleep deprivation (SDEP)

	Time (min)	5	10	15	20	25	30
Heart rate (beats min^{-1})†‡	CON	163 (10)	168 (11)	173 (12)	177 (12)	178 (9)	183 (11)
	SDEP	157 (15)	166 (12)	171 (9)	170 (10)	170 (9)	181 (9)
T_{re} (°C)†‡	CON	38.0 (0.2)	38.3 (0.2)	38.5 (0.3)	38.7 (0.4)	39.0 (0.5)	39.3 (0.4)
	SDEP	37.9 (0.2)	38.2 (0.3)	38.2 (0.5)	38.4 (0.6)	38.6 (0.6)	38.9 (0.4)
T_{sk} (°C)†	CON	29.5 (1.3)	29.9 (1.4)	30.2 (1.6)	30.3 (1.8)	30.4 (2.0)	30.4 (2.3)
	SDEP	29.6 (0.6)	30.0 (1.0)	30.3 (1.2)	30.4 (1.3)	30.7 (1.2)	30.7 (1.3)
RPE†	CON	10.9 (1.9)	13.2 (1.1)	14.6 (1.1)	15.7 (0.9)	16.5 (1.5)	18.2 (0.8)
	SDEP	11.6 (1.6)	13.3 (1.2)	14.3 (1.1)	15.3 (1.7)	16.5 (1.7)	18.5 (1.4)
Speed (km h^{-1})†	CON	12.1 (2.0)	12.3 (2.1)	12.6 (2.1)	12.7 (1.8)	12.4 (2.0)	14.8 (2.5)
	SDEP	11.8 (2.1)	12.0 (1.7)	12.2 (1.6)	12.0 (1.4)	12.2 (2.0)	15.1 (2.3)

Values are mean ± (SD), $n = 11$ for heart rate, rating of perceived exertion (RPE) and speed, $n = 10$ for core temperature, $n = 7$ for mean skin temperature. Main effect of time † $P < 0.05$. Main effect of condition ‡ $P < 0.05$

present findings might therefore be considered more consistent for a detrimental effect of sleep deprivation on exercise performance than those previously reported. However, when considering the recently reported similar sensitivity of both time trials and of TTE tests to detect differences between experimental conditions (Amann et al. 2008), the seemingly more consistent results of the present investigation might also be explained by the proportionally smaller signal to noise ratio of distance test compared with TTE. A limitation TTE test is that they are unable to examine the role of pacing. Therefore a novel finding of the present investigation was that sleep deprivation did not significantly alter pacing during the 30 min distance test. That is, the absence of significant interaction during the distance test for speed suggests that sleep deprivation has a limited effect on pacing during endurance performance.

The effect of one night of sleep deprivation on core temperature is equivocal with investigations reporting either no difference (Dewasmes et al. 1993; Savourey and Bittel 1994) or a significant reduction in resting core temperature (Landis et al. 1998). In the present investigation resting core temperature following sleep deprivation was reduced (CON: 37.27 (0.23)°C and SDEP: 37.18 (0.25)°C), but not significantly so, which is similar to previous investigations (Dewasmes et al. 1993; Sawka et al. 1984). More consistent reductions in core temperature have been reported with periods of sleep deprivation lasting longer than 50 h (Fiorica et al. 1968; Kolka et al. 1984). Although a decrease in core temperature brought about by pre-cooling (0.4°C) has been shown to improve endurance performance in temperate conditions (Hessemer et al. 1984; Lee and Haymes 1995) it was not surprising in the present study that the small decrease in core temperature at rest and during the sub-maximal exercise after sleep deprivation (≤0.2°C) did not translate into improved performance. Furthermore, heat storage (0.8°C) and mean skin temperature were not different during sub-maximal exercise which further suggests a limited effect of sleep deprivation on thermoregulation during short-term sub-maximal exercise in a temperate environment. Core temperature was shown to be significantly lower throughout the distance test on sleep deprivation compared with control which is more than likely due to the reduced heat production from completing less work. In summary, the present investigation shows that sleep deprivation has a limited effect on thermoregulation and does not appear to impair heat dissipation during exercise in a temperate environment. Consequently, these results suggest an unlikely role for thermoregulation in the observed reduction in endurance performance in temperate conditions following sleep deprivation. Nevertheless, sleep deprivation may alter thermoregulation and exercise performance during more intense or prolonged exercise in temperate conditions or during exercise in the heat (Sawka et al. 1984).

After sleep deprivation heart rate was lower by 7–8 beats min^{-1} at 20 and 25 min during the distance test. This lower heart rate likely reflects the decreased distance completed on the distance test. Cardio-respiratory parameters measured during the steady state pre-load exercise were largely unaffected by the sleep deprivation. These findings are consistent with previous studies (Martin and Haney 1982; Martin 1981; Martin and Gaddis 1981; Mougin et al. 1991) and therefore it can be suggested short-term sleep deprivation has little effect on cardio-respiratory function during sub-maximal exercise. Despite less total distance completed on the distance test following sleep deprivation participants perception of effort was similar. The same perception of effort despite a tendency for lower selected running speed suggests that perception of effort would be greater for the same absolute workload. Therefore, the mechanism responsible for the observed reduction in endurance performance after one night without sleep may be an increased perception of effort. As RPE was not different between trials during the pre-load steady state exercise (60% $\dot{V}O_{2\,max}$) it might be hypothesised that sleep deprivation influences perception of effort during high intensity exercise to a greater extent than moderate intensity exercise. In support of this hypothesis, RPE was shown only to be greater during high intensity exercise and not low intensity exercise after 30 h of sleep deprivation (Martin and Gaddis 1981). Consequently, sleep deprivation may have a particularly detrimental effect on competition performance.

In conclusion, one night of sleep deprivation decreased endurance performance with limited effect on pacing, cardio-respiratory or thermoregulatory function. Despite running less distance after sleep deprivation compared with control, participants' perception of effort was similar indicating that altered perception of effort may account for the decrease in endurance performance after a night without sleep.

References

Amann M, Hopkins WG, Marcora SM (2008) Similar sensitivity of time to exhaustion and time-trial time to changes in endurance. Med Sci Sports Exerc 40:574–578. doi:10.1249/MSS.0b013e31815e728f

Borg GA (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14:377–381

Chen HI (1991) Effects of 30-h sleep loss on cardiorespiratory functions at rest and in exercise. Med Sci Sports Exerc 23:193–198. doi:10.1249/00005768-199102000-00008

Cunningham JJ (1980) A reanalysis of the factors influencing basal metabolic rate in normal adults. Am J Clin Nutr 33:2372–2374

Dewasmes G, Bothorel B, Hoeft A, Candas V (1993) Regulation of local sweating in sleep-deprived exercising humans. Eur J Appl Physiol Occup Physiol 66:542–546. doi:10.1007/BF00634307

Fiorica V, Higgins EA, Iampietro PF, Lategola MT, Davis AW (1968) Physiological responses of men during sleep deprivation. J Appl Physiol 24:167–176

Grandjean AC, Reimers KJ, Bannick KE, Haven MC (2000) The effect of caffeinated, non-caffeinated, caloric and non-caloric beverages on hydration. J Am Coll Nutr 19:591–600

Hessemer V, Langusch D, Bruck LK, Bodeker RH, Breidenbach T (1984) Effect of slightly lowered body temperatures on endurance performance in humans. J Appl Physiol 57:1731–1737

Kolka MA, Martin BJ, Elizondo RS (1984) Exercise in a cold environment after sleep deprivation. Eur J Appl Physiol Occup Physiol 53:282–285. doi:10.1007/BF00776603

Landis CA, Savage MV, Lentz MJ, Brengelmann GL (1998) Sleep deprivation alters body temperature dynamics to mild cooling and heating not sweating threshold in women. Sleep 21:101–108

Lee DT, Haymes EM (1995) Exercise duration and thermoregulatory responses after whole body precooling. J Appl Physiol 79:1971–1976

Martin BJ (1981) Effect of sleep deprivation on tolerance of prolonged exercise. Eur J Appl Physiol Occup Physiol 47:345–354. doi:10.1007/BF02332962

Martin BJ, Gaddis GM (1981) Exercise after sleep deprivation. Med Sci Sports Exerc 13:220–223. doi:10.1249/00005768-198104000-00002

Martin B, Haney R (1982) Self-selected exercise intensity is unchanged by sleep loss. Eur J Appl Physiol Occup Physiol 49:79–86. doi:10.1007/BF00428966

Mougin F, Simon-Rigaud ML, Davenne D, Renaud A, Garnier A, Kantelip JP, Magnin P (1991) Effects of sleep disturbances on subsequent physical performance. Eur J Appl Physiol Occup Physiol 63:77–82. doi:10.1007/BF00235173

Oliver SJ, Laing SJ, Wilson S, Bilzon JL, Walsh N (2007) Endurance running performance after 48 h of restricted fluid and/or energy intake. Med Sci Sports Exerc 39:316–322. doi:10.1249/01.mss.0000241656.22629.57

Pickett GF, Morris AF (1975) Effects of acute sleep and food deprivation on total body response time and cardiovascular performance. J Sports Med Phys Fit 15:49–56

Ramanathan LM (1964) A new weighting system for mean surface temperature of the human body. J Appl Physiol 19:531–532

Ricardo JS, Cartner L, Oliver SJ, Laing SJ, Walters R, Bilzon JL, Walsh NP (2009) No effect of a 30-h period of sleep deprivation on leukocyte trafficking, neutrophil degranulation and saliva IgA responses to exercise. Eur J Appl Physiol 105:499–504. doi:10.1007/s00421-008-0931-3

Savourey G, Bittel J (1994) Cold thermoregulatory changes induced by sleep deprivation in men. Eur J Appl Physiol Occup Physiol 69:216–220. doi:10.1007/BF01094791

Sawka MN, Gonzalez RR, Pandolf KB (1984) Effects of sleep deprivation on thermoregulation during exercise. Am J Physiol 246:R72–R77

Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, Stachenfeld NS (2007) American College of Sports Medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc 39:377–390. doi:10.1249/01.mss.0000272779.34140.3b

Weil JV, Kryger MH, Scoggin CH (1978) Sleep and breathing at high altitude. In: Guilleminault G, Dement W (eds) Sleep apnea syndromes. Liss, New York, pp 119–136