Effect of a moderate caffeine dose on endurance cycle performance and thermoregulation during prolonged exercise in the heat

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Abstract

Objectives: This study investigated the influence of a moderate caffeine dose on endurance cycle performance and thermoregulation during prolonged exercise in high ambient temperature.

Design: Double-blind cross-over study.

Methods: Eight healthy, recreationally active males (Mean ± SD; age: 22 ± 1 y; body mass: 71.1 ± 8.5 kg; VO_{2peak}: 55.9 ± 5.8 $mL \cdot kg^{-1} \cdot min^{-1}$; W_{max}: 318 ± 37 W) completed one VO_{2peak} test, one familiarisation trial and two experimental trials. After an overnight fast, participants ingested a placebo or a 6 $mg \cdot kg^{-1}$ caffeine dose 60 min before exercise. The exercise protocol consisted of 60 min of cycle exercise at 55% W_{max}, followed by a 30 min performance task (total kJ produced) in 30°C and 50% RH.

Results: Performance was enhanced (Cohen's *d* effect size=0.22) in the caffeine trial (363.8 ± 47.6 kJ) compared with placebo (353.0 ± 49.0 kJ; p=0.004). Caffeine did not influence core (p=0.188) or skin temperature (p=0.577) during exercise. Circulating prolactin (p=0.572), cortisol (p=0.842) and the estimated rates of fat (p=0.722) and carbohydrate oxidation (p=0.454) were also similar between trial conditions. Caffeine attenuated perceived exertion during the initial 60 min of exercise (p=0.033), with no difference in thermal stress across trials (p=0.911).

Conclusions: Supplementation with 6 $mg \cdot kg^{-1}$ caffeine improved endurance cycle performance in a warm environment, without differentially influencing thermoregulation during prolonged exercise at a fixed work-rate versus placebo. Therefore, moderate caffeine doses which typically enhance performance in temperate environmental conditions also appear to benefit endurance performance in the heat.

Key words: Stimulants; supplements; core temperature; exercise; fatigue; substrate oxidation

Introduction

Caffeine (1,3,7-trimethylxanthine) is a well-established ergogenic aid commonly consumed by endurance athletes.[1] Intakes of low to moderate doses (3-6 $mg \cdot kg^{-1}$) consistently enhance performance in temperate environmental conditions (~20°C), especially when exercise is performed for 30 min or longer.[2] Few studies have investigated the ergogenic effects of caffeine in the heat, with some,[3,4] but not all,[5, 6, 7] reporting improved performance following caffeine ingestion. Hence, from the limited data available, it is unclear whether caffeine benefits endurance performance in the heat, despite a high prevalence of intake among athletes competing in warm environments[1].

The progressive impairment in endurance capacity with increasing ambient temperature is well-documented.[8] Several explanations for this deterioration in performance have been proposed, including an increased physiological burden to dissipate heat via the skin and an elevated core temperature[9]. The resulting hyperthermia and increased brain temperature reduce central drive to continue exercise, thus precipitating the onset of fatigue.[10] During prolonged exercise in the heat, caffeine has elicited higher core temperatures than placebo.[5,6,11] Therefore, these perturbations to thermoregulation might explain the lack of performance benefit in the heat after caffeine intake.[5] Interestingly, larger caffeine doses ($\geq$ 9 $mg \cdot kg^{-1}$) consistently induce elevations in core and body temperature during exercise in the heat.[6,11] Hence, the provision of smaller doses (~6 $mg \cdot kg^{-1}$), which typically improve performance in temperate conditions,[2] might prove a more useful strategy to enhance performance in the heat.

Supplementation with 6 $mg \cdot kg^{-1}$ caffeine enhanced maximal voluntary contraction of the quadriceps after prolonged cycle exercise in a hot (36°C) environment.[4] However, during exercise under the same environmental conditions, the same caffeine dose co-administered with carbohydrates elicited a higher core temperature than isolated carbohydrate intake.[12] To date, only two laboratory-based studies have examined the influence of 6 $mg \cdot kg^{-1}$ caffeine on endurance cycle performance in the heat without additional carbohydrates.[5,3] Roelands et al. (2011)[5] reported no ergogenic effect of caffeine but an increase in core temperature during prolonged exercise at a fixed work-rate, while Ganio et al.

(2011)[3] observed an improvement in endurance cycle performance but no thermogenic effects. Hence, it is unclear whether moderate caffeine doses influence endurance cycle performance or thermoregulation during prolonged exercise in the heat. Given the widespread intake of caffeine by athletes,[1] it would be of interest to determine whether moderate doses which consistently enhance performance in temperate conditions,[2] also confer performance benefits in the heat.

Consequently, the aim of this study was to examine the performance and thermoregulatory responses to prolonged exercise in the heat following the ingestion of a 6 $mg \cdot kg^{-1}$ caffeine dose versus a placebo condition.

Methods

Eight healthy, recreationally active, low-caffeine consuming, non-heat acclimated males (116 ± 46 $mg \cdot day^{-1}$; age: 22 ± 1 y; body mass: 71.1 ± 8.5 kg; height: 1.74 ± 0.08 m; VO_{2peak}: 55.9 ± 5.8 $mL \cdot kg^{-1} \cdot min^{-1}$; peak power output at VO_{2peak} [W_{max}]: 318 ± 37 W) took part in this investigation, which employed a double-blind, randomised, repeated-measures, cross-over design. Participants provided written informed consent and were free from chronic disease. The experimental protocol was approved by the Ethics Approvals (Human Participants) Sub-Committee of Loughborough University, UK (Ref: R15-P104).

All participants completed one maximal exercise test, one familiarisation trial and two experimental trials. The initial visit consisted of an incremental exercise test to volitional exhaustion conducted on an electronically braked cycle ergometer (Lode Corival, Groningen, Holland) to determine W_{max} and the power required to elicit 55% and 75% of W_{max}. This test was performed in temperate conditions (~20^{o}C). After a brief recovery period (15 min), participants completed the performance task used in the familiarisation and experimental trials to practice pacing and control of the ergometer. After 5-7 days, the familiarisation trial was undertaken to ensure that participants became fully accustomed to the procedures employed during the investigation and to minimise any learning or anxiety effects.

This trial was performed in environmental conditions maintained at 30°C and 50% RH and was identical to the experimental trials in all respects, although no treatment was administered.

The familiarisation and experimental trials were separated by 7 to 10 days to minimise the development of heat acclimation. Additionally, all trials were performed at the same time of day to minimise circadian-type variance. Participants were instructed to record their dietary habits and physical activity patterns during the 24 hours before the familiarisation trial and to replicate this in the 24 hours preceding each experimental trial. Furthermore, no strenuous exercise or caffeine intake was permitted during this period and participants were provided with a list of commonly consumed caffeinated foods and drinks to help achieve this. On the evening before each trial, participants ingested a radio-telemetry pill (CoreTemp, HQ Inc, Palmetto, Florida, USA) to enable the measurement of core temperature.

Participants arrived at the laboratory in the morning (8-9 am) after an overnight fast (10-12 hours) with the exception of ingesting 500 mL of plain water approximately 90 min before arrival. Post-void nude body mass was recorded upon arrival (Adam AFW-120, Milton Keynes, UK) and a heart rate telemetry band (Polar Beat, Kempele, Finland) was positioned. Skin surface thermistors (Grant Squirrel SQ800, Cambridgeshire, UK) were attached to four sites (chest, upper arm, thigh and calf) for the determination of weighted mean skin temperature.[13] Next, an indwelling 21 g cannula was inserted into an antecubital vein to enable repeated blood sampling; this was flushed with a small volume of saline after each sample to ensure patency. After 15 min of seated rest at room temperature (20°C), a baseline 7 mL venous sample was collected, following which participants ingested a capsule containing either 6 $mg \cdot kg^{-1}$ of caffeine (Sigma-Aldrich, UK) or 250 mg of starch (placebo; BDH Ltd, Poole, UK) with 50 mL of plain water. All capsules were indistinguishable with regards to dimension, weight and colour. Participants then remained seated for a further 60 min at room temperature. After 45 min, core and skin temperature and heart rate were recorded at 5 min intervals, with a second 7 mL venous sample collected at 60 min.

Participants then entered the climatic chamber (Weiss-Gallenkamp, UK) maintained at 30°C and 50% RH and began 60 min of cycle exercise at a workload corresponding to 55% W_{max}. During this period, core and skin temperature and heart rate were recorded every 5 min. Rating of perceived exertion (RPE)[14] and perceived thermal stress (using a 21 point scale ranging from -10, unbearable cold, to +10, unbearable heat) were recorded every 10 min. Expired gas samples (1 min) were collected every 30 min using the Douglas bag method; these values were used to determine the rates of substrate oxidation during exercise.[15] Participants were provided with 150 mL of plain water (temperature: 20°C) every 15 min and a third 7 mL venous sample was collected at 60 min while participants remained seated on the ergometer.

Subsequently, there was a 2-3 min delay while the ergometer was programmed for the performance task. Participants were instructed to produce as much work (kJ) as possible within 30 min; this method is consistent with previous studies.[6,3] Before starting, all participants were encouraged to produce a maximal effort. The initial workload was set at 75% W_{max}, but participants were free to adjust their power output as desired from the outset. During this period, participants received information regarding time elapsed and cadence, but no other information or verbal encouragement was provided. Core and skin temperature and heart rate were recorded every 5 min. A final 7 mL venous sample was collected immediately after the performance task while participants remained seated on the ergometer. The cannula, telemetry band and skin thermistors were then removed and after a short rest period, nude body mass was recorded after participants towelled dry. The change in body mass, corrected for fluid intake, was used to estimate sweat rate.

All venous samples were collected into dry syringes. A small volume (2 mL) was dispensed into tubes containing K_2EDTA and duplicate 100 μL sub-samples were deproteinised in 0.3 M perchloric acid. These were centrifuged, and the resulting supernatant was used to determine plasma glucose concentrations using a commercially available assay (GOD-PAP, Randox Ltd, UK). Haemoglobin (cyanmethemoglobin method) and haematocrit (microcentrifugation) values were used to estimate percentage changes to blood and plasma volumes relative to the baseline sample.[16] The remaining 5 mL was dispensed into tubes containing clotting activator and left for approximately 1 hour prior to

centrifugation at 1750 g for 10 min at 4°C. The resulting serum was stored at -21°C for the subsequent determination of cortisol and prolactin with ELISA (DRG diagnostic, Germany) and caffeine with reverse-phase HPLC.[17]

All data were analysed using IBM SPSS statistics version 22.0. Normality of distribution was determined using the Shapiro-Wilk test. Exercise performance, pre-exercise body mass, initial core temperature, fasting plasma glucose, and estimated sweat rates were examined using a paired *t*-test. Cohen's *d* effect size (ES) for differences in total work produced during the performance task was determined ([mean 1 - mean 2]/pooled SD) and interpreted as trivial (0-0.19), small (0.2-0.49), medium (0.5-0.79) or large (≥0.8) as described.[18] Variables measured throughout each trial were examined with a two-way (trial x time) repeated-measures ANOVA. The Greenhouse-Geisser correction was applied where the assumption of sphericity had been violated. Where a significant main effect or interaction was identified, Bonferroni adjusted paired *t*-tests for normally distributed data or Bonferroni adjusted Wilcoxon Signed Rank tests for non-normally distributed data were used. Data are presented as mean ± SD throughout. Statistical significance was accepted at $p<0.05$.

Results

Pre-exercise body mass ($p=0.732$), initial core temperature ($p=0.279$) and fasting plasma glucose ($p=0.454$) were not different between trials, suggesting that participants began each trial in a similar physiological state.

All eight participants completed both trials, no adverse effects were reported. There was a small increase (ES=0.22) in total work produced during the caffeine trial (363.8 ± 47.6 kJ) than placebo (353.0 ± 49.0 kJ; $p=0.004$). This represents a percentage increase in performance of 3.2 ± 2.4% (range: -0.4 to 7.7%; Figure 1). Post-study questionnaires revealed that three of the eight participants (37.5%) correctly identified the caffeine trial, thus blinding can be considered successful as these odds are less than what would be expected purely by chance.

Pre-exercise core temperature was similar between trials ($p=0.718$; Figure 2A). There was a main effect of time during the initial 60 min of exercise ($p<0.05$), but no main effect of trial ($p=0.188$) or trial x time interaction ($p=0.112$). There were main effects of time ($p<0.05$) and trial ($p=0.006$), as well as an interaction effect ($p=0.005$) during the performance task. Higher values were recorded from 20 to 30 min during the caffeine trial compared with placebo ($p<0.05$; Figure 2A). Pre-exercise skin temperature was similar between trials ($p=0.429$; Figure 2B). There was a main effect of time during the initial 60 min of exercise ($p<0.05$), but no main effect of trial ($p=0.577$) or trial x time interaction ($p=0.116$). Similarly, during the performance task there was a main effect of time ($p<0.05$), but no main effect of trial ($p=0.970$) or interaction effect ($p=0.311$; Figure 2B).

Heart rate (Figure 2C), RPE (Figure 2D), and perceived thermal stress (Figure 2E) all increased throughout the initial 60 min of exercise (all $p<0.05$). There was also a main effect of trial for RPE ($p=0.033$), but there were no other trial ($p>0.644$) or interaction effects ($p>0.253$) for these variables. During the performance task heart rate showed main effects of time ($p<0.05$) and trial ($p=0.011$), but no interaction effect ($p=0.904$; Figure 2C).

Caffeine concentrations remained below the limit of quantification during the placebo trial and for the baseline sample during the caffeine trial, increasing to 33.0 ± 5.7, 35.3 ± 10.9, and 32.6 ± 8.1 μM at 60, 120 and 150 min post-capsule ingestion, respectively.

Serum cortisol and prolactin both showed main effects of time ($p<0.05$), but no main effects of trial ($p>0.572$) or interaction effects ($p>0.148$; Table 1). Similarly, plasma glucose and the percentage change to blood and plasma volumes all showed main effects of time ($p<0.05$), but no main effects of trial ($p>0.056$) or trial x time interactions ($p>0.111$) occurred (Table 1).

There were no main effects of time ($p>0.363$), trial ($p>0.454$) or interaction effects ($p>0.410$) for fat and carbohydrate oxidation and RER. Oxygen uptake showed a main effect of time ($p=0.001$), but no main effect of trial ($p=0.361$) or interaction effect ($p=0.188$). Over the entire 90 min of exercise, estimated sweat rates were higher in the caffeine trial (2.31 ± 0.43 L) than placebo (2.20 ± 0.37 L;

p=0.036). Accordingly, percentage body mass loss after exercise was greater during the caffeine trial (2.30 ± 0.36) than placebo (2.16 ± 0.31; p=0.029).

Discussion

This study investigated the performance and thermoregulatory effects of a 6 mg·kg^{-1} caffeine dose during prolonged exercise in the heat. This caffeine dose consistently improves endurance performance in temperate environmental conditions,[2] yet there are conflicting reports when exercise is performed in the heat.[5,3] In the study by Roelands et al. (2011),[5] a 6 mg·kg^{-1} caffeine dose administered 60 min before exercise failed to enhance time-trial performance but increased core temperature during exercise in 30^{o}C. Conversely, Ganio et al (2011)[3] reported enhanced work production during a 15 min cycle performance task with no difference in core temperature between trials when 3 mg·kg^{-1} caffeine was ingested 60 min before and 45 min during exercise in 33^{o}C. The results of the present study agree with the latter findings, as caffeine provided a small, but significant ergogenic effect (Figure 1), with no difference in core or skin temperature between trials (Figure 2A and B).

Several studies report no performance benefit in the heat after caffeine ingestion,[5,6,7] attributing this response to an elevation in core temperature during exercise.[5] However, even large caffeine doses (9 mg·kg^{-1}) result in only mild thermogenic effects,[6,11] which is typically undetected by participants.[11] In addition, five days of controlled caffeine intake (3 and 6 mg·kg^{-1}) did not influence the core temperature response during exercise in 37^{o}C.[19] Alternatively, some researchers suggest that a high environmental temperature might negate the efficacy of caffeine.[6] These authors reported no performance benefit in 40^{o}C after ingestion of 9 mg·kg^{-1} caffeine. The lower environmental temperature and/or caffeine dose employed in the present study might account for these divergent findings. Additionally, 21 km race time in hot and humid conditions was not influenced by caffeine intakes of 5 or 9 mg·kg^{-1}.[7] However, participants in this study became ~4% dehydrated during exercise, thus it is unknown if caffeine would have enhanced performance if fluid-balance was

maintained. When hydration status is controlled across cool (12°C) and warm (33°C) environmental conditions, caffeine still improves endurance cycle performance.[3]

The ergogenic effect of caffeine was attributed to changes in fat metabolism during exercise, resulting in a glycogen sparring effect.[20] However, there is compelling evidence caffeine enhances performance through direct actions within the central nervous system.[21] Caffeine increases synaptic dopamine concentrations in exercising rats, although large doses (10-30 mg·kg^{-1}) are required to induce this response.[22] Using positron emission topography, a moderate caffeine dose (300 mg) did not influence *in vivo* dopamine release in the human brain.[23] Attenuated prolactin concentrations would suggest an increase in dopamine,[24] but similar values were observed across trials (Table 1). Alternatively, caffeine influences key neuronal signaling proteins which mediate increases in physical activity and potentiates adenosine-dopamine receptor binding in striatum.[25,26] A reduced perception of effort is a common response to caffeine intake, which might account for approximately 29% of its ergogenic effect.[27] Participants in the present study reported lower RPE values during the initial hour of exercise with caffeine (Figure 2D), which is likely mediated by a reduced activity of cortical premotor and motor areas.[28]

Previous reports demonstrated that 6 mg·kg^{-1} caffeine enhanced sweat-electrolyte losses in 36°C,[12] while 3 mg·kg^{-1} augmented sweat rates during submaximal cycle exercise in 24°C.[29] In the present study, higher sweat rates were observed during the caffeine trial than placebo over the entire 90 min of exercise (2.31 ± 0.43 L vs. 2.20 ± 0.37 L; p=0.036). This small difference likely reflects the higher work rate during the performance task in the caffeine trial and the concomitant elevation in core temperature (Figure 2A). During prolonged exercise at a fixed work-rate, caffeine did not adversely influence fluid-balance, sweat rate or serum osmolality in cool (12°C) and warm (33°C) environmental conditions compared with placebo.[3] Additionally, there were no differences in fluid, electrolyte, or renal indices of hydration after 5 days of controlled caffeine intake (3 and 6 mg·kg^{-1}) versus placebo.[30]

Conclusion

In conclusion, supplementation with 6 mg·kg^{-1} caffeine 60 min before prolonged exercise in 30^{o}C and 50% RH improved endurance cycle performance in non-heat acclimated participants, without any measureable change to thermoregulation versus placebo. There appeared to be a developing trend for core temperature during the initial 60 min of exercise (interaction effect, P=0.112), suggesting that a longer period of fixed-intensity might enable caffeine to elicit a greater increase in core temperature than placebo under these environmental conditions. However, the difference at the end of the preload was small (0.03^{o}C, Figure 2A), which was also undetected by participants (Figure 4B). These data, together with previous reports,[3] suggest that moderate caffeine doses which typically improve endurance performance in temperate environmental conditions,[2] also benefit endurance cycle performance in the heat.

Practical applications

- Moderate caffeine doses appear to be ergogenic to endurance cycle performance for recreationally active, non-heat acclimated, fasted individuals competing in the heat.
- Supplementation with 6 mg·kg^{-1} caffeine does not significantly influence core or skin temperature up to 60 min of cycle exercise at a fixed work-rate.
- During prolonged fixed-intensity exercise in the heat, moderate caffeine intakes attenuate perceived exertion compared with placebo.

Word count: 2,909

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Table 1 Circulating concentrations of cortisol, prolactin and glucose and the percentage change to blood and plasma volumes during the experimental trials.

	Treatment	-60	0	60	90
Cortisol (nM)	placebo	449.1 ± 127.6	483.7 ± 115.3	519.4 ± 105.5	701.1 ± 130.4*
	caffeine	450.4 ± 140.7	458.4 ± 137.6	524.3 ± 135.0	734.8 ± 142.6*
Prolactin ($mIU \cdot L^{-1}$)	placebo	182.7 ± 73.1	152.8 ± 30.6	405.8 ± 61.8*	534.2 ± 105.6*
	caffeine	160.7 ± 38.9	146.6 ± 36.7	380.3 ± 71.1*	529.8 ± 126.7*
Glucose ($mmol \cdot mL^{-1}$)	placebo	4.33 ± 0.35	4.23 ± 0.39*	4.88 ± 0.36*	6.06 ± 0.17*
	caffeine	4.34 ± 0.38	4.25 ± 0.38*	4.88 ± 0.37*	6.17 ± 0.16*
Blood volume (%)	placebo	0.0 ± 0.0	0.19 ± 0.56	-1.67 ± 0.99*	-4.87 ± 2.45*
	caffeine	0.0 ± 0.0	0.13 ± 0.67	-2.02 ± 0.95*	-5.49 ± 1.95*
Plasma volume (%)	placebo	0.0 ± 0.0	0.20 ± 1.42	-3.29 ± 1.83*	-8.25 ± 2.67*
	caffeine	0.0 ± 0.0	0.02 ± 1.34	-3.88 ± 1.69*	-9.20 ± 2.67*

Values are mean ± SD. *significant difference ($P<0.05$) from -60.

Figure Captions

Figure 1: Total kJ produced (bars) and individual responses (lines) during the experimental trials.

Figure 2: Core temperature (a), skin temperature (b), heart rate (c), RPE (d), and perceived thermal stress (e) during the experimental trials. *denotes a significant difference ($P<0.05$) between trials.

Figure 1

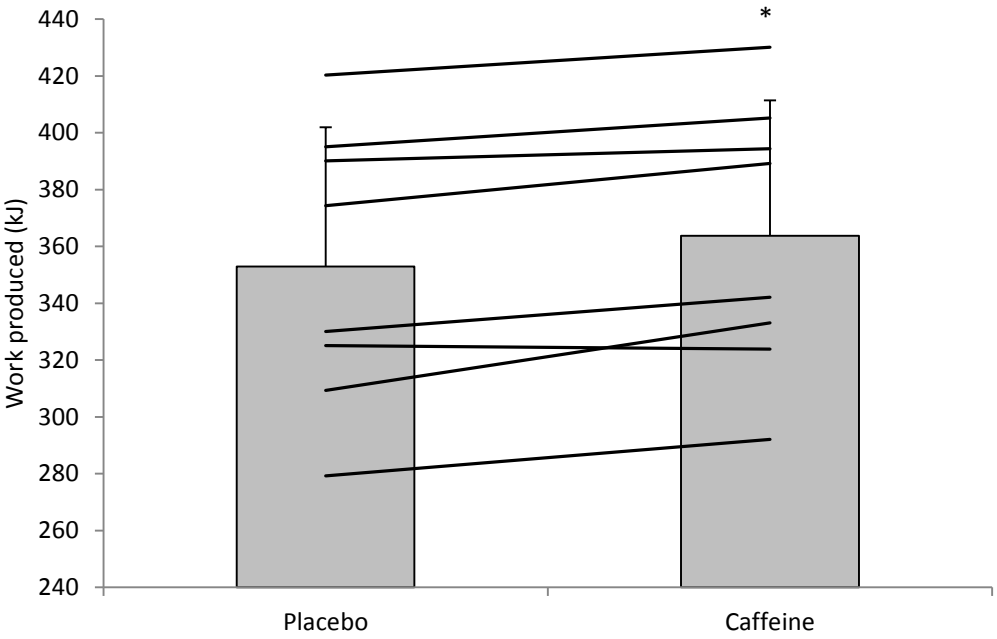

440
420
400
380
360
340
320
300
280
260
240
Work produced (kJ)
*
Placebo
Caffeine

Figure 2A

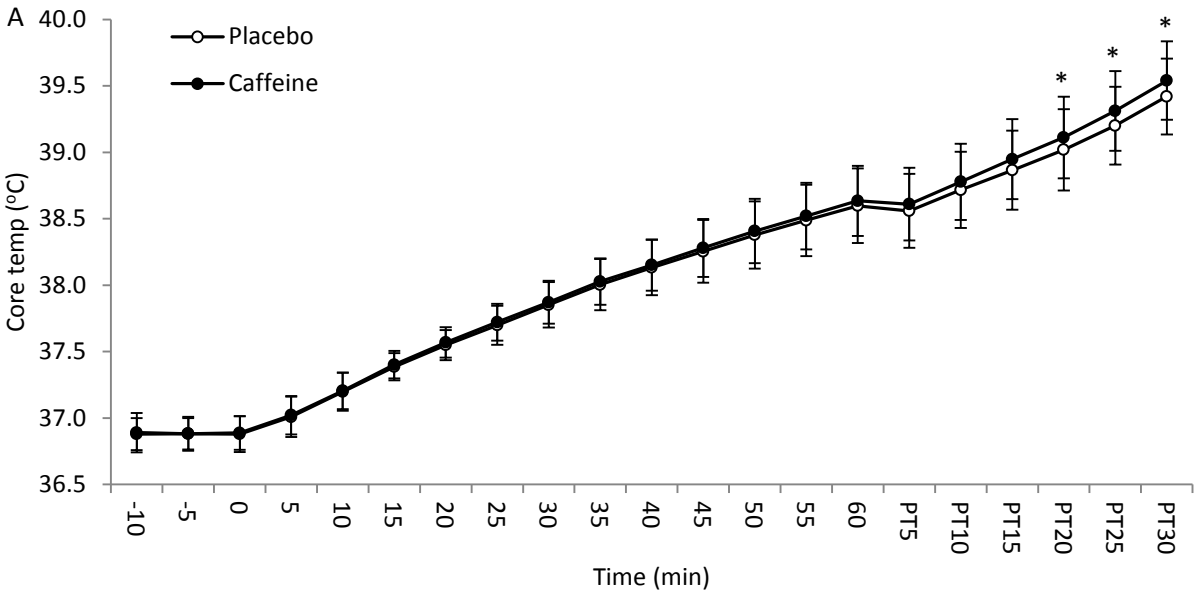


Figure 2

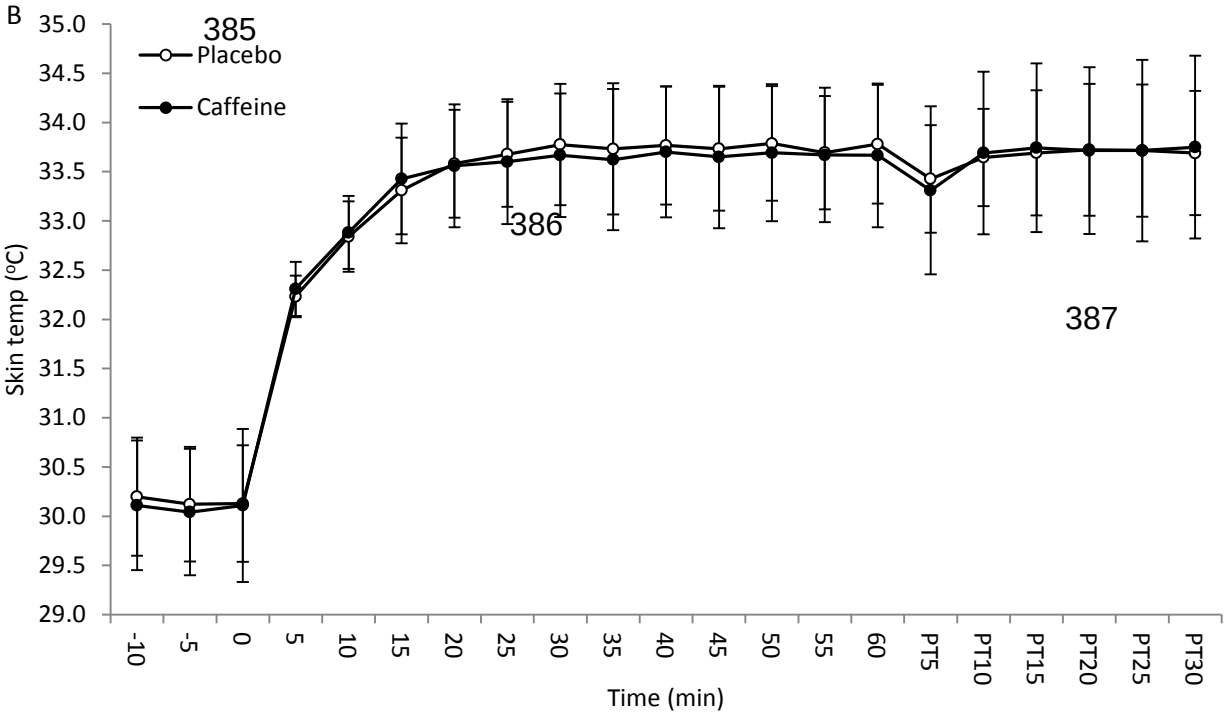


Figure 2C

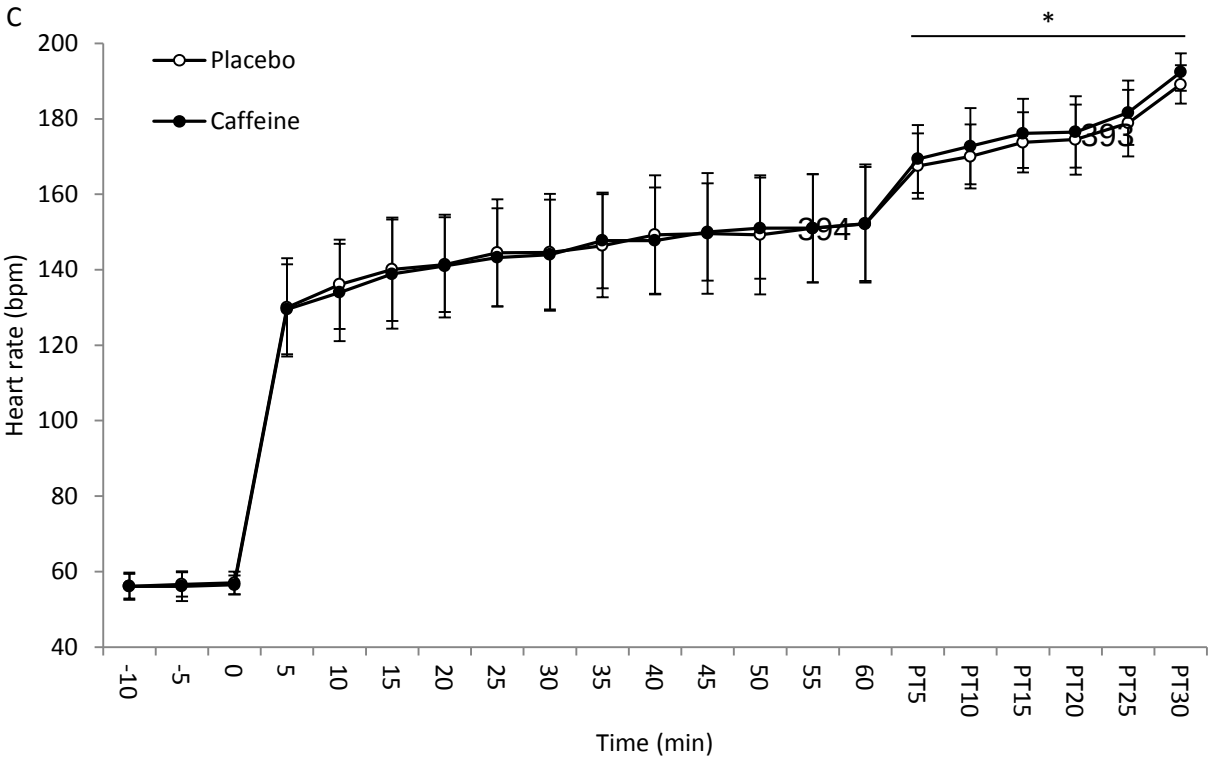


Figure 2D

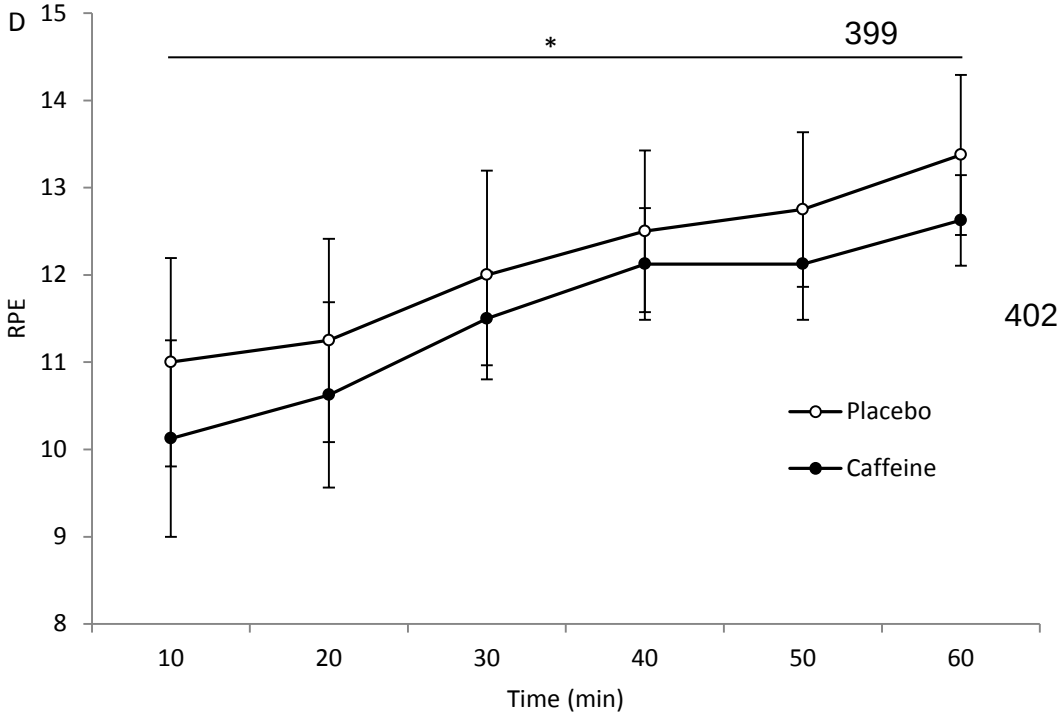
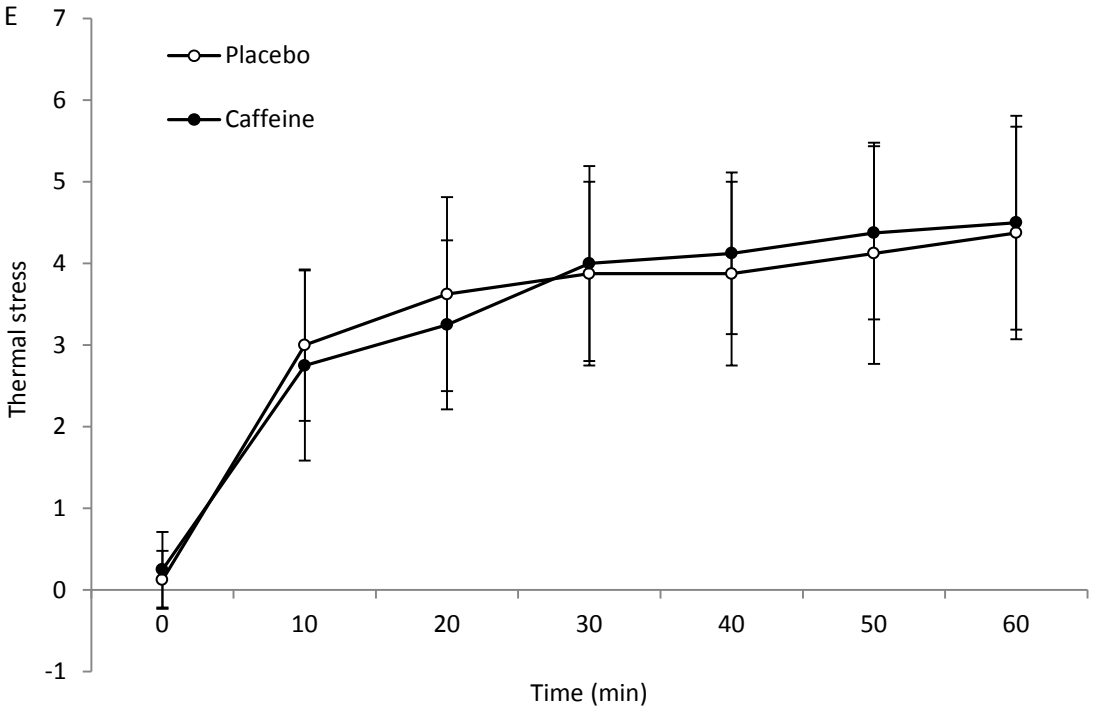


Figure 2E


E
Placebo
Caffeine
Thermal stress
7
6
5
4
3
2
1
0
-1
0
10
20
30
40
50
60
Time (min)