Title: Physiological and thermoregulatory effects of oral taurine supplementation on exercise tolerance during forced convective cooling

Running head: Taurine and exercise in cold

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Abstract

We investigated the effects of taurine supplementation on cycling time to exhaustion in cold conditions. Eleven males cycled to exhaustion at a power output equivalent to the mid-point between ventilatory threshold and maximum aerobic power following 15-min rest in the cold (apparent temperature of ~ 4 °C; air flow of 4.17 $m \cdot s^{-1}$). Two-hours before, participants ingested taurine (50 $mg \cdot kg^{-1}$) or placebo beverage. Pulmonary gases, carbohydrate (CHO) and fat oxidation, body temperatures, mean local sweat rate, heart rate, rate of perceived exertion (RPE) and thermal comfort were recorded. Time to exhaustion was not different between trials (taurine = 14.6 ± 4.7 min; placebo = 13.4 ± 5.6 min, $P = 0.061$, $d = 0.27$). There were no effects ($P > 0.05$) of taurine on core temperature, mean skin temperature or local sweat rates. However, the placebo condition showed greater ($P < 0.05$) reductions in arm-to-finger temperature gradient (i.e. vasodilation) across pre-exercise passive cold exposure and increased CHO oxidation ($P < 0.05$). Participants also reached a thermally '*comfortable*' level quicker in the taurine condition ($P < 0.05$). A 50 $mg \cdot kg^{-1}$ dose of taurine did not statistically benefit endurance exercise after moderate cold exposure but conferred some potential vascular and metabolic effects.

Key words: Amino acids; ergogenic aids; environmental physiology; cycling

Introduction

The sulphur-based amino acid, taurine, is found in abundance in human tissue, with comparatively high concentrations found in excitable cells of skeletal muscles and neurons (Huxtable, 1992). Taurine has been shown to facilitate skeletal muscle contractility and fatigue resistance by increasing Ca^{2+} uptake from the sarcoplasmic reticulum, as well as improving the sensitivity of contractile filaments to the presence of Ca^{2+} (Bakker & Berg, 2002; Hamilton et al., 2006). Taurine is also found in higher concentrations in type I compared to type II muscle fibres (Harris et al., 1998). Here, it acts as a buffer to maintain the mitochondrial pH across the inner membrane, thus enhancing efficiency of oxidative metabolism (Hansen et al, 2010). Others have reported an anti-oxidative effect of taurine supplementation and corresponding increases in aerobic capacity (Zhang et al., 2004). These potential effects on muscle contractility and oxidative efficiency or capacity might explain the ergogenic effects elicited by oral taurine supplementation in humans, leading to improvements in maximal muscle force production (Lim et al., 2018), endurance (Balshaw et al., 2013; Waldron et al. 2018a; 2018c), or intermittent performance (Warnock et al., 2017), as well as improved exercise efficiency (Paulucio et al., 2017). Indeed, despite some studies demonstrating no overall performance effects of taurine supplementation, the reported increases in fat oxidation rates have indicated enhanced metabolic efficiency and potential for glycogen sparing (Rutherford et al., 2010; De Carvalho et al., 2018). These effects could be more noticeable in environments where metabolic demand and glycogen utilisation are increased, such as during cold exposure (Jacobs et al., 1985; Martineau & Jacobs, 1988).

Exercise in cold environments presents a significant challenge to thermoregulation, with exaggeration of the thermal gradient from core-to-environment facilitating heat loss, primarily via convective and conductive pathways (Young & Castellani, 2001). Cold exposure elicits reflex increases in efferent skin sympathetic activity, leading to peripheral vasoconstriction and reductions in skin blood flow to delay heat losses (Castellani & Young, 2016). These thermoregulatory reflexes occur when skin surface temperature decreases ~3-4 °C below a thermoneutral threshold of ~34 °C (Greaney et al., 2015). During prolonged cold exposure, shivering becomes important for thermoregulation to generate metabolic body heat (Castellani & Young, 2016). Initial

vasoconstriction leads to increased intra-thoracic pressure, central blood pressure, cardiac output and myocardial oxygen demand (Doubt, 1991). Thus, coupled with the thermogenic (shivering) responses, the primary effects of cold exposure increase the net O_2 cost at rest and exercise (Cheuvront et al. 2001). Higher rates of glycogenolysis are also observed in cold, driven by increased activation of the sympathetic nervous system due to cold exposure (Jacobs et al., 1985; Martineau & Jacobs, 1988). Collectively, these acute physiological responses to moderately cold exposure could have negative effects on exercise efficiency, potentially leading to an earlier onset of fatigue and impaired endurance performance (Galloway & Maughan, 1997).

It is feasible that the suggested enhancement of exercise efficiency and relative preference for fat oxidation induced by taurine ingestion might offset the deleterious effects of cold exposure on endurance exercise. However, the vaso-active properties of taurine complicate this reasoning. For example, oral administration of taurine can elicit vasodilatory effects on the peripheral vasculature (Sun et al., 2016; Ulusoy et al., 2017), which have been suggested to contribute to the control of central blood pressure in thermally neutral environments (Waldron et al., 2018b). Indeed, there is some evidence to support taurine's role in suppression of sympathetic nervous system activity (Mizushima, 1996; Hano, 2009). Thus, taurine-induced peripheral vasodilation could potentially work in opposition to the acute vasoconstriction typically observed during cold exposure. Whilst this might assist in offsetting cold-induced blood pressure increases, it is also likely to enhance heat dissipation via convective pathways, particularly when skin-surface convective air flow is high (Ishigaki et al., 1993). However, taurine's roles in rodent vasculature are known to differentially modulate vascular wall function to maintain haemodynamic homeostasis, which is dependent on the background muscle tone (Nishida & Satoh, 2009). In this instance, it is possible that increasing the presence of plasma taurine could counteract the cold-induced hyper-excitable vasculature tone, acting to maintain homeostasis of blood flow. Therefore, it is unclear whether taurine administration will facilitate or impair peripheral temperature and blood flow during exercise and whether this will affect tolerance to the cold.

The purpose of this study was to examine the effects of acute taurine (50 $mg \cdot kg^{-1}$) ingestion on thermoregulation and cycling time to exhaustion (TTE) in cold conditions

7 °C dry bulb temperature, with high air flow (4.17 $m \cdot s^{-1}$; apparent temperature ~ 4 °C) at a sub-maximal intensity, corresponding to the mid-point between the ventilatory threshold and maximal aerobic power (VTΔ50). It was hypothesised that taurine would improve TTE in the cold and that whole-body metabolic substrate utilisation would be altered in preference of higher fat oxidation.

Methods

Participants

Eleven healthy males provided written informed consent to take part in this study (age 23 ± 5 years, stature 181.2 ± 5.1 cm, body mass 79.4 ± 8.3 kg, maximal oxygen uptake ($\dot{V}O_{2max}$) 40.1 ± 4.3 $ml \cdot kg^{-1} \cdot min^{-1}$, maximum aerobic power 267 ± 25 W). Participants were recruited from university and local sports clubs, and had various endurance backgrounds such as cycling, rowing and football. G* Power (Version 3.0.10; Universität Düsseldorf, Germany) was used to determine an *a priori* sample size of 10, using the *t*-test matched pairs function, with an alpha level of 0.95 and a 1-β of 0.80, and an Cohen's d effect size of 1.14 (Waldron et al. 2018a). Participants were requested to refrain from any nutritional supplementation or alcohol consumption, as well as avoiding strenuous exercise in the 48-h prior to testing. In addition, participants were instructed to eat the same pre-trial breakfast each time. Trials were all performed between the hours of 10:00 and 14:00. Ethical approval was granted by the ethics committee at St Mary's University (SMEC_2017-18_053).

Design

This study was conducted using a double-blind, crossover design, with a randomly chosen treatment order following $\dot{V}O_{2max}$ testing. Participants were required to visit the laboratory on three separate occasions, each at least 48-h apart. The initial visit for all participants involved a $\dot{V}O_{2max}$ test to establish the subsequent TTE intensity. During the subsequent two visits, the participants ingested either taurine (50 $mg \cdot kg^{-1}$ body mass) or placebo (250 ml water) 2-h prior.

Procedures

Preliminary testing

During the first laboratory visit, participants performed an incremental test to volitional exhaustion to establish $\dot{V}O_{2max}$. The power output started at 112 W, with a ramp rate of 16 $W \cdot min^{-1}$. All trials were conducted using a cadence of 80 $rev \cdot min^{-1}$ using a mechanically-braked cycle ergometer (Monark Exercise AB, Ergomedic 874E, Varberg, Sweden). All subsequent trials were conducted using the same ergometer and seat height for each participant. Respiratory gases were collected and measured breath-by-breath (Jaeger Vyntus CPX, Hoechberg, Germany). Maximum aerobic power (MAP) was determined as the 30-s average power output that corresponded to $\dot{V}O_{2max}$. Breath-by-breath $\dot{V}O_2$ and $\dot{V}CO_2$ data from the incremental cycling test was used to plot ventilatory threshold (VT), using the simplified v-slope method (Scheider et al., 1993). The external power output corresponding to the mid-point between VT and $\dot{V}O_{2max}$ (VTΔ50) was used for the subsequent experimental trials.

TTE trials

All experimental trials were conducted in an environmental chamber (Sporting Edge UK, Basingstoke, UK), in a controlled cold environment. Dry bulb temperature (T_{db}) was set to 8 °C, with a 24 inch fan (Sealey HVD24 Industrial High-Velocity Drum Fan, Jack Sealey Ltd., Suffolk, UK) set 1 m in front of the participant. Air flow from the fan generated a 4.17 $m \cdot s^{-1}$ wind speed, creating an effective wind chill of 4.18 °C, using the following equation (Quayle & Steadman, 1998):

$$\text{Wind chill} = 1.41 - 1.162V + 0.980T + 0.0124V + 0.0185(VT) \quad \text{[equation 1]}$$

where V = wind speed ($m \cdot s^{-1}$), and T = air temperature (degrees Celsius).

Participants were exposed to these conditions from the moment they entered the chamber, until the end of exercise.

Prior to entering the chamber, participants self-inserted a rectal thermistor (Edale instruments Ltd., Cambridge, UK) 10 cm beyond the anal sphincter to measure core temperature (T_{core}). Skin thermistors (Grant Instruments Ltd., Cambridge, UK) were taped to the right quadriceps, right medial calf, right forearm and chest. Mean skin temperature (T_{skin}) was calculated as: T_{skin} = 0.3 x (T_{chest} + T_{arm}) + 0.2 x (T_{thigh} + T_{calf}) (Ramanathan, 1964). An additional thermistor was fitted to the dorsal aspect of the right index finger in order to measure arm-to-finger temperature gradient (House & Tipton, 2002). T_{core} and T_{skin} were continuously recorded from the point of entering the chamber until the end of the trial using a data logger (SQ2010, Grant Instruments Ltd., Cambridge, UK).

On entering the chamber, the participants mounted the ergometer and sat passively resting for 15-min pre-exercise. This period was used to induce mild cold stress in the participants based on the early profiles demonstrated in response to these environmental conditions (Muza et al., 1988). In the final 2-min of the 15-min rest period, a face mask was fitted and breath-by-breath gases were recorded until the end of the trial (Jaeger Vyntus CPX, Hoechberg, Germany). $\dot{V}O_2$, $\dot{V}CO_2$, minute ventilation ($\dot{V}e$) and respiratory exchange ratio (RER) were recorded. The TTE commenced at VTΔ50 for 15-min at 80 rev·min^{-1} and continued to volitional exhaustion. Strong verbal encouragement was given repeatedly at 1-minute intervals throughout the trial. Encouragement became constant if cadence dropped below 75 rev·min^{-1}, and trials were ended where cadence had dropped below 70 rev·min^{-1} for longer than 5-s. Heart rate (HR) and thermal comfort (on an 8-point scale, where 0 = “unbearably cold”, 4 = “comfortable” and 8 = “unbearably hot” (Young et al., 1987) were recorded at 5-min intervals during the 15-min rest period and at 1-min intervals during the TTE. Ratings of perceived exertion (6-20; RPE) were recorded a 1-min intervals during the TTE.

Whole-body rates of carbohydrate (CHO) and fat oxidation were calculated during the TTE, using $\dot{V}O_2$ and $\dot{V}CO_2$ collected from gas analysis. The non-protein RER was used, according to Peronnet and Massicotte (1991):

$$\text{CHO oxidation (g·min}^{-1}) = [4.585 \times \dot{V}CO_2\ (\text{L·min}^{-1})] - [3.226 \times \dot{V}O_2\ (\text{L·min}^{-1})] \quad \text{[equation 2]}$$

Fat oxidation ($g \cdot min^{-1}$) = [1.695 × $\dot{V}O_2$ ($L \cdot min^{-1}$)]–[1.701 × $\dot{V}CO_2$ ($L \cdot min^{-1}$)] [equation 3]

Local sweat rates

Local sweat rate was measured using a Q-Sweat system (WRMedical ElectronicsCo., Stillwater, MN). Ventilated capsules were fixed proximal to the skin thermistors on the right side of the body. Dry air was continuously delivered through Teflon-lined tygon tubing at a fixed flow rate of 60 $sccm \cdot min^{-1}$ between four separate sweat capsules (size = 0.781 cm^2) mounted on the skin's surface and the Q-sweat device. Fluid released from the sweat glands is transiently incorporated into the dry air, with the change in temperature and relative humidity monitored by the Q-Sweat device. Sweat rate was calculated using standard vapour pressure equations and expressed in $nL \cdot min^{-1}$. Mean sweat rate was calculated by averaging the four sweat sites and reported every 1-min. Mean sweat rate data ($nL \cdot min^{-1}$) as a mean of the four sites was taken at 0.25-s intervals throughout the trials.

Supplementation

All taurine supplements were prepared in powder form and weighed using an analytical balance (Precisa 125A; Precisa Gravimetrics AG, Zurich, Switzerland). Both taurine and placebo supplements were prepared and ingested in 250 ml water using a non-caloric sweetener (strawberry). Drinks were administered 2-h prior to commencement of the trials. The 2-h timeframe has previously been reported to allow plasma taurine levels to reach peak level (Ghandforoush-Sattari et al., 2010). Dosage of 50 $mg \cdot kg^{-1}$ body mass was in agreement with previous studies (Waldron et al., 2018a; Warnock, et al., 2017), and all supplements were sourced from the same company (My Protein, Manchester, UK). Participants were not asked if they could identify the substance being ingested in either trial. None voluntarily suggested they might know or suspect which substance was ingested in either trial.

Statistical analysis

A two-way repeated measures analysis of variance (RM-ANOVA) was conducted using condition (taurine or placebo) and time (10% epochs during TTE) as the independent variables. During the 15-min pre-exercise period, time was separated into three levels (0-5-min, 5-10-min and 10-15-min). Where the assumption of sphericity was violated, a Greenhouse-Geisser correction was applied. Post-hoc Bonferroni tests were used to determine pairwise effects. A paired samples *t*-test was used to identify differences in TTE between conditions. Statistical significance was accepted at $P < 0.05$. Analysis was carried out using IBM SPSS Statistics (Version 24; IBM Corp., Armonk, NY, USA). Cohen's *d* effect sizes (ES ± 95% confidence intervals) were calculated, with thresholds set as: 0.2 small; 0.6 moderate; 1.2 large; 2.0 very large (Hopkins et al., 2009).

Results

Pre-exercise passive rest

T_{core}, T_{skin} and arm-to-finger temperature gradients during the pre-exercise passive resting period are shown in Figure 1. There were no condition ($F_{(1,10)} = 0.583$, $P = 0.463$) or time effects on T_{core} ($F_{(2,20)} = 0.489$, $P = 0.620$) across the 15-min pre-exercise period. Similarly, there were no condition effects on T_{skin} ($F_{(1,8)} = 0.030$, $P = 0.869$), yet there was a decline across time ($F_{(2,16)} = 4.28$, $P = 0.019$). The arm-to-finger gradient was also not affected by condition ($F_{(1,8)} = 0.02$, $P = 0.886$), but did decrease across time ($F_{(2,16)} = 5.05$, $P = 0.026$) and an interaction with condition ($P = 0.047$), with *post-hoc* tests revealing differences between 0-5 min and 10-15 min in the placebo condition ($P < 0.001$, $d = 1.2$).

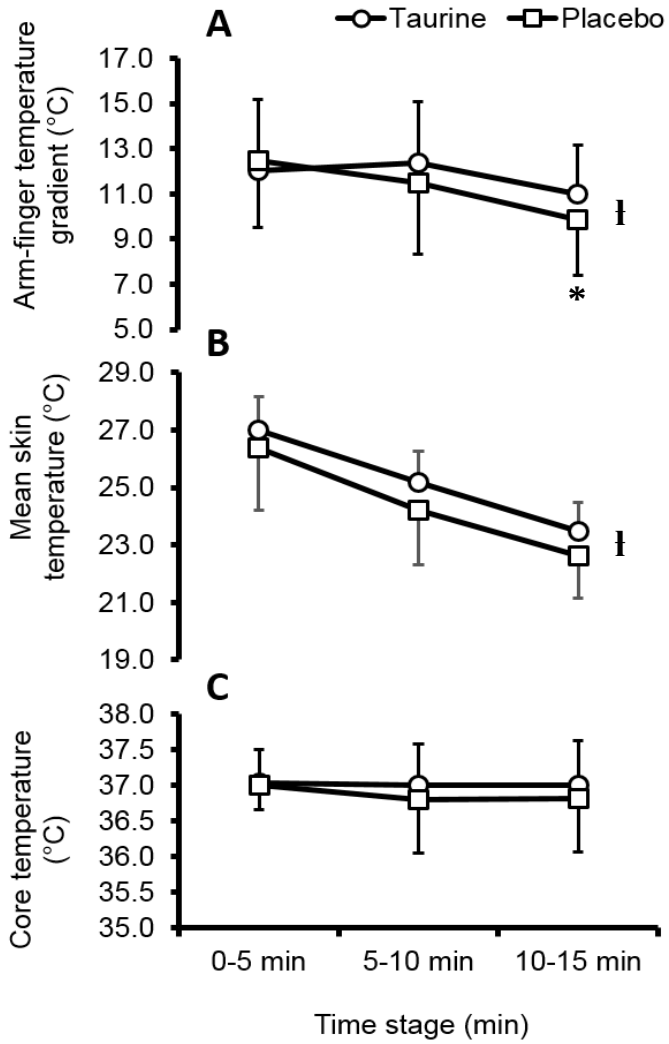

Figure 1. Mean ± SD for arm-to-skin temperature gradient (A), mean skin temperature (B) and core temperature (C) during 0-5 min, 5-10 min and 10-15 min of pre-exercise seated rest in simulated cold (7 °C) and windy (4.17 $m \cdot s^{-1}$) conditions. **ł** = main effect of time. * = different to 0-5 min period for the placebo condition.

During the pre-exercise period, there were no condition ($F_{(1,10)}$ = 0.132, P = 0.724) or time ($F_{(2,20)}$ = 0.449, P = 0.645) effects for heart rate (Taurine = 77 ± 11 vs. placebo = 77 ± 12 $beats \cdot min^{-1}$). There were also no effects of condition on thermal comfort ($F_{(1,10)}$ = 1.070, P = 0.325; Taurine = 1.7 ± 0.7 vs. Placebo = 1.8 ± 0.8) but there were effects for time, showing a decrease in thermal comfort across the three pre-exercise stages ($F_{(2,20)}$ = 9.614, P = 0.001; 0-5 min = 2 ± 0.7, 5-10 min = 1.7 ± 0.7, 10-15 min = 1.5 ± 0.8).

TTE trials

There was no difference in TTE between taurine and placebo conditions ($t_{(10)}$ = 2.112 P = 0.061, d = 0.27; Taurine = 14.2 ± 5.2-min *vs.* Placebo = 13.7 ± 5.2-min).

Thermal responses to TTE trials

T_{core} increased across time ($F_{(9,81)}$ = 11.734, P < 0.001) but there was no effect of condition ($F_{(1,9)}$ = 1.051, P = 0.332) (Figure 2E). T_{skin} was not affected by condition ($F_{(1,8)}$ = 3.262, P = 0.114) but it did increase across time ($F_{(9,73)}$ = 9.864, P < 0.001) (Figure 2C). There were no condition effects on arm-to-finger gradient ($F_{(1,8)}$ = 1.997, P = 0.207) but there was a decrease over time ($F_{(9,73)}$ = 7.309, P < 0.001) (Figure 2A).

Sweat responses to TTE

Mean local sweat rates were not different between conditions ($F_{(1,10)}$ = 0.231, P = 0.641) but increased across time ($F_{(9,90)}$ = 7.585, P < 0.001), with no interactions (P = 0.998) (Figure 2B).

Perceptual responses to TTE trials

There were condition ($F_{(1,10)}$ = 5.813, P = 0.037) and time effects ($F_{(9,90)}$ = 5.813, P = 0.037), showing increased thermal comfort in the taurine condition ($F_{(9,90)}$ = 14.365, P < 0.001), but no interactions (P = 0.279) (Figure 2F). There were no condition effects for RPE ($F_{(1,10)}$ = 3.721, P = 0.083), but there was an increase across time ($F_{(9,90)}$ = 172.385, P < 0.001) and interactions with condition, showing taurine increased RPE ($F_{(9,90)}$ = 4.785, P < 0.001) (Figure 2D). *Post-hoc* tests revealed differences between conditions at 10% (P = 0.001, d = 0.58), 20% (P = 0.031, d = 0.70), 40% (P = 0.01, d = 0.34) and 50% P = 0.029, d = 0.25) of the TTE for RPE.

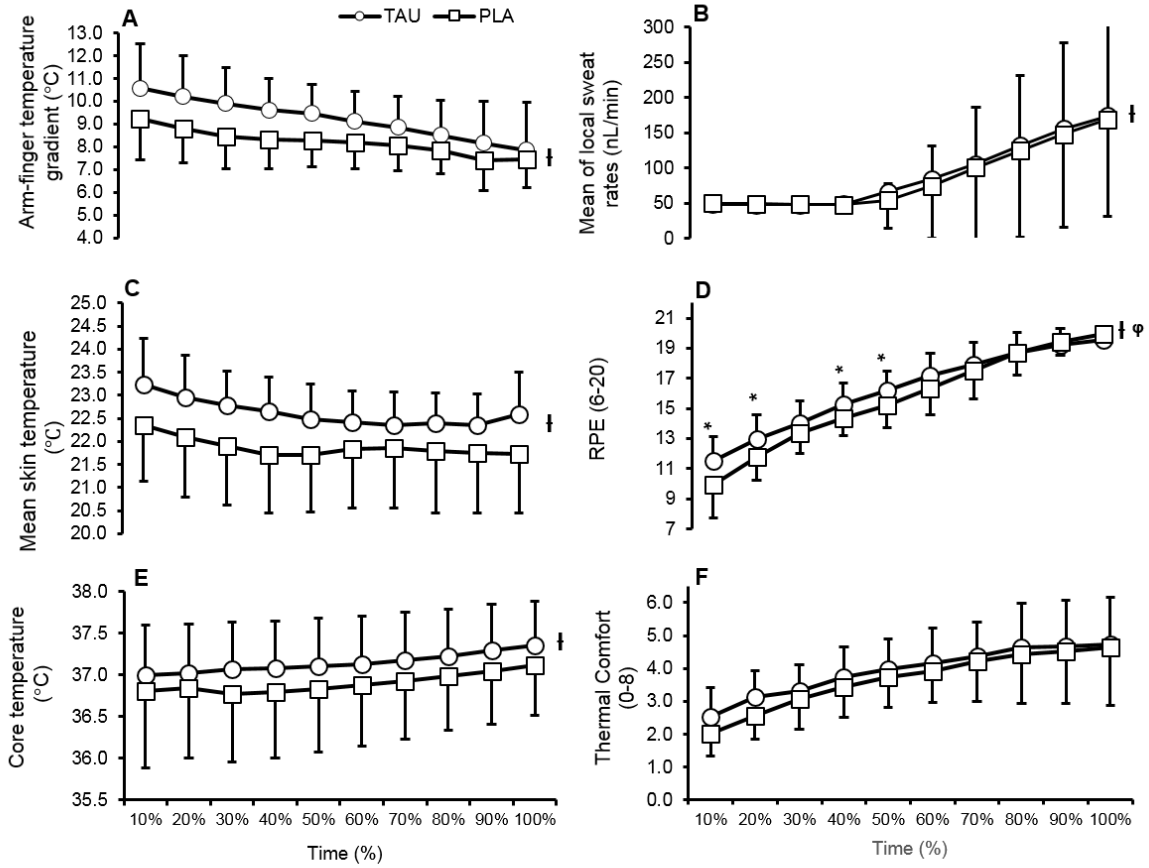

Figure 2. Mean ± SD for arm-to-finger temperature gradient (A), mean of local sweat rates (B), mean skin temperature (C), RPE (D), core temperature (E) and thermal comfort (F) during 10% epochs of time to exhaustion in cold (7 °C) and windy (4.17 $m \cdot s^{-1}$) conditions. ǂ = main effect of time. φ = interaction between condition and time. ɣ = main effect of condition. * = pairwise difference ($P < 0.05$) between conditions.

Cardiorespiratory responses to TTE

Heart rate was not different between conditions ($F_{(1,10)}$ = 1.200, P = 0.302) but increased across the trial ($F_{(9,90)}$ = 122.702, P < 0.001), with no interaction effects (P = 0.439). $\dot{V}O_2$ ($F_{(1,10)}$ = 0.029, P = 0.868), $\dot{V}CO_2$ ($F_{(1,10)}$ = 0.521, P = 0.487), $\dot{V}e$ ($F_{(1,10)}$ = 0.354, P = 0.656) and RER ($F_{(1,10)}$ = 0.318, P = 0.105) were not different between

conditions but were each increased across time (P < 0.05) (Figure 3). There was an interaction between condition and time for $\dot{V}CO_2$ ($F_{(9,90)}$ = 2.909, P = 0.005), but no pairwise differences were identified between conditions at any stage of the TTE (P > 0.05).

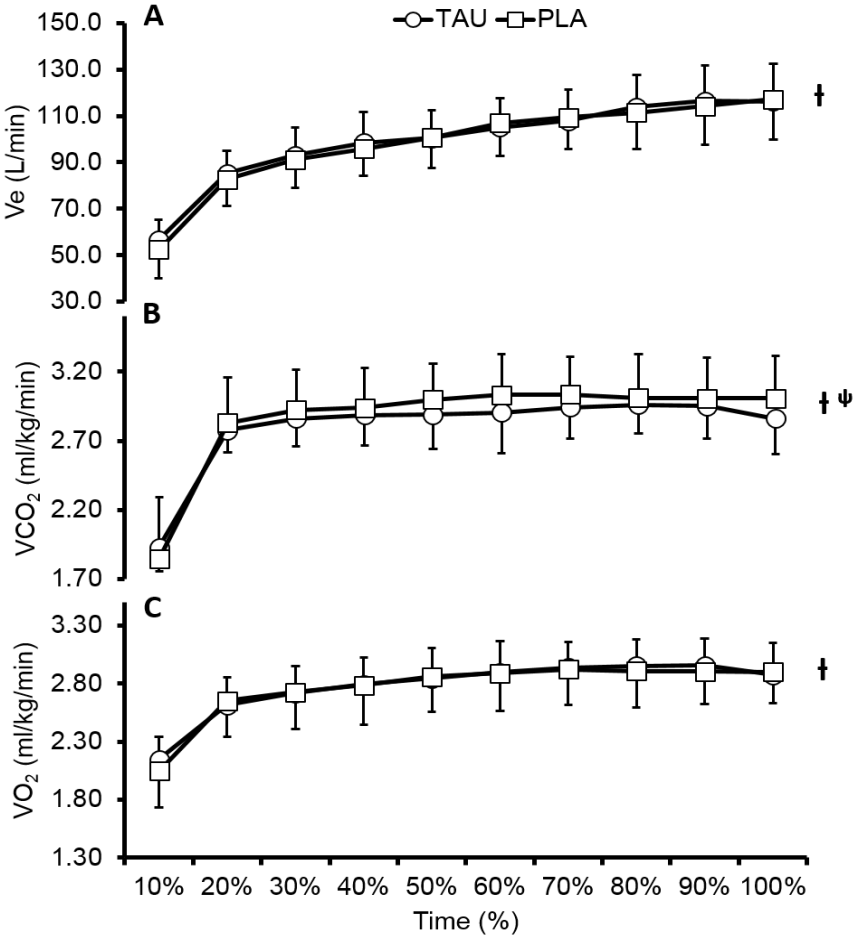

Figure 3. Mean ± SD of minute ventilation ($\dot{V}e$) (A), carbon dioxide production ($\dot{V}CO_2$) (B), oxygen consumption ($\dot{V}O_2$) (C), during 10% epochs of time to exhaustion in cold (7 °C) and windy (4.17 $m \cdot s^{-1}$) conditions. ł = main effect of time. Φ = interaction between condition and time.

Fat and carbohydrate oxidation during TTE trials

CHO oxidation rates were lower in the taurine condition ($t_{(10)}$ = 2.23, P = 0.049, d = 0.91), but there were no differences between conditions in fat oxidation rates ($t_{(10)}$ = 0.53, P = 0.608, d = 0.29) (Figure 4).

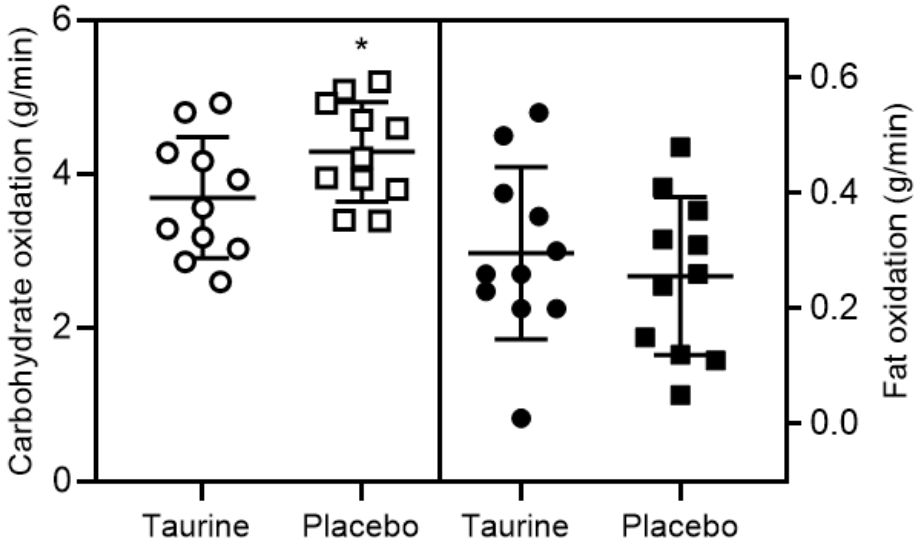

Figure 4. Mean ± SD of carbohydrate and fat oxidation rates during exercise in cold (7 °C) and windy (4.17 $m \cdot s^{-1}$) conditions. ***** = difference to taurine group ($P < 0.05$).

Discussion

This study investigated the effects of acute taurine supplementation on thermoregulation in cold conditions and its subsequent effect on exercise tolerance. Despite finding no statistically significant performance effects of taurine (*d* = 0.27, 8.7%, *P* = 0.061), there were *small* increases in TTE. There were no effects of taurine supplementation among many of the measured variables, relating to thermal control and physiological responses to cold or exercise. However, the observed reduction in pre-exercise, cold-induced arm-to-finger gradients in the placebo condition across the three 5-min stages were not found in the taurine condition. We also report a decreased CHO oxidation rate during cold exercise in the taurine compared to the placebo condition, alongside periods of lower $\dot{V}CO_2$ in the taurine condition, thus indicating an effect of taurine on whole-body metabolism and substrate utilisation. There was an increase in perceived exertion and thermal comfort following taurine supplementation, despite no changes in body temperature or work rate. Based on the current findings, there appears to be *negligible-to-small* effects of taurine on thermoregulation and exercise in mild cold, yet possible alterations in metabolic and vascular processes provide preliminary evidence of taurine's potential roles in thermoregulatory control.

There is growing evidence to suggest that endurance exercise, performed in thermoneutral environments, can be improved by acute supplementation of taurine (Waldron et al., 2018c; Souza et al., 2016). These benefits have been attributed to increases in muscle function and mechanical efficiency (Balshaw et al., 2013; Paulucio et al., 2017), increased fat oxidation (de Carvalho et al., 2018), as well as enhanced endurance capacity (Waldron et al., 2018a). We reasoned that these changes should, theoretically, counteract many of the negative effects of cold exposure on exercise efficiency. In partial support of our hypotheses, there were changes in substrate utilisation between conditions, with taurine supplementation *moderately* reducing whole-body CHO oxidation rate, and taurine eliciting *small* (yet non-significant) effects on fat oxidation. Exposure to cold conditions has been found to increase CHO metabolism (Jacobs et al., 1985; Martineau & Jacobs, 1988), which would also be the predominant substrate utilised to support exercise at the designated intensity (VTΔ50). Thus, the reduced reliance on CHO utilisation in preference of small increases in fat

oxidation in the taurine condition could be important for prolonging exercise in the cold. Furthermore, these changes occurred without significant alterations in exercise intensity, exercise tolerance or heart rate. Therefore, we provide the first evidence that taurine supplementation could assist with exercise efficiency in the cold, partly via metabolic substrate utilisation changes. However, the physiological challenge presented by the whole-body cold stimulus, as demonstrated by hypothermal mean T_{skin} and perceptual data, appear to have dampened the more commonly reported ergogenic effects elicited by taurine, with other energy-demanding metabolic or thermoregulatory processes taking preference. A more prolonged exercise period at lower intensity might have been necessary to realise the effect of these alterations. We do not have evidence to provide a mechanism responsible for these changes but those suggested by others, such as activation of intra-cellular second messengers involved in substrate metabolism (Rutherford et al., 2010; de Carvalho et al., 2020), could explain the alteration in substrates used to support exercise.

The statistically insignificant effects of taurine on TTE reported here should be considered alongside the ~ 8.7% *small* increases, which are typical of reports in thermoneutral environments (Waldron et al. 2018c) and similar to the 10% increase in TTE of an equivalent intensity reported by Page et al. (2019) in hot (~ 35 °C) conditions. The extended exercise tolerance in the heat was partly attributed to increased sweat production during the early stages of exercise, leading to reductions in T_{core} (Page et al., 2019). In the current study, we did not find any effects of taurine on sweating, despite increases across time. Thus, it would appear that the hotter environmental stimulus is necessary to recognise the effects of taurine on sudomotor function and evaporative cooling potential. However, during the pre-exercise passive cold exposure period (which induced shivering, low T_{skin} temperatures set a '*cold*' thermal sensation), there were significant reductions in arm-to-finger temperature gradient in the placebo group but not in taurine, which is indicative of less vasodilation (or greater sustained vascular tone) in the taurine condition when presented with a cold environmental stimulus (House & Tipton, 2002). These findings are surprising, given that taurine is typically shown to promote vasodilation of macro-vasculature in normothermia (Ulusoy et al., 2017; Sun et al., 2016), but could highlight a more particular role of taurine in the peripheral sub-cutaneous micro-vasculature in response to cold environments. Our results infer that the taurine supplement permitted

less vasodilation, thus delaying convective heat losses at the periphery. This could be related to the bimodal vaso-active properties of taurine shown in animal models to defend acute blood pressure changes (Nishida & Satoh, 2009) but further direct assessments of blood flow are needed to understand this. While the arm-to-finger differences were also non-significant during the exercise bout, the pre-exercise differences meant that the TTE commenced under different levels of shell-temperature. It was anticipated that this would lead to enhanced T_{core} in the taurine condition, which did not occur, despite descriptively higher values (~ 0.2 °C) pre- and during exercise.

Increased thermal comfort in the taurine condition indicated that the participants reached a '*comfortable*' perception of the environment more rapidly than without taurine ingestion. We attribute these results to the descriptive increases in body temperature following taurine ingestion, which have a known influence on thermal perception and behaviour (Schlader et al., 2013). Similarly, the increased RPE in the early stages of exercise might have been based on feedback from thermal afferents emanating from the receptors at the skin surface or peripheral vessels (Crewe et al., 2008). The combination of the two current findings indicate that ingesting taurine in tolerably cold weather could enhance feelings of comfort at the expense of increased perceived exertion.

Conclusion

This is the first study to examine the effects of acute taurine supplementation on exercise performance in cold conditions. Although there were no effects on exercise performance, we have found preliminary evidence of possible effects on metabolic and vascular control processes. Future research should extend these findings to prolonged exercise at colder body temperatures, where the *small* effects revealed here could have greater influence on human performance and cold tolerability.

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