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ORIGINAL ARTICLE

The effect of self-regulated neck-cooling on physical and cognitive performance during heat stress

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ABSTRACT

This study investigated the physiological, perceptual, cognitive, and performance effects of self-regulated neck-cooling during heat stress. Nine, healthy, non-heat acclimated, participants undertook two experimental trials in the heat (35°C; 50% rh) during which they completed bouts of supine rest (30min), submaximal cycling exercise (20min at ~140bpm), and supine recovery (15min). Participants wore a novel electronic cooling collar in one trial (COOL) and were able to personalise the frequency and intensity of the cooling to maintain thermal comfort using a tablet-based application. Participants reduced the collar temperature over time which reduced their mean neck temperature throughout (-2.2 ± 0.6°C) and local neck thermal sensation during the rest and exercise bouts. The collar had no effect on physiological (rectal temperature [Δ 0.0 ± 0.1°C], aural temperature [Δ 0.0 ± 0.2°C], skin temperature [Δ 0.1 ± 0.3°C], or heart rate [Δ -4 ± 7 bpm]) or perceptual strain (whole-body thermal sensation and comfort) during rest or exercise bouts nor did it improve cognitive performance (reaction time, movement time, and spatial working memory), mood, or overhead press performance. The demands of the protocol investigated may have been insufficient to alter physiological strain or mood sufficiently to necessitate neck cooling despite improved localized thermal sensation.

Keywords: Performance analysis, Thermoregulatory behaviour, Thermal sensation, Encapsulation, Skin temperature, Physiological parameters, Exercise physiology, Physiological responses.

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INTRODUCTION

Many occupations require individuals to undertake physical work in hot environments - conditions which can make the completion of occupational tasks more challenging. Physical work in the heat increases the physiological strain faced compared to similar work in cooler conditions (Galloway & Maughan, 1997) and compromise physical and complex cognitive performance (Gaoua, 2010; Gonzalez-Alonso et al., 1999; Piil et al., 2017), as well as health, well-being, and productivity (Flouris et al., 2018). The heat stress is exacerbated in occupations that require the individual to wear protective clothing that restricts heat dissipation e.g., fire-fighters, military personnel, and Formula One pit crew members (Phillips et al., 2018) and in such situations strategies that mitigate the heat stress and strain are sought. Heat adaptation is probably the most effective heat mitigation strategy (Racinais et al., 2023; Tyler et al., 2024); however, it is time-consuming and logistically challenging and so acute, localised cooling may be a more practical alternative. The effectiveness of cooling strategies depend on factors such as the magnitude of thermal strain experienced, clothing, the cooling power provided, the surface area cooled, and the metabolic rate (Faulkner et al., 2019; Minett et al., 2011; Tetzlaff et al., 2025). Cold-water immersion and cooling vests are commonly adopted cooling strategies in occupational and sporting scenarios because they can cool a relatively large surface area of the body and can improve physical performance (van de Kerkhof et al., 2024), but both lack practicality especially when individuals are required to wear encapsulating clothing and access to the skin is severely restricted. In such situations, often only the skin of the head, face and neck are available for conductive cooling.

The head, neck, and face are areas of high alliesthesial thermo-sensitivity (Cotter & Taylor, 2005) and cooling such areas can lower the magnitude of perceived thermal strain, allowing individuals to tolerate greater core temperatures prior to volitional termination (Tyler & Sunderland, 2011a). Cooling the neck rarely lowers physiological strain (Bright et al., 2019; Moss et al., 2021; Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b) (although a recent paper suggests that brain temperature may be reduced at rest if the cooling power is sufficiently high (Lavinio et al., 2024)), but it may still offer a benefit to physical (Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b) and some components of cognitive performance (Gaoua et al., 2011; Lee et al., 2014; Mazalan et al., 2022), especially if perceived thermal strain is reduced. Performance benefits have been observed following the application of menthol gel (Jeffries & Waldron, 2019) and the subsequent activation of transient receptor potential channels (specifically TRPM8) providing further support for the role of altering thermal sensation (rather than actual strain) on performance in the heat (Schlader et al., 2011). Having said this, it is worth noting that neck cooling does not always improve performance with (Bright et al., 2019) or without (Moss et al., 2021) reductions in local thermal sensation.

Reducing perceived thermal strain (i.e. improving thermal sensation and comfort) can improve subsequent performance (Schlader et al., 2011; Tyler & Sunderland, 2011b, 2011a); however, there are a large inter-individual differences in how a temperature is perceived (e.g., some participants may like a cold stimulus whereas some may find it the same cooling magnitude unpleasant). To date, the ability to change and/or customise the magnitude of neck cooling provided by the devices assessed has been limited to replacing the device as it warms-up over time (Tyler & Sunderland, 2011b). In the present study, we utilised a novel application-controlled neck-cooling device that allowed participants to regulate and individualise the magnitude of cooling provided (in a blinded manner) while they undertook a passive-active-passive protocol in the heat while wearing a fire-resistant suit. It was hypothesised that although the cooling device would not reduce whole-body physiological strain, participants would lower their neck skin temperature sufficiently to maintain thermal comfort and subsequently perform better on cognitive and physical tasks in the heat.

MATERIALS AND METHODS

Participants

Nine, healthy non-heat acclimated participants (F = 4; age: 26 ± 4 y; stature: 174.6 ± 9.7 cm; body mass: 75.6 ± 10.5 kg; percentage body fat: 19.5 ± 10.1%; $\dot{V}O_{2peak}$: 3.6 ± 0.8 $l \cdot min^{-1}$) attended the laboratory on three occasions. A health screen (American College of Sports Medicine Position Stand and American Heart Association, 1998) was completed prior to each trial. All participants were fully informed of the experimental procedures and possible risks prior to giving written informed consent. Participants arrived at the laboratory having refrained from alcohol and strenuous exercise for 24 h and from food for 4 h. A 24 h diet and activity log was completed prior to the first experimental trial and repeated prior to the second. The study was approved by the ethical advisory committee of the University of Roehampton and performed according to the Declaration of Helsinki.

Pre-trial visit

A pre-trial visit was completed 3-10 days prior to the first experimental trial. Upon arrival, stature (Holtain Harpenden Stadiometer; Holtain UK ltd, Pembrokeshire, United Kingdom), body mass (Robusta 813; Seca, Birmingham, United Kingdom), and body composition were measured (BodPod; Cosmed, Rome, Italy). Participants then performed a modified maximal oxygen consumption ($\dot{V}O_{2max}$) test (Kuipers et al., 1985). During this test, participants cycled on a cycle ergometer (Monark 874E; Monark, Vansbro, Sweden) for 5 min at 70 W before the intensity was increased by 25 $W \cdot min^{-1}$ until volitional exhaustion. Participants completed the test after donning a HR chest-strap (H10; Polar, Kemple, Finland) and an appropriately sized multi-use silicone face mask (Cosmed, Rome, Italy). Maximal power output was calculated from which the experimental exercise intensity (40%) was calculated. Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured using an online gas analyser (Cortex Metalyzer 3B; Cortex-Medical, Leipzig, Germany) and defined as the highest value achieved using a 30 s mean average. Participants were familiarised with the cognitive tasks during this visit.

Experimental procedures

Participants performed two experimental trials in a randomised, counter-balanced order. In one of the experimental trials, participants wore an application-controlled neck-cooling device (COOL). Prior to arrival, participants either recorded or repeated their 24 h diet and activity log and consumed 500ml of water 2 h prior to the trial in attempt to ensure euhydration. Euhydration (urine specific gravity ≤1.020) was confirmed (COOL: 1.003 ± 0.002; CON: 1.008 ± 0.006) using a refractometer (Atago PEN-Urine S.G. 3741, Atago, Tokyo, Japan). Participants recorded a nude pre-trial BM before self-inserting a rectal thermistor (REC-U-VL-0; Grant Instruments [Cambridge] Ltd, Cambridgeshire, United Kingdom) approximately 10 cm past the anal sphincter, donning a HR chest-strap (H10; Polar, Kemple, Finland), and having eight wireless temperature loggers (iButtons, DS1992L Thermochron; Measurement Systems Ltd, Newbury, United Kingdom) affixed. Wireless loggers were affixed to the mid-belly of the right quadriceps, gastrocnemius, flexi carpi radials, and pectoral muscle for the calculation of mean-weighted skin temperature (Ramanathan, 1964), and evenly across the posterior aspect of the neck (n = 4) for the calculation of mean neck temperature (T_{neck}). Wireless loggers were attached to the skin with transparent dressing (Tegaderm; 3M, St Paul, MN) and waterproof tape (Transpore; 3M). Participants then donned the fire-resistant overalls (SPARCO Race suit, SPARCO, Volpiano, Italy) and completed the mood and cognitive test assessment before entering the hot (35˚C; 50% rh) environmental chamber (Design Environmental, Wales, UK). Participants rested in a supine position for 30 min then repeated the cognitive test battery. Participants then performed an 8 min standardised warm-up (2 min at 50% VO_{2peak}, 1 min at 60% $\dot{V}O_{2peak}$, 1 min at 70% VO_{2peak}, 1 min at 50% $\dot{V}O_{2peak}$, and 3 min of self-selected dynamic stretching) before cycling for 20 min at an intensity which elicited

140 b·min^{-1} during the pre-trial visit (Monark 874E; Monark, Vansbro, Sweden) and completing a 30 s overhead lift test using a 20 kg plate. During the overhead lift test, participants were requested to perform as many complete lifts as possible in 30 s – a lift was considered complete if the participant maximal extended their elbows with the plate above their head and lowered it so that it touched the ground. The exercise bout was designed to replicate a bout of occupational activity while the 20 kg lift was performed to simulate the moving of a Formula 1 car tire. Following the exercise phase, participants rested in a supine position for a 15 min recovery period. Participants then completed the mood and cognitive test battery, exited the chamber, towel dried and recorded a post-exercise nude BM. Sweat loss (1.3 ± 0.6 vs. 1.1 ± 0.5 l, p = .35) was calculated considering body mass changes and the volume of fluid consumed (100 ml per 15 min of room temperature water).

Mood and cognitive performance assessment

Mood and cognitive performance were assessed using the 40-item abbreviated profile of mood states (POMS) (Grove & Prapavessis, 1992), a motor-cognitive Perdue Pegboard assembly test (Tiffin & Asher, 1948), a 5-choice reaction time (RT) task, and a spatial working memory (SWM) test (Cambridge Neuropsychological Test Automated Battery (CANTAB). In the Perdue Pegboard Test, participants were asked to create as many 'units' of the four components as possible in 1 min using both hands. RT and SWM tests were performed on an iPad (iPad Air Wi-Fi, Apple Inc., CA, USA) and yielded RT, movement time, and accuracy (number of errors) data (5-choice RT Test) and error count and a strategy score (SWM Test). The cognitive performance test battery and mood assessment were completed three times per visit, before entering the environmental chamber (CF_{PRE} and $POMS_{PRE}$), after REST (CF_{REST} and $POMS_{REST}$), and after REC (CF_{REC} and $POMS_{REC}$).

Physiological and perceptual data

During the trials, rectal temperature (T_{rec}), T_{skin}, T_{neck}, HR, and aural temperature (T_{aural}; Braun ThermoScan 6022, London, United Kingdom), were recorded every 5 min. Rating of perceived exertion (Borg, 1982), whole-body thermal sensation (TS), neck thermal sensation (TS_{neck}), and thermal comfort (TC) was recorded every 5 min and the mean values were calculated for each stage of the experiment. Participants were asked to differentiate their whole-body and neck-specific TS using a seven-point scale ranging from 1 (*cold*) to 7 (*hot*) (Young et al., 1987). TC was determined using a four-point scale ranging from 1 (*comfortable*) to 4 (*very uncomfortable*) (Gagge et al., 1967).

The application-controlled neck cooling device

In the COOL trial, participants wore a battery-powered, personal neck-cooling device (Neuronguard S. R. L., Mercato Ortofrutticolo, Italy). Participants donned the collar and were provided with a hand-held device (iPad Air Wi-Fi, Apple Inc., CA, USA) from which they could control the cooling provided. Participants were asked to alter the cooling delivered by pressing the plus or minus buttons as frequently as they desired to maintain the temperature as a desirable level. The participants were blinded to the temperature chosen. Following the trials, the temperature data were retrieved by the researchers.

Statistical analyses

Parametric data are presented as means ± SDs whereas non-parametric data are presented as median [range]. Two-way analyses of variance (ANOVAs) with repeated measures were conducted for pegboard performance, reaction time, movement time, spatial working memory, T_{neck}, T_{skin}, HR, T_{aur}, and T_{rec}. POMS data were analysed using Friedman ANOVA with post hoc Wilcoxon Signed Rank analyses. Mean perceptual data, sweat loss, OHP, USG and fluid consumption in the CON and COOL trials were analysed using 1-tailed paired *t*-tests. Bonferroni adjustments for multiple comparisons were made when appropriate. Statistical significance was set at an alpha level of $P \leq .05$.

RESULTS

Collar temperature, neck temperature, and thermal sensation of the neck

Over the entire trial, mean self-selected collar temperature reduced over time ($p < .001$) starting at 18.0 ± 5.8°C and finishing at 5.1 ± 0.2 °C (Figure 1). The median self-selected set temperature decreased from 20°C at 5 min (0/9 selected 5°C [the lowest temperature]) to 5°C at 90 min (8/9 selected 5°C). Individual responses demonstrated a large degree of variation and as a result, mean temperature was not statistically different up until 60 min ($p > .227$) but was lower thereafter ($p < .045$). Mean self-selected collar temperature reduced from 18.0 ± 5.8°C at 5 min to 10.3 ± 7.7°C during rest ($p < .001$) then from 10.3 ± 7.7 °C to 6.9 ± 3.2°C during exercise ($p < .001$) and then from 6.9 ± 3.2°C to 5.1 ± 0.2 °C during recovery ($p = .073$). The largest 5-min changes were observed between 5 and 10 min (-3.2°C), 10 and 15 min (-3.7°C) and 60 – 65 min (-1.4°C), all other 5-minute reductions were < 1.0°C (-0.0 – -0.8°C). By design, and due to the self-selected reductions in collar temperature, T_{neck} was lower in CC throughout rest, exercise (main effect trial, time, and interaction: all $p < .001$) and recovery (main effect trial and time $p < .001$; interaction: $p = .41$).

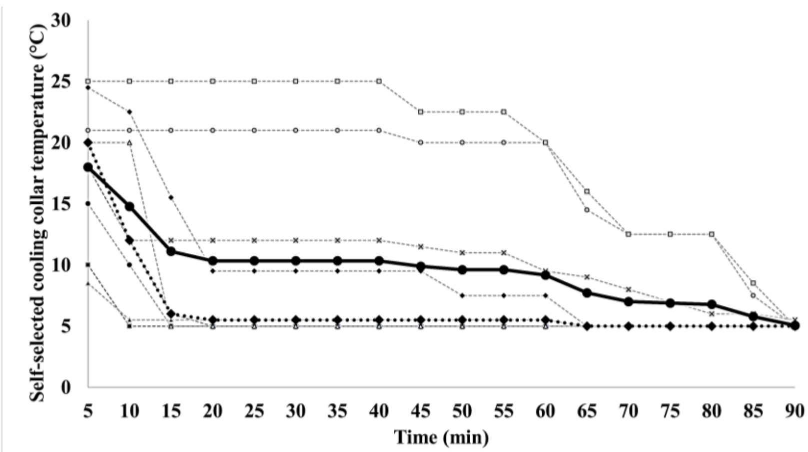

Figure 1. Mean (solid line and circular marker), median (dashed line and diamond markers), and individual (dashed grey lines) self-selected collar temperature.

The effect of neck-cooling on physiological and perceptual responses while at rest in the heat

T_{rec}, T_{au}, and T_{skin} increased over time (main effect time: $p = .003$, < .001, and < .001) but were unaffected by the collar (main effect trial: $p = .78$, .14, and .39). The responses were similar across both trials for T_{rec} and T_{au} (interaction effect: $p = .57$ and .21) but T_{skin} started lower and increased faster in CON (interaction: $p = .02$). HR did not change over time ($p = .67$) and was unaffected by the collar (main effect trial: $p = .30$; interaction: $p = .18$). Lowering T_{neck} reduced TS_{neck} during rest (3.4 ± 0.5 vs. 4.2 ± 0.5; $p < .001$) but whole-body TS (4.4 ± 0.7 vs. 4.2 ± 0.5; $p = .41$) and TC (1.0 ± 0.0 vs. 1.0 ± 0.0; $p > .99$) were not different between trials.

The effect of neck-cooling on physiological and perceptual responses during exercise in the heat

T_{rec}, T_{au}, T_{skin}, and HR increased over time (main effect time: < .001) but there was no effect of the collar (main effect trial: $p = .50$, .53, .79, and .28). The responses were similar across both trials for T_{rec}, T_{au}, and T_{skin} (interaction effect: $p = .50$, .32, and .23), but HR increased more quickly in COOL (interaction: $p = .02$).

TS_{neck} (5.0 ± 1.1 vs. 5.9 ±0.8; $p < .001$) and RPE (12.7 ± 2.6 vs. 13.8 ± 2.4; $p = .002$) were lower in COOL, but whole-body TS (5.9 ± 0.9 vs. 5.9 ± 0.8; $p = .92$) and TC (2.3 ± 0.8 vs. 2.4 ± 0.8; $p = .48$) were not different between trials.

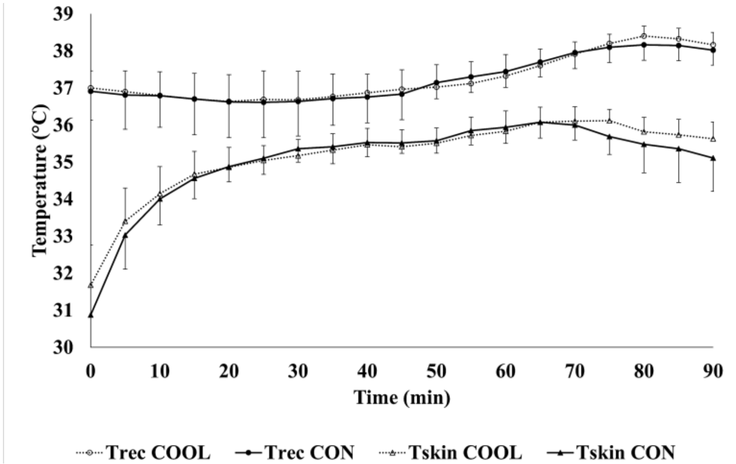

Figure 2. Mean (± SD) rectal (Trec) and weighted-skin temperature (Tskin) during cooling collar (COOL) and control (CON) trials.

The effect of neck-cooling on physiological and perceptual responses during recovery in the heat

T_{au}, T_{skin}, and HR decreased over time (main effect time: < .001) but T_{rec} did not change ($p = .07$). The collar did not alter the T_{rec}, T_{au}, T_{skin}, or HR response (main effect trial: $p = .36$, .32, .11, and .94). The responses were similar across both trials for T_{rec}, T_{au}, T_{skin}, and HR (interaction effect: $p = .40$, .40, .59, and .44). TS_{neck} was not different during recovery (4.8 ± 0.8 vs. 5.0 ± 1.1; $p = .40$), but whole-body TS (5.5 ± 1.0 vs. 5.0 ± 1.1; $p = .01$) and TC (2.0 ± 0.9 vs. 1.6 ± 0.7; $p = .03$) were both higher (worse) in COOL ($p = .01$ and .03).

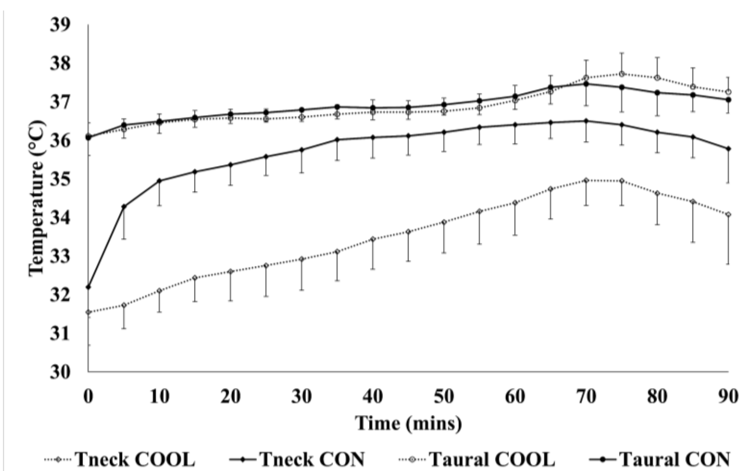

Figure 3. Mean (± SD) aural (Taural) and neck skin (Tneck) temperature during cooling collar (COOL) and control (CON) trials.

Table 1. The mean (± SD) cognitive test data from the battery of tests performed at the beginning, mid-point and conclusion of the test

	CON			COOL			Trial	Time	Trial x Time
	Pre	Mid	Post	Pre	Mid	Post			
Pegboard (units)	36.3 ± 9.3	36.7 ±6.5	39.1 ± 9.2	35.4 ± 6.6	37.2 ± 4.8	37.6 ± 5.6	0.701	0.173	0.415
RT (ms)	365.6 ± 27.2	366.9 ± 26.9	357.5 ± 24.3	370.1 ± 32.7	374.0 ± 31.1	355.8 ± 29.7	0.638	0.005	0.687
MT (ms)	197.9 ± 44.0	192.4 ± 52.0	198.1 ± 39.2	196.5 ± 38.7	201.9 ± 39.3	198.6 ± 37.9	0.703	0.979	0.422
SWM$_{btwn}$ (n)	1.3 ± 2.5	2.8 ± 5.2	1.9 ± 3.0	4.3 ± 7.4	0.7 ± 0.9	1.1 ± 2.4	0.962	0.687	0.131
SWM$_{btwn12}$ (n)	10.0 ± 11.4	11.1 ± 6.2	11.7 ± 11.4	18.0 ± 13.7	16.4 ± 16.1	13.9 ± 9.8	0.157	0.894	0.584
SWM$_{stgy68}$ (n)	3.9 ± 3.0	4.2 ± 2.8	4.6 ± 2.1	4.7 ± 3.2	3.8 ± 2.5	3.8 ± 2.2	0.773	0.843	0.251
SWM$_{stgy612}$ (n)	7.3 ±5.2	7.3 ± 4.9	7.9 ± 4.3	8.7 ± 5.9	7.3 ± 4.7	7.2 ± 4.8	0.797	0.606	0.424

Note. RT = reaction time; MT = movement time; ms = milliseconds; SWM = spatial working memory; btwn = between; stgy = strategy.

Table 2. The median (IQR) scores for the POMS subscales.

Item	Between trials				
	CON	COOL			
	Trial median	Trial median	Pre median	Mid median	Post median
Tension	1 (0 – 4)	0 (0 – 3)	**1.5 (0.0 – 6.0)**^{M,P}	0.0 (0.0 – 2.5)	0.0 (0.0 – 2.0)
Depression	0 (0 – 1)	0 (0 – 2)	0.0 (0.0 – 3.5)	0.0 (0.0 – 1.0)	0.0 (0.0 – 1.3)
Anger	0 (0 – 1)	0 (0 – 1)	0.0 (0.0 – 2.3)	0.0 (0.0 – 1.0)	0.0 (0.0 – 1.0)
Fatigue	5 (2 – 6)	5 (2 – 6)	4.5 (1.8 – 6.0)	2.5 (0.0 – 5.0)	**6.0 (5.0 – 11.0)**^{Pr,M}
Confusion	1 (0 – 2)	1 (0 – 3)	**1.0 (0.0 – 3.0)**^{M}	1.0 (0.0 – 2.3)	0.5 (0.0 – 3.3)
Vigour	6 (1 – 9)	5 (2 – 7)	**5.5 (2.5 – 9.0)**^{M}	3.0 (0.0 – 6.3)	5.0 (1.5 – 7.3)
Esteem related affect	11 (8 – 15)	11 (9 – 15)	11.0 (9.5 – 15.0)	10.0 (8.8 – 14.3)	11.5 (8.0 – 17.0)
Total mood disturbance	-6 (-16 – 0)	-6 (-14 – 2)	-6.0 (-16.8 – 7.0)	-7.0 (-16.8 – 0.5)	-6.0 (-13.3 – 1.8)

Item	Within trials					
	CON			COOL		
	Pre	Mid	Post	Pre	Mid	Post
Tension	**2.0 (0.0 – 6.0)**^{M,P}	0.0 (0.0 – 2.5)	1.0 (0.0 – 2.5)	1.0 (0.0 – 4.0)	0.0 (0.0 – 4.0)	0.0 (0.0 – 2.0)
Depression	0.0 (0.0 – 2.0)	0.0 (0.0 – 0.5)	0.0 (0.0 – 2.5)	0.0 (0.0 – 5.0)	0.0 (0.0 – 2.0)	0.0 (0.0 – 1.5)
Anger	0.0 (0.0 – 2.5)	0.0 (0.0 – 1.0)	0.0 (0.0 – 1.5)	0.0 (0.0 – 4.0)	0.0 (0.0 – 1.5)	0.0 (0.0 – 0.5)
Fatigue	4.0 (1.0 – 5.5)	2.0 (1.5 – 4.5)	**6.0 (5.5 – 11.0)**^{Pr,M}	5.0 (2.0 – 6.0)	4.0 (0.0 – 5.5)	6.0 (0.0 – 9.5)
Confusion	1.0 (0.0 – 3.5)	1.0 (0.0 – 2.5)	1.0 (0.0 – 2.5)	2.0 (0.0 – 3.5)	1.0 (0.0 – 2.5)	0.0 (0.0 – 3.5)
Vigour	6.0 (0.5 – 9.5)	4.0 (1.0 – 8.0)	7.0 (1.0 – 10.5)	5.0 (3.5 – 8.0)	**3.0 (0.0 – 5.5)**^{P}	5.0 (1.5 – 6.5)
Esteem related affect	11.0 (9.0 – 15.0)	11.0 (8.5 – 14.5)	13.0 (8.0 – 17.0)	11.0 (9.0 – 14.5)	10.0 (8.5 – 15.5)	11.0 (9.5 – 16.0)
Total mood disturbance	-4.0 (-16.0 – 3.0)	-8.0 (-17.5 – -1.5)	-6.0 (-17.0 – 7.0)	-9.0 (-18.5 – 10.5)	-6.0 (-16.0 – 4.5)	-6.0 (-13.5 – -0.5)

Note. Pr = different compared to Pre (p < .05); M = different compared to Mid (p < .05); P = different compared to post (p < .05).

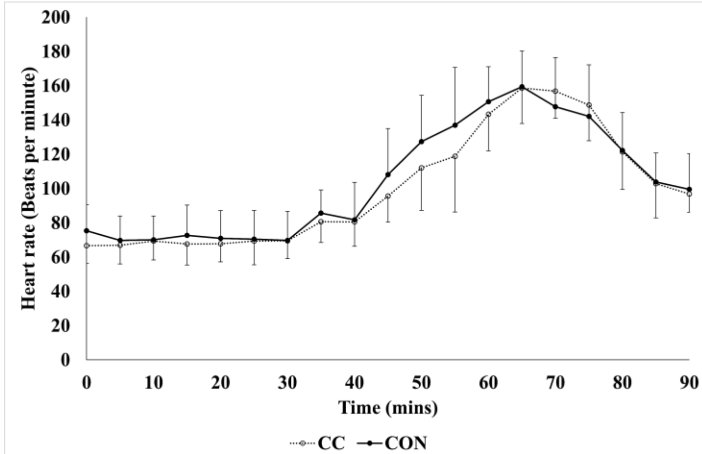

Figure 4. Mean (± SD) heart rate during cooling collar (COOL) and control (CON) trials.

The effect of neck-cooling on overhead press performance, cognitive performance, and mood

There was no difference in the number of overhead press repetitions completed (11 ± 3 repetitions in each trial; $p = .32$) nor were there were any statistically significant main effects for any of the cognitive battery data (Table 1) except for a main effect for time for Reaction Time ($p < .005$). Post hoc analyses revealed that reaction time was slower in CF_{REC} than CF_{REST} ($p = .044$). There was no statistical difference between pre- and mid-test ($p = .781$) or between pre- and post-test ($p = .089$). There was no statistical main effect between trials for any of the POM subscales ($p = .056$ – .999; Table 2) but there was a main effect for time for tension ($p = .008$), fatigue ($p < .001$), confusion ($p = .03$), and vigour ($p = .041$). There was no effect of time for any other sub-scale ($p = .097$ – .874). Tension, confusion, and vigour were higher at $POMS_{PRE}$ than $POMS_{REST}$ ($p = .011$; $p = .014$; $p = .006$) and tension was also higher at $POMS_{PRE}$ than $POMS_{REC}$ ($p = .013$). Fatigue was higher in $POMS_{REC}$ than $POMS_{PRE}$ ($p = .007$) and $POMS_{REST}$ ($p < .001$). When performing a paired samples non-parametric sign-rank test, there was a statistically significant difference in the perceived levels of fatigue between the beginning of the test and the conclusion in the control group (*p*-value .0087), while in the intervention group the difference was not significant.

DISCUSSION

To the authors' knowledge, this is the first study to investigate the effect of cooling the neck using a device that allowed participants to regulate and individualise the magnitude of cooling provided during passive and active heat stress. The device allowed participants to reduce their neck temperature throughout the during of the cooling trial, but (as hypothesised) the reduction in neck temperature had no effect on body temperature or heart rate during rest, exercise, or recovery. Lowering neck temperature reduced localised thermal sensation during the rest and exercise bouts and rating of perceived exertion during exercise and increased perceived thermal strain during recovery. The reduction in localised thermal sensation did not result in improved physical or cognitive performance.

The neck makes up only ~1% of the body's surface area (Cuttell et al., 2016) and so it is unsurprising that physiological strain was unaffected by cooling this site in the present study and in previous work (Bright et al., 2019; Cuttell et al., 2016; Moss et al., 2021; Tyler & Sunderland, 2011b, 2011b). Reductions in perceived thermal strain and exertion can result in subsequent performance benefits without concomitant physiological changes (Tyler & Sunderland, 2011b, 2011b, 2011a), but the reductions in localized thermal strain in the present study did not result in such benefits. The effectiveness of cooling strategies depend on factors such as the magnitude of thermal stress and strain experienced and the cooling power provided (Faulkner et al., 2019; Minett et al., 2011; Tetzlaff et al., 2025) and the magnitude of thermal strain in the present study was somewhat low. In the present study, T_{rec} peaked at ~38.2°C which is similar to data reported elsewhere when no benefit of neck-cooling was observed (Bright et al., 2019; Cuttell et al., 2016), but lower than studies that have seen an ergogenic effect of neck-cooling (Tyler & Sunderland, 2011b, 2011a). In combination, this supports previous suggestions that there may be a magnitude of thermal strain below which neck-cooling is not warranted or beneficial (Bright et al., 2019; Tyler et al., 2010). The studies to-date have used self- or externally controlled running and cycling exercise tests whereas the present study used a 30 s strength test. Short exercise tests (< 75 s) are rarely improved by per-cooling (Douzi et al., 2019) and so it is also possible that the lack of performance benefit was due to the exercise test used.

As with physical performance, cognitive performance was unaffected in the present study. It is frequently reported that simple cognitive performance is largely unaffected by heat stress (only impaired when individuals are experiencing very high magnitudes of thermal strain), whereas more complex tasks are more vulnerable to impairment (Gaoua et al., 2011; Piil et al., 2017; Racinais et al., 2008). In the present study neither simple (reaction time) nor more complex (spatial working memory and Perdue Pegboard Test performance) were impaired in CON, and so unsurprising neck cooling did not alter performance. Similar data were reported by Ando et al. (2015) with comparable magnitudes of thermal strain ($T_{tympanic}$ = ~38.4°C). Even when heat strain is higher (T_{rec}: ~39.5°C), the effects of neck cooling on cognitive performance are mixed. For example, Lee et al (2014) observed improvements in search and memory performance with neck cooling during heat strain but reported no effects on simple cognitive performance. Cognitive function in occupational settings is dependent on many factors and recently mood has been linked to cognitive performance of formula one race team members in the heat (O'Neill et al., 2020). O'Neill et al. (2020) observed a relationship between cognitive performance and mood such that reductions in mood were related to reduced cognitive performance. Although some aspects of mood changed over time in the present study (e.g., fatigue was higher at the end than at the start), cooling the neck had no effect on most of them, a difference in the stability of the levels of fatigue in favour of neck cooling was identified, when performing further exploratory analysis of the dataset. It is possible that scenarios in which mood is altered to a greater extent may benefit from an intervention that reduces the change.

CONCLUSION

Occupational heat strain commonly negatively impacts upon worker health and productivity and effective interventions are sought (Flouris et al., 2018). Despite some cooling interventions effectively alleviating heat strain and improving subsequent physical and cognitive performance (Bongers et al., 2017; Donnan et al., 2023), the present data does not support the use of the assessed individualized cooling device to improve worker safety or performance when low levels of physiological strain are likely to be experienced. It appears that the demands of the protocol investigated were insufficient to alter physiological strain or mood enough to necessitate (and therefore benefit from) neck cooling despite the collar improving localized thermal sensation. The potential effect on the perception of fatigue, highlighted by the exploratory analysis, should be further investigated.

AUTHOR CONTRIBUTIONS

ARB, CJT and HHM devised and designed the experiment. ARB and HHM collected the data which was analysed by CJT. All authors wrote, revised, and approved the manuscript.

SUPPORTING AGENCIES

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DISCLOSURE STATEMENT

EG is the CEO of Neuronguard and provided the cooling device used in this experiment. EG was not involved in the design of the experiment nor the data collection. EG provided the cooling-devices and was involved in the writing of the manuscript. ARB, CJT and HHM have no conflicts of interest to declare.

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