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Thermal and cardiovascular strain imposed by motorcycle protective clothing under Australian summer conditions

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Abstract

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THERMAL AND CARDIOVASCULAR STRAIN IMPOSED BY MOTORCYCLE PROTECTIVE CLOTHING UNDER AUSTRALIAN SUMMER CONDITIONS

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CONFLICTS OF INTEREST

There are no conflicts of interest.

RUNNING HEAD: Motorcycle clothing and physiological strain

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Abstract

Motorcycle protective clothing can be uncomfortably hot during summer, and this experiment was designed to evaluate the physiological significance of this burden. Twelve males participated in four, 90-min trials (cycling 30 W) across three environments (25^{o}C, 30^{o}C, 35^{o}C [all 40% relative humidity]). Clothing was modified between full and minimal injury protection. Both ensembles were tested at 25^{o}C, with only the protective ensemble investigated at 30^{o} and 35^{o}C. At 35^{o}C, auditory canal temperature rose at 0.02^{o}C.min^{-1} (SD 0.005), deviating from all other trials (P<0.05). The thresholds for moderate (>38.5^{o}C) and profound hyperthermia (>40.0^{o}C) were predicted to occur within 105 min (SD 20.6) and 180 min (SD 33.0), respectively. Profound hyperthermia might eventuate in ~10 h at 30^{o}C, but should not occur at 25^{o}C. These outcomes demonstrate a need to enhance the heat dissipation capabilities of motorcycle clothing designed for summer use in hot climates, but without compromising impact protection.

Keywords: core temperature, heat loss, heat strain, metabolic heat production, motorcycle clothing, protective clothing, protective equipment

Practitioner's Summary

Motorcycle protective clothing can be uncomfortably hot during summer. This experiment was designed to evaluate the physiological significance of this burden across climatic states. In the heat, moderate (>38.5^{o}C) and profound hyperthermia (>40.0^{o}C) were predicted to occur within 105 min and 180 min, respectively.

1. INTRODUCTION

It has long been recognised that personal protective clothing and equipment, when used during moderate to heavy work, can push individuals to the limits of physiological regulation (Gonzalez, 1988; Goldman, 2001; Fogarty *et al*., 2004; Caldwell *et al*., 2011, 2012; McLellan *et al*., 2013; Taylor and Patterson, 2015). What is less certain is the physiological strain imposed by such ensembles during light to moderate workloads, such as those encountered during motorcycle riding, and whether or not one need even consider the impact of such levels of strain. Nonetheless, evidence already exists to indicate that thermal discomfort is a key disincentive to the wearing of motorcycle protective clothing in hot weather (de Rome *et al*., 2011a; Wishart, 2009; Zwolinska, 2013), even though the efficacy of such protective ensembles is well established (de Rome *et al*., 2011a, 2011b). However, there is a paucity of information pertaining to the capacity of such protective ensembles to disturb either thermal homoeostasis or the cognitive processes necessary for safe motorcycle riding, particularly when climatic conditions conspire to unfavourably tilt the balances for physiological or cognitive performance. Therefore, the purpose of this investigation was to quantify thermal and cardiovascular strain during simulated, urban motorcycle rides conducted under controlled laboratory conditions.

The impact of personal protective clothing and equipment occurs firstly through an elevation in metabolic heat production, due both to its combined mass (Goldman and Iampietro, 1962; Soule and Goldman, 1969; Taylor *et al*., 2012) and to its restriction of joint movements (Nunneley, 1989; White *et al*., 1989; Dorman and Havenith, 2009). The second effect relates to the trapping of heat, for all garments create a layer of air between the skin and the outer surface of the clothing. Since air is one of the best insulators known, the thicker this boundary layer becomes, the greater will be its impediment to both heat penetration and heat loss (Benedict *et al*., 1919; Gonzalez, 1988). For those working in thermally stressful environments, the objective of such clothing is to elevate thermal insulation and protection from external heat. For motorcyclists, protective ensembles are designed to maintain a barrier between the road surface and skin during an accident, with impaired heat loss, due to increased insulation and reduced moisture permeability, coming as an undesired, albeit necessary, consequence. It follows then that heat loss becomes increasingly more difficult as the protective properties of each ensemble are enhanced. This could compromise physiological and possibly cognitive performance.

It was hypothesised that the combined influences of metabolic heat production during a simulated, urban motorcycle ride in hot summer weather (Australia), when wearing the recommended protective clothing, would not result in either moderate hyperthermia (deep-body temperature >38.5^{o}C [Taylor *et al.*, 2008]) or excessive cardiovascular strain (heart rate >180 beats.min^{-1} [Taylor and Patterson, 2015]) within 90 min. To test this hypothesis under controlled conditions, twelve males participated in four simulations during which the physiological consequences of two levels of rider protection and three climatic states were evaluated, whilst metabolic heat production was matched to that observed in six experienced motorcyclists during urban riding.

2. METHODS

This experiment was comprised of two discrete parts. Firstly, two field trials were undertaken using experienced motorcyclists, who performed controlled urban and rural rides; pilot tests one and two. From continuous oxygen consumption measurements made during those trials, the metabolic heat production of such controlled riding was derived. The main experiment involved laboratory trials during which the thermal and cardiovascular impact of three climatic states and two levels of rider protection were investigated. In those trials, participants exercised at an intensity that replicated the average heat production observed in the pilot trials.

2.1 Participants

For the pilot investigations, six experienced motorcyclists (males) were used (average age 43.0 y [standard deviation (SD) 9.3], height 170.6 cm [SD 7.6]). An additional 12, asymptomatic males were recruited to provide a diverse population sample for the laboratory experiment (age 31.1 y [range 20-61], 82.9 kg [range 64.3-121.2], height 179.6 cm [range 168.5-188.5], sum of eight skinfold thicknesses 108.1 mm [range 46.5-276.0]). All participants provided written, informed consent, and were screened to eliminate individuals with a contraindicative history of either cardiovascular or thermoregulatory problems. All procedures were approved by the Human Research Ethics Committee (University of Wollongong) in accordance with the National Health and Medical Research Council (Australia) and in compliance with the Declaration of Helsinki.

2.2 Procedural overview

The main experiments were the laboratory-based trials, and these involved three experimental conditions (Table 1). Each was investigated in a climate-regulated chamber, in which air temperature was changed, but the relative humidity was kept constant (40%): 25°C (water vapour pressure 1.3 kPa), 30°C (1.7 kPa) and 35°C (2.25 kPa). Every trial commenced with a 5-min, resting baseline period at the experimental temperature, followed by three consecutive, 30-min stages, which consisted of 25 min of light-intensity external work (cycling 30 W) and 5 min of rest. Trials then differed in two ways (Table 1). Firstly, air temperature and ambient water vapour pressure were altered across three levels. Secondly, the clothing configuration was modified between two ensembles: the control state (street clothing) and fully protected. Subjects were tested at 25°C in both clothing configurations (Trials A and B), but at 30°C (Trial C) and 35°C (Trial D), they only wore the protective clothing and equipment. Therefore, each participant was his own control, and took part in four trials. These were administered in a balanced order (Latin square) to eliminate order effects, and at approximately the same time of day to avoid circadian influences on deep-body (core) temperature. In most instances, one week separated consecutive trials on the same individual to minimise adaptation affects (Barnett and Maughan, 1993; Tipton *et al.*, 2008). Drinking and eating were not permitted during any testing.

INSERT TABLE 1 ABOUT HERE

2.3 Procedural details

Simulating heat production during motorcycle riding: Since performing this experiment in the field would involve significant, uncontrollable and potentially irreproducible metabolic and climatic variations, it was essential to undertake testing within a climate chamber. However, this first necessitated simulating both the metabolic energy transformation (metabolic heat production minus the external work performed) associated with motorcycle riding and representative summer thermal loads. For this, six experienced motorcyclists (males) were used, including five riding instructors. Each rider wore his own protective ensemble (mean combined body, clothing and protective equipment mass: 89.3 kg [SD 22.5]), and performed two, 20-min rides under controlled road conditions (dry motorcycle training track). Motorcycle engine capacities ranged from 125-750 cm^3 and the motorcycles had a average mass of 153.2 kg (SD 32.3).

The first pilot trial involved an urban street simulation that included traffic lights, a roundabout, stop signs, damaged road surfaces and a variety of urban street formations. The second (pilot) ride simulated open-road conditions, which also included traffic lights and damaged surfaces, along with a rail crossing, a hair-pin bend and a gravel section. Riders repeated laps of both circuits until the designated time expired (20 min), upon which they completed the current lap before returning to the start/finish point. Full-face helmets were replaced with open-face helmets so that riders could wear a portable, open-circuit, expired gas analysis and ventilation system (Metamax 3B, Cortex Biophysik, Leipzig, Germany: mass = 1.82 kg). Oxygen consumption was directly measured from separate determinations of minute ventilation, and expired oxygen and carbon dioxide fractional concentrations. Data were recorded on a breath-by-breath basis and analysed over 15-s intervals. Equipment was calibrated prior to going into the field, with calibration verifications performed throughout testing.

For these individuals, the resting (seated), but fully clothed, oxygen consumption averaged 0.40 $L.min^{-1}$ (95% confidence interval [CI] 0.33-0.47). Across the urban simulations, oxygen consumption averaged 0.59 $L.min^{-1}$ (95% CI 0.44-0.73), whilst during the simulated rural rides, the mean was 0.54 $L.min^{-1}$ (95% CI 0.37-0.71). Accordingly, it was decided to use an external work rate that would elicit an oxygen consumption of 0.6 $L.min^{-1}$, as urban riding is more thermally stressful when wearing protective clothing due to the lower relative wind speed and to its intermittent nature. Since it was also important to retain a riding posture within the experimental environments, cycle ergometry was chosen as the exercise mode (Monark Ergomedic 828E, Monark Exercise AB, Vansbro, Sweden), and the external work rate was set to 30 W (60 $revs.min^{-1}$). It was recognised, however, that the resulting leg movement would pump air through the trousers, and that this would enhance both convective and evaporative cooling.

Simulating Australian summer climates: The hottest air temperature (35^{o}C) was chosen to approximate the average 86th percentile mean daily maximal temperatures for summer in Australia's seven largest cities (Bureau of Meteorology, Australian Government: http://www.bom.gov.au/climate/data/). Those cities include about 65% of the Australian population, and were thereby likely to represent the majority of urban motorcyclists. The logic of this temperature selection was that, if excessive thermal strain was to occur, it was most likely to be encountered under conditions that approached the worst-case climate. The lowest temperature (25°C) approximated the 14th percentile mean daily maximal temperatures for those cities, with the middle temperature being equidistant. A substantial radiant heat source was applied throughout each trial. Three, 500-W infra-red lamps were positioned above the subject to approximate the solar load encountered with the sun overhead (~800 $W.m^{-2}$; Santee and Gonzalez, 1988); two were located in front (1.0 m), whilst the third was behind (0.7 m). To more realistically simulate urban riding, during which relative air movement enhances both convective and evaporative heat exchanges, a large-diameter fan (830 mm) was positioned at chest height 2.2 m in front of the subject. Wind velocity was kept constant during cycling (30 $km.h^{-1}$), and was reduced to <1 $km.h^{-1}$ during each rest period. Since the use of overhead radiant heaters and relative wind movement necessitated a posture closely resembling that of motorcycle riding, cycle ergometry was deemed to be the most appropriate form of exercise. The ergometer was then positioned facing the fan and immediately below the three radiant heaters. In this position and with that posture, the body surfaces exposed to radiant heating best matched those of motorcycle riding, and involved the head, shoulders, the dorsal surfaces of both arms and the upper back.

Clothing configurations: For every laboratory trial, each participant wore correctly sized and identical socks, steel-capped boots (mass range 2.38-3.04 kg), motorcycle gloves and open-faced helmets (visors down: 1.36 kg), with helmets satisfying the relevant standard for motorcycling (AS/NZS 1698:2006). Since the test laboratory held a stock of steel-capped, industrial boots that satisfied the Australian standard from structural fire fighting (AS/NZS 4821:2006), these were considered to be an adequate protective-footwear substitute, and were provided to all subjects. For Trial A, participants wore their own swimming costumes (briefs), with denim jeans and long-sleeved cotton t-shirts of the same style and brand (as provided by the investigators). This ensemble constituted the control, or minimally protected state (street clothing with insufficient accident protection), the total mass of which ranged from 6.60-7.28 kg. Neither the thermal insulation of this ensemble nor its vapour permeability were derived.

For Trials B-D (25°, 30° and 35°C), the protective riding ensemble was used. In this state, participants wore short-sleeved t-shirts (provided as above) along with protective trousers and jackets designed for motorcycle riding. These suits were selected from a range of all-season garments available to motorcyclists in Australia. The ensemble choice was based on having a low water-vapour permeability so that its influence on evaporative cooling was maximised; vapour permeability index (0.09 dimensionless) and thermal insulation (0.358 $m^2.K.W^{-1}$; unpublished measurements; RMIT University, Melbourne, Australia). Both components consisted of an outer shell of abrasion-resistant, polyester fabric. Each part had an inner waterproof, thermal liner that was removed for these trials. Finally, both garments contained fitted, motorcycle armour on the back, shoulders, elbows, hips and knees. These inserts conformed with *Conformité Européenne* (CE) standards (EN 1621-1:2012 and EN 1621-2:2003), and were retained *in situ* during testing. Each participant wore correctly sized garments of the same style, provided by the same manufacturer, with the overall mass of the complete protective ensemble varying from 9.02-10.12 kg.

Zippered ventilation ports were provided for the chest, back, arms and legs, but all of these remained closed, and thereby provided a superior evaluation of the fabrics typically used in the construction of motorcycle clothing. In addition, since the location of some ports may actually compromise rider protection, it was important to conduct this testing within a state of optimal impact and abrasion protection. Thus, without garment ventilation, subjects were tested under conditions most likely to disturb thermal homoeostasis, should it occur during any of these simulations. This was a deliberate strategy, since if physiologically significant strain could not be established under these conditions, then it would be much less likely to occur when wearing less stressful ensembles.

Pre-experimental standardisation: Subjects for the laboratory trials were instructed how to prepare and present in a well-hydrated, post-absorptive state. This involved drinking 15 $mL.kg^{-1}$ of additional water before going to bed on the night before testing, and eating a high-carbohydrate, low-fat evening meal and breakfast. On the morning of testing, subjects were asked to drink 500 mL of fluid with breakfast. Participants refrained from strenuous exercise, heavy alcohol consumption and tobacco use during the 12-h period prior to each trial, and the consumption of caffeine for 2 h before testing. On presentation, urine specific gravity was measured to verify hydration state (Clinical Refractometer, Model 140, Shibuya Optical, Tokyo, Japan), after which an isotonic drink (10 $mL.kg^{-1}$) was provided, with subjects asked to consume as much as comfortably possible.

2.4 Physiological and psychophysical measurements

Deep-body temperature was assessed from the auditory canal, and monitored using an ear-moulded plug with a thermistor protruding 1 cm (FF mini thermistor, Edale instruments Ltd., Cambridge, U.K.). The average phase delay between the sudden immersion of these sensors in warm water and the first recorded temperature rise was 4.2 s. The sensor was located within the external auditory meatus and insulated with cotton wool, over which a correctly fitted motorcycle helmet was positioned. This method prevented airflow around each ear and it also minimises thermal artefacts within the auditory canal, permitting canal temperature to validly track oesophageal and central blood temperatures (Taylor *et al*., 2014), particularly during temperate and heated states (Cotter *et al*., 1995; Todd *et al*., 2014). Skin temperatures become more uniform in the heat (Werner and Reents, 1980; Taylor *et al*., 2014), particularly those under protective clothing (Taylor and Patterson, 2015). Therefore, mean skin temperature was derived from the weighted summation of just four skin sites (chest, arm, thigh, leg; Ramanathan, 1964). Thermistors were attached with a single layer of waterproof tape (Type EU, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, U.S.A.). All temperatures were recorded at 15-s intervals (1206 Series Squirrel, Grant Instruments Ltd., Cambridge, U.K.). Thermal data (only) were lost for one subject in Trial B due to equipment failure.

Central cardiovascular strain was evaluated from heart rate responses, which were monitored continuously (15-s intervals) from ventricular depolarisation (Vantage NV, Polar Electro Sport Tester, Kempele, Finland). Whole-body sweat rate (Taylor and Machado-Moreira, 2013), clothing moisture retention and evaporation rates were determined from gross body (wearing swimming costumes only), and clothing and equipment masses measured before and after each trial (fw-150k, A&D scale, CA, U.S.A.: ±20 g).

Psychophysical data were sampled twice during each of the three exercise periods (10, 25, 40, 55, 70, 85 min) and again at the end of each rest period (30, 60, 90 min). Thermal sensation was monitored using a modified Gagge scale (Gagge *et al*., 1967), with the end points extended (scale: 1 = unbearably cold, 13 = unbearably hot). Using the same scale, but different sensation indicators, skin or clothing wetness sensations were similarly recorded (scale: 1 = unbearably dry, 13 = totally saturated). For these sensations, subjects were asked: "*How does the temperature of your body feel?*" and "*How wet or moist does your skin or clothing feel?*" Subjective thermal and wetness discomfort votes were also recorded (Gagge *et al*., 1967: scale: 1 = comfortable, 5 = extremely uncomfortable) in response to the questions: "*How comfortable do you feel with the temperature of your body?*" and "*How comfortable do you feel with the wetness of your skin or clothing?*"

2.5 Design and analysis

This experiment was based upon a repeated-measures design, with subjects participating in every trial and acting as their own controls. Since the principal objective was to characterise the level of thermal strain that might be encountered by motorcyclists during an urban ride in summer, physiological and psychophysical data were first analysed to provide standard descriptive parameters, with subsequent comparisons performed using paired *t*-tests and two-way analysis of variance, both with *alpha* set at the 0.05 level. Data are presented as means with standard deviations (SD) or 95% confidence intervals (CI) to highlight data distributions. Temperature and heart rate data for each participant were individually modelled using least-squares, best-fit, linear regression analysis, with slopes and intercepts reported as trial averages across the 12 participants. These parameters were used to predict times to reach states of moderate and profound hyperthermia for each participant.

3. RESULTS

3.1 Pre-experimental standardisation

On presentation, participants were classified as well hydrated on the basis of urine specific gravity measurements (Armstrong *et al*., 1994), and commenced each trial in a very similar hydration state: Trial A 1.014 (urine specific gravity; 95% CI 1.009-1.019), Trial B 1.013 (95% CI 1.007-1.019), Trial C 1.009 (95% CI 1.004-1.014) and Trial D 1.015 (95% CI 1.011-1.019). This status was also reflected within the between-trial stability of the baseline body mass: Trial A 82.9 kg (SD 14.9), Trial B 82.4 kg (SD 14.5), Trial C 82.3 kg (SD 14.5) and Trial D 82.6 kg (SD 14.8). Accordingly, variations in physiological strain among trials that related to changes in hydration state, could only be ascribed to within-trial effects accompanying modifications in either the clothing worn (Trials A and B) or the level of external thermal stress (Trials B, C and D).

Similarly, the pre-experimental, auditory canal temperatures were not significantly different among trials (P>0.05): 36.5^{o}C (Trial A; SD 0.3), 36.6^{o}C (Trial B; SD 0.3), 36.6^{o}C (Trial C; SD 0.4) and 36.6^{o}C (Trial D; SD 0.3). Since the baseline status was evaluated after participants were fully dressed, and after first entering each environmental state, then the pre-exposure heart rates for Trials A and B provided a resting index of the cardiovascular burden imposed by this protective clothing. As one would predict, the least stressful resting state was the control condition (Trial A 72 beats.min^{-1} [SD 11]), with the corresponding heart rates for Trials B-D all being significantly (*P*<0.05), albeit very slightly, elevated: Trial B 76 beats.min^{-1} (SD 11), Trial C 79 beats.min^{-1} (SD 10) and Trial D 81 beats.min^{-1} (SD 12). With this level of experimental control, it can reasonably be assumed that subsequent differences in physiological and psychophysical strain were due to changes in the level of rider (impact and abrasion) protection (Trials A and B) or to external thermal modifications (Trials B, C and D).

3.2 The impact of modifying injury protection

Trials A and B (25^{o}C) were conducted to evaluate the influence of modifying the level of injury protection under temperate conditions. In that state, it is not unusual to observe people wearing long-sleeved t-shirts and trousers when sitting comfortably outside on a windy day. With a low level of metabolic heat production, thermal comfort can even be achieved in strong winds, so these two temperate trials provided control references for the physiological changes associated with simply wearing the appropriate protective clothing, and for its combined effect with increments in the external thermal load. Auditory canal and mean skin temperatures are illustrated in Figure 1, with every subject completing Trials A and B. For auditory canal temperatures during these two trials, significant inter-trial differences were not observed (*P*>0.05). Indeed, these data remained stable and virtually superimposed (Figure 1A), averaging 36.7^{o} and 36.8^{o}C (respectively) across those trials. Over the last 10 min of these exposures, auditory canal temperatures had only risen by 0.2^{o}C above baseline. On the other hand, mean skin temperatures were displaced vertically from Trial A to B (Figure 1B), with an average offset across the entire simulation of 2^{o}C (31.4^{o} versus 33.6^{o}C; *P*<0.05), but without evidence of a time-related deviation (*P*>0.05). This increased the skin-to-air temperature gradient for heat loss (-6.4^{o} [SD 0.5] versus -8.8^{o}C [SD 0.6]; *P*<0.05), and it was accompanied by a similar parallel shift of the steady-state heart rate (Figure 2), with respective trial means of 80 (SD 10) and 92 beats.min^{-1} (SD 12; *P*<0.05). Also apparent within each 5-min rest period (25, 55 and 85 min) are reductions in cardiovascular strain, due to a transient cessation of exercise, and concomitant elevations in mean skin temperature that accompanied reduced convective heat loss when the fan speed was reduced.

INSERT FIGURES 1 AND 2 ABOUT HERE

Sweat production doubled from Trials A to B (0.20 [SD 0.19] versus 0.46 $L.h^{-1}$ [SD 0.21]; *P*<0.05), but was not excessive. In the control state (Trial A), all of this sweat evaporated. However, when protective clothing was worn (Trial B), only about 60% evaporated (0.27 $L.h^{-1}$ [SD 0.15]), leaving the balance trapped within the ensemble (0.19 $L.h^{-1}$ [SD 0.13]). Each of the psychophysical indices was significantly elevated from Trial A to B (Table 2; *P*<0.05). Thus, although central thermal strain was minimal and very similar, subjects reported feeling hotter, more sweaty and less comfortable when wearing the motorcycle protective clothing.

INSERT TABLE 2 ABOUT HERE

3.3 The impact of thermal loading upon protected motorcyclists

Physiological strain within Trials B-D reflected changes in the ambient conditions and the permissible dry and evaporative heat losses to the chamber air. Looking first at the skin temperature responses, one finds that the negative skin-to-air temperature gradient observed within Trial B (indicating heat loss) was sustained in every individual, albeit reduced, with increments in ambient temperature: Trial B -8.8°C (SD 0.6), Trial C -5.2°C (SD 0.5) and Trial D -1.4°C (SD 0.4; *P*<0.05 for all comparisons). This apparently paradoxical outcome resulted from the mean skin temperatures shifting upwards and in an approximately parallel, but not equivalent, fashion (Figure 1B). Thus, dry heat losses were reduced, whilst evaporative cooling remained minimal under these insulating and almost encapsulating garments (McLellan *et al*., 2013). However, the transient elevations in mean skin temperature during each rest period were still evident, though dampened as air temperatures increased.

The consequence of reduced heat loss was an inexorable rise in deep-body temperature (Figure 1A). Indeed, in Trial D, during which the air temperature most closely approximated that of the deep tissues, auditory canal temperature climbed at an average rate of $0.02^{o}C.min^{-1}$ (SD 0.005), and deviated significantly over time relative to each of the other trials (*P*<0.05). For two individuals known to be much less physically active than the rest of the sample (body mass 82.0 and 121.2 kg), higher baseline auditory canal temperatures were evident (36.5° and 36.9°C) and both experienced moderate hyperthermia (>38.5°C). Nevertheless, on average, this population sample was predicted to reach that threshold within 105 min (range 49.8-127.2; SD 20.6): auditory canal temperature = 36.5 + 0.02 * time (min: r^2 0.97). Thus, for the most extreme trial, the first part of the working hypothesis was not accepted. Moreover, if this elevation remained unchecked, one would predict that a profoundly hyperthermic state (>40°C; Taylor *et al.*, 2008) would obtain within 180 min (range 95.5-225.6; SD 33.0). In fact, whilst all subjects completed Trials B and C, one individual (S12: age 22 y, body mass 121.2 kg) terminated Trial D in less than half of the group mean prediction time (73 min) due to symptoms of nausea and syncope, as well as attaining the auditory canal temperature withdrawal criterion (39.5°C). His auditory canal temperature climbed at 0.03°C.min^{-1}, potentially resulting in profound hyperthermia (>40°C) at 95.5 min, or in just over half the average predicted time for the entire sample. Two other individuals reported some light headedness and mild headaches (age 23 and 21 y, body mass 65.0 and 82.0 kg), but were willing and easily able to continue. For Trials A and B, profound thermal strain would not have been reached, regardless of how long the simulation continued, while for Trial C, it would have taken >10 h to be achieved (auditory canal temperature = 36.6 + 0.007 * time [min]; r^2 0.81).

Similarly, central cardiovascular strain rose progressively during Trial D (Figure 2), yielding a mean predicted time of 190 min (range 109.0-300.4; SD 59) to reach a heart rate of 180 beats.min^{-1} (heart rate = 87.3 + 0.5 * time [min]; r^2 0.92); the point of hypothetical cardiac insufficiency (Barcroft and Edholm, 1945; Taylor and Patterson, 2015). However, no individual reached that state under any of the experimental conditions, with the highest recorded heart rates from Trial D ranging from 105-165 beats.min^{-1}. Therefore, the second part of the working hypothesis could be accepted. Interestingly, these maxima were not necessarily age-dependent, as the lowest exercising heart rates for these fixed absolute work rates in Trial D were observed within the oldest individual (61 y: 105 beats.min^{-1}), whilst the highest was seen in the second youngest subject (22 y: 165 beats.min^{-1}), even though both participants had maximal heart rates in excess of 180 beats.min^{-1}. Instead, these outcomes are more likely to have reflected differences in habitual exercise behaviour.

Sweat secretion across these trials also revealed step-wise increments (Trial B 0.46 L.h^{-1} [SD 0.21], Trial C 0.74 L.h^{-1} [SD 0.21], Trial D 1.12 L.h^{-1} [SD 0.28]), with every between-trial difference being statistically significant (P<0.05). As the climatic states became more stressful, progressively more sweat was retained within the clothing; Trial B 41%, Trial C

53% and Trial D 60% (P<0.05 for all comparisons). In the protective motorcycle clothing, the undergarments gradually became more saturated. If one assumes that, beyond 60 min, all subjects had commenced sweating and that the skin was completely wet in Trials B-D, then the mean water-vapour pressure gradients between the skin and the air for these trials were conducive to an elevated evaporative heat loss: -3.0 (SD 0.2, Trial B), -3.4 (SD 0.1, Trial C) and -3.8 kPa (SD 0.1, Trial D; P<0.05 for all comparisons). Nevertheless, even though these vapour gradients were larger, a greater evaporation of sweat did not occur because the moisture permeability of the garments was low.

With the exception of Trial A, each of the psychophysical indices increased very gradually as time progressed, and in moving from Trial B through to Trial D, these data were progressively shifted upwards. Thus, when averaged across each trial, significant between-trial differences were observed for each index (Table 2; P<0.05 for all comparisons). Furthermore, at the conclusion of the most stressful simulation, participants reported, on average, being hot-very hot (thermal sensation: 10.8 [SD 1.0]) and being uncomfortable to very uncomfortable with the resulting body temperature (thermal discomfort: 3.5 [SD 0.8]). Moreover, they perceived the skin or clothing to be wet-very wet (wetness sensation: 10.6 [SD 0.8]) and found that level of wetness to range between uncomfortable and very uncomfortable (thermal discomfort: 3.4 [SD 1.0]).

4. DISCUSSION

The principal outcomes from this experiment were that, within air temperatures approximating the normothermic deep-body temperature (37^{o}C), motorcyclists similar to those used in this investigation would, on average, be likely to approach moderate hyperthermia (>38.5^{o}C) within 105 min. Both profound hyperthermia (>40.0^{o}C) and potentially debilitating central cardiovascular strain would ensue within 190 min when riding under these conditions within an urban setting. In more sedentary individuals, these thresholds would most likely be reached significantly earlier (Tipton *et al*., 2008; Taylor, 2014), and in some people (*e.g*., S12 from the current sample), in almost half the time. However, at air temperatures of 25^{o} and 30^{o}C, those outcomes would be unlikely to eventuate during recreational riding. What remains uncertain is whether or not the level of physiological strain encountered at 35^{o}C would have an adverse impact upon cognitive function, perhaps, for instance, through reducing cerebral blood flow (Wilson *et al*., 2006), which may, in turn, elevate the risk of an accident. This possibility forms the basis of research currently being undertaken. In addition, the possibility also exists that riders may be less able to maintain postural stability, and this too warrants further investigation.

Whilst some helmets do not impose a significant additional thermal load on the wearer, relative to non-protective headwear, during exercise of a similar intensity (Caldwell *et al.*, 2007; Taylor *et al.*, 2008), the impact of helmets *per se* on heat loss and thermal comfort (Brühwiler *et al.*, 2006), particularly from closed-face motorcycle helmets (Bogerd and Brühwiler, 2009; Bogerd *et al.*, 2011), is significant. However, that impact remained constant within this investigation, with every subject wearing the same, correctly sized helmet for each laboratory trial. Nevertheless, the necessary use of open-face helmets for this experiment, albeit with the visors down, would mean that heat loss would be greater than if closed-face helmets were used. Consequently, the current observations tend to under-represent the thermal strain imposed by the helmet.

Since the main thermal outcomes were based upon auditory canal temperature measurements, then it is first necessary to consider the validity of that index relative to other deep-body indices (see Taylor *et al.* [2014] for an extended discussion). It has long been recognised, although not always appreciated, that an insulated auditory canal temperature reliably tracks variations in deep-body temperature (Cooper *et al.*, 1964; Greenleaf and Castle, 1972; Edwards *et al.*, 1978; Hayward *et al.*, 1984; Cotter *et al.*, 1995; Taylor *et al.*, 2014), particularly within higher air temperatures, and certainly when the ears are further insulated by the wearing of a motorcycle helmet. This was perhaps most clearly illustrated by Todd *et al.* (2014) who sinusoidally varied heat production and deep-body temperature, finding the auditory canal index tracked oesophageal temperature, and therefore central blood temperature (Cooper *et al.*, 1964; Hayward *et al.*, 1984). Earlier work by the same group established the phase delay between these two indirect indices to be about 90 s (Russell, 1999). However, it has also been established that the auditory canal reveals a thermal bias towards the prevailing ambient conditions (Gibbons, 1967; Greenleaf and Castle, 1972; Morgans *et al.*, 1981), and it is slightly lower in normothermic states (Taylor *et al.*, 2014). Accordingly, one may conclude the current data faithfully tracked temperature changes within the blood perfusing the brain and driving thermoregulation, but perhaps with a slight offset.

When considering the two clothing states at 25°C, minimal strain differences were evident. Nevertheless, the vertical displacement of the mean skin temperatures (Figure 1B), which was seen in every condition, reflected two important interactions. Firstly, there was increased heat trapping within the protective jacket and trousers that was less evident when wearing jeans and t-shirts. This, of course, was predictable, since the protective ensembles chosen were poorly permeable to water vapour and had a high thermal insulation. Secondly, when the ambient temperature was modified, the thermal gradient necessary for heat dissipation was progressively reduced, and since metabolic heat production remained constant, then heat storage, and therefore deep-body temperature, must be elevated (Figure 1A). The fact that this temperature rise was not apparent at 25°C can be attributed to the dry heat loss, which was principally of a convective nature that approximated the rate of heat production.

At normal body temperatures, an increase in skin temperature will stimulate cutaneous vasodilatation (Caldwell *et al*., 2014), and thereby increase the delivery of central-body heat to the skin for dissipation. This also helps explain the significantly greater skin temperatures and the thermal gradient observed in Trial B. Therefore, this hotter skin was thermally advantageous, as it permitted heat loss to keep pace with heat production, even in the presence of heavy clothing insulation. While skin blood flows were not measured, this interpretation can be assumed on the basis of the central cardiac responses, which, in the absence of a significant central thermal change, resulted in the heart rates being elevated beyond that required for oxygen delivery to the working muscles (Figure 2). This increase was necessary to regulate mean arterial pressure in the face of a whole-body, cutaneous vascular engorgement (Fogarty *et al*., 2004; Taylor *et al*., 2008). When the air temperature was increased, further chronotropic changes were seen, and these could be assigned to four concurrent factors; sustained oxygen delivery, continued skin heating due to greater heat trapping (reduced dry heat loss), further cutaneous vasodilatation driven now by the rise in deep-body temperature and subserving thermoregulation (Werner *et al*., 2008), and a direct thermal (Q_{10}) effect upon the heart itself. Nevertheless, stable blood pressure regulation was not always achieved, and symptoms of syncope within three individuals in the hottest condition imply they were at the cusp of cardiovascular insufficiency (Barcroft and Edholm, 1945; Bass *et al*., 1955; Noakes, 2008; Taylor and Patterson, 2015).

From a practical perspective, previous psychophysical evidence that motorcyclists who wear the full protective ensemble in summer may become thermally stressed (de Rome *et al*., 2011a; Wishart, 2009; Zwolinska, 2013), has now been supported by physiological evidence. Indeed, one might expect such riders to experience significant, time-dependent thermal strain when riding in an urban environment during the heat of an Australian summer, or when air temperatures approach the normothermic deep-body temperature (37^{o}C). In some sedentary and less-healthy individuals, this will occur much more quickly, as will the corresponding rise in cardiovascular strain. Of course, the current experiment was designed to approximate near worst-case states, so riders opening the clothing ventilation ports will be slightly less stressed. Nonetheless, whilst the lower predicted temperature threshold (38.5^{o}C) is both conservative and arbitrary, as it is well tolerated in habitually active and healthy individuals, it does signify the presence of a significantly stressful thermal load, and this level of strain was observed in the two youngest and most sedentary participants (Trial D). The upper predicted threshold (40^{o}C) is routinely experienced by serious marathoner runners (Pugh *et al*., 1967; Maughan *et al*., 1985). However, it can have critical clinical implications in non-adapted, chronically sedentary, overweight and unhealthy individuals, and the time-dependent nature of these deep-body temperature increases indicate that profound hyperthermia may become inevitable in some people during extended summer motorcycling in urban conditions.

5. CONCLUSIONS

This experiment was designed to provide an evaluation of the physiological consequences of these impact-protective ensembles under close to worst-case conditions. The outcomes indicate that greater design attention is required to enhance dry and evaporative heat dissipation from motorcycle clothing intended for summer use in hotter climates. Such modifications must be undertaken without compromising injury protection. In addition, it remains to be determined whether or not the physiological strain observed at an air temperature of 35^{o}C would have an adverse impact upon cognitive function and accident risk, and this possibility is currently being investigated.

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TABLES:

Table 1: Overview of the experimental conditions. Trials A and B differed in clothing configuration but not air temperature, whilst Trials B, C and D differed only in air temperature.

Air temperature	Trial A	Trial B	Trial C	Trial D
25°C	Control			
25°C		Fully protected		
30°C			Fully protected	
35°C				Fully protected

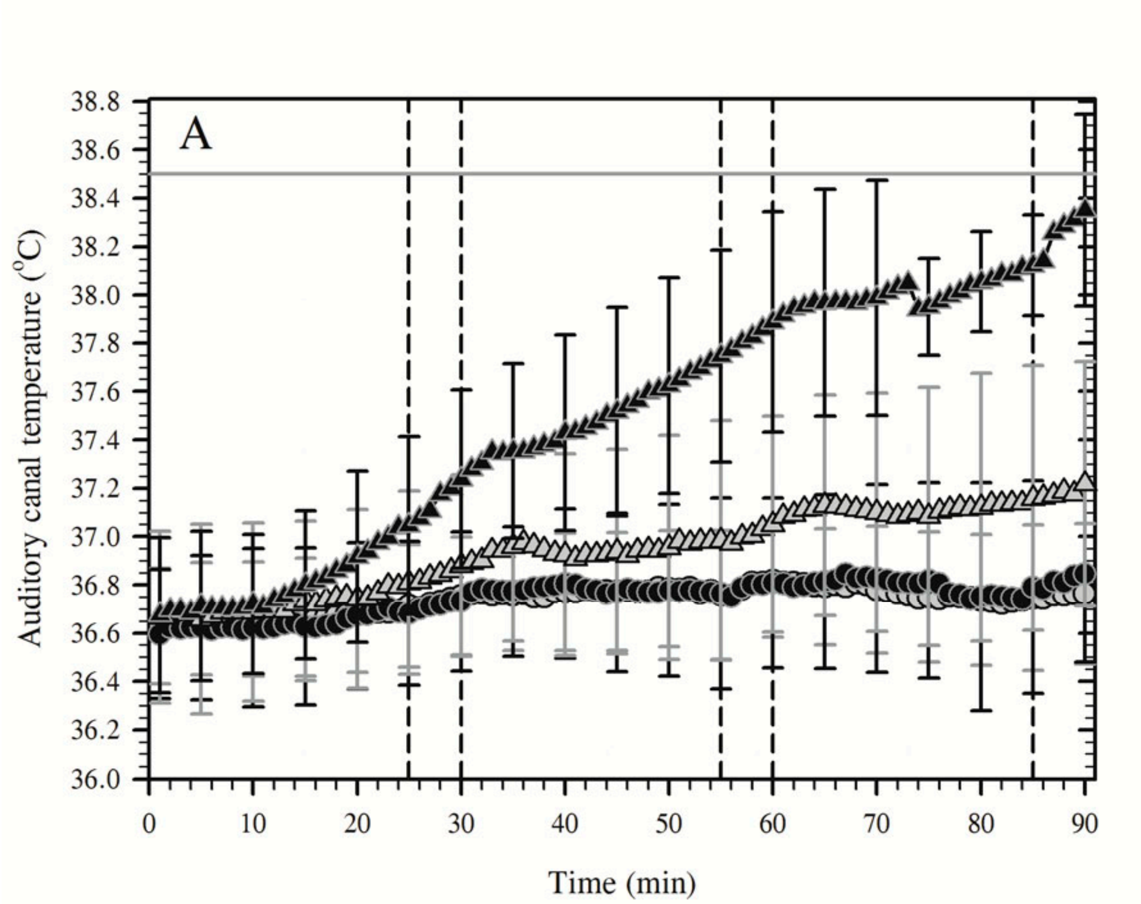
Table 2: Psychophysical strain indices recorded during steady-state cycling (30 W) in a temperate climate with two levels of motorcycle protective clothing (Trial A [control]: street clothes, helmet, boots and gloves; Trial B: motorcycle protective clothing), and within three different thermal states when wearing the protective ensemble (Trials B, C and D). Data were collected twice during each of the three exercise phases (six data points) and once during each rest period (three points), and are reported below as trial means with standard deviations in parenthesis (N=12). Significant differences between trials are indicated by the superscript symbols (P<0.05): * (Trial A versus Trial B), † (B versus C), ‡ (B versus D) and § (C versus D).

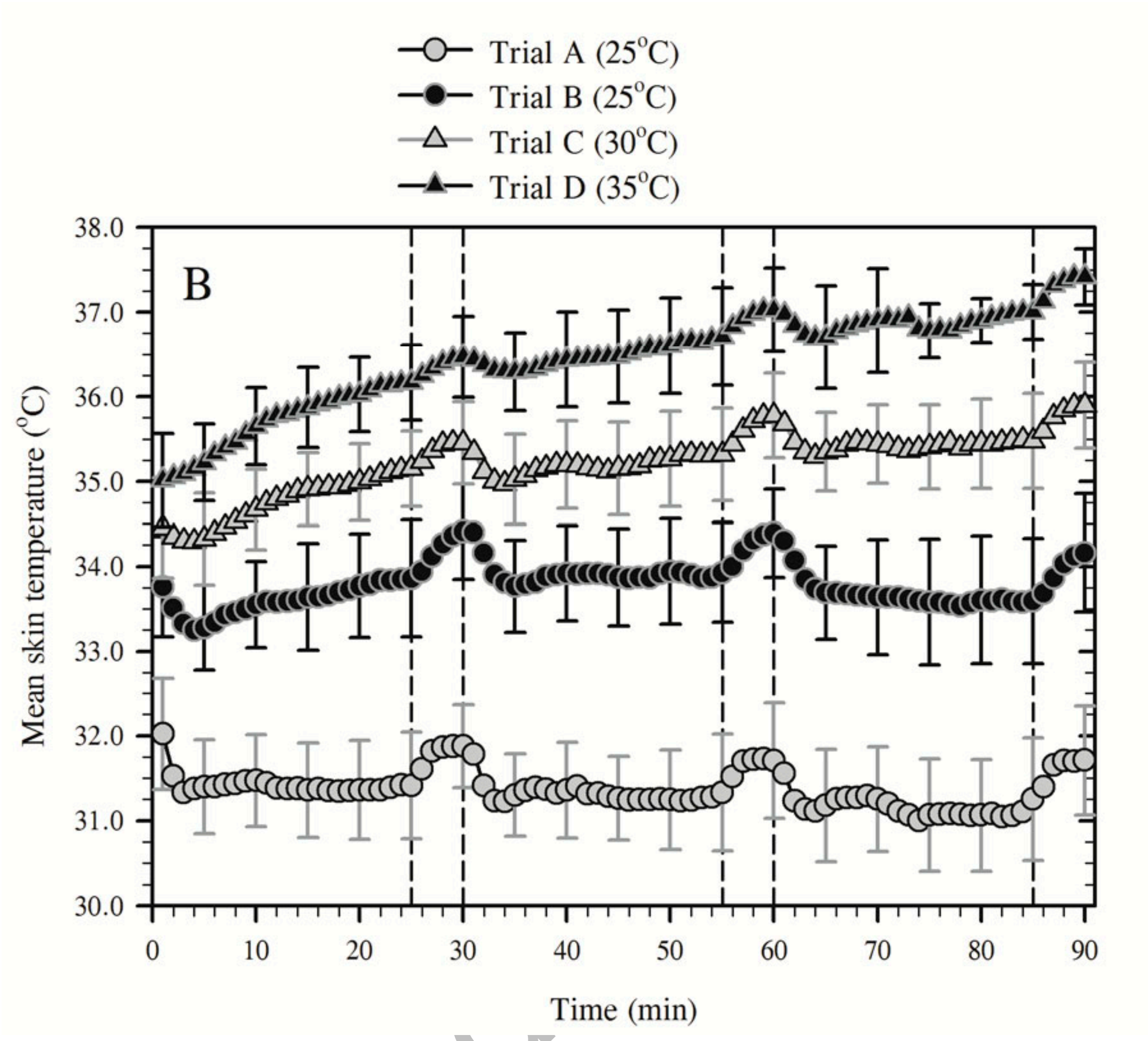
Psychophysical index	**Trial A** (25°C)	**Trial B** (25°C)	**Trial C** (30°C)	**Trial D** (35°C)
Thermal sensation (scale 1-13)	7.0 (0.7)	8.5 (0.6)*	9.3 (0.7)†	10.0 (0.8)‡,§
Thermal discomfort (scale 1-5)	1.1 (0.1)	1.7 (0.4)*	2.1 (0.5)†	2.8 (0.6)‡,§
Wetness sensation (scale 1-13)	6.1 (1.2)	8.3 (0.7)*	9.2 (0.8)†	9.7 (0.9)‡,§
Wetness discomfort (scale 1-5)	1.0 (0.1)	1.7 (0.4)*	1.9 (0.5)	2.5 (0.7)‡,§

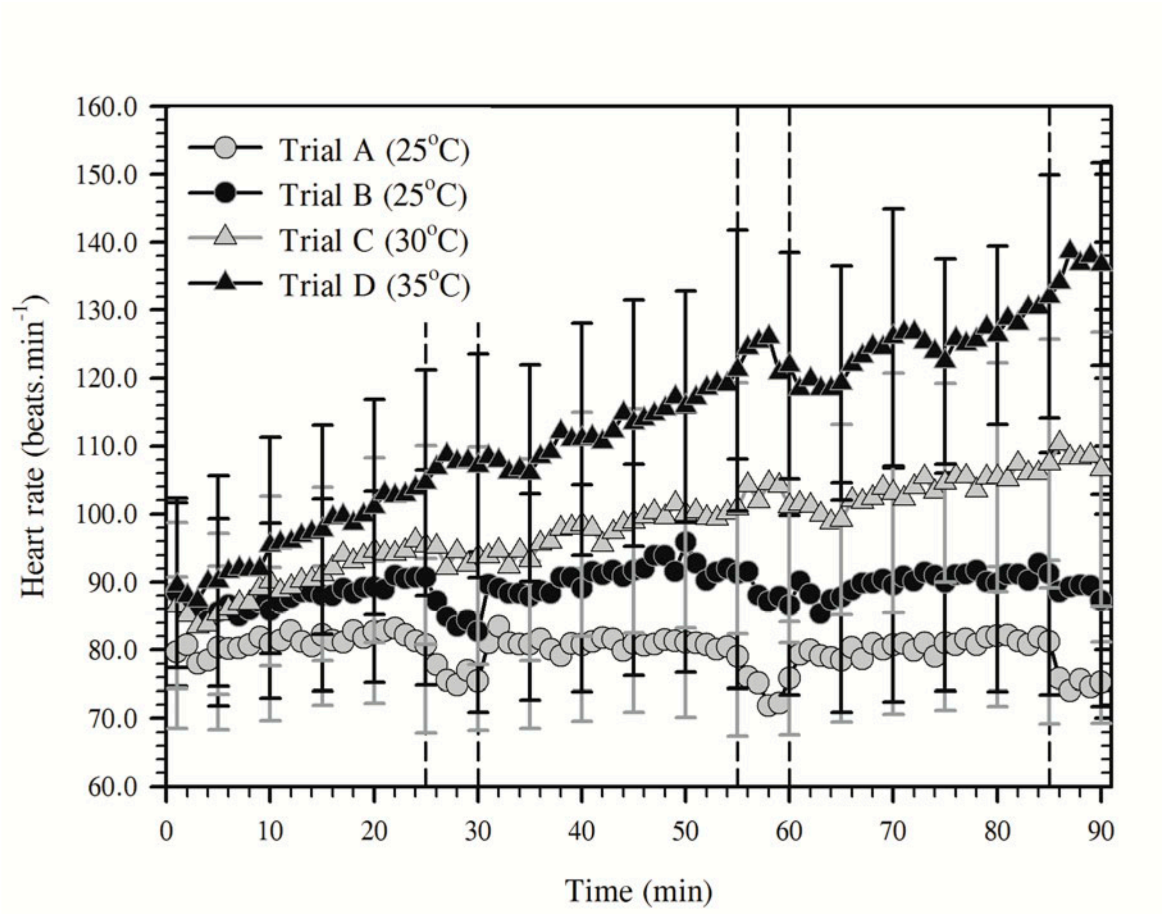
FIGURE CAPTIONS:

Figure 1: Deep-body (auditory canal: Figure 1A) and mean skin temperature (Figure 1B) responses during steady-state cycling (30 W) with two levels of motorcycle protective clothing in a temperate climate (25°C; Trial A [control]: street clothes, helmet, boots and gloves; Trial B: motorcycle protective clothing), and when wearing the same protective ensemble within three thermal states (Trials B [25°C], C [30°C] and D [35°C]). All trials started with 5 min rest, with data graphed from the commencement of exercise. Data are means with standard deviations at 5-min intervals (*N*=12). The grey horizontal line defines a deep-body temperature threshold of 38.5°C (moderate hyperthermia). Dashed vertical lines define the 5-min rest periods that followed each of three, 25-min exercise blocks. One subject terminated exercise in Trial D at 73 min due to impending syncope and attaining the deep-body temperature withdrawal criterion (39.5°C), but he then completed the final rest period.

Figure 2: Cardiovascular strain (heart rate) observed during steady-state cycling (30 W) in a temperate climate (25°C) with two levels of motorcycle protective clothing (Trial A [control]: street clothes, helmet, boots and gloves [partial protection]; Trial B: motorcycle protective clothing), and within three thermal states when wearing the protective ensemble (Trials B [25°C], C [30°C] and D [35°C]). Data are means with standard deviations at 5-min intervals (*N*=12), and are plotted from the commencement of exercise. Dashed vertical lines define the 5-min rest periods that followed each exercise block.


A
Auditory canal temperature (°C)
38.8
38.6
38.4
38.2
38.0
37.8
37.6
37.4
37.2
37.0
36.8
36.6
36.4
36.2
36.0
0
10
20
30
40
50
60
70
80
90
Time (min)


Trial A (25°C)
Trial B (25°C)
Trial C (30°C)
Trial D (35°C)
B
Mean skin temperature (°C)
Time (min)
38.0
37.0
36.0
35.0
34.0
33.0
32.0
31.0
30.0
0
10
20
30
40
50
60
70
80
90


Trial A (25°C)
Trial B (25°C)
Trial C (30°C)
Trial D (35°C)
Heart rate (beats.min-1)
Time (min)
160.0
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
0
10
20
30
40
50
60
70
80
90