

Characterisation of Physiological Performance Measures in Arid and Humid Military Operational Environments

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Research

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Abstract

Background

Military personnel often deploy into hot environments that impose substantial strain on physical and cognitive performance. Hot environments can present as arid or humid and occur in different terrains, requiring different operational approaches. The aim of this study was to characterise the physiological, cognitive and perceptual strain experienced by military personnel during typical operations in arid and humid environments.

Methods

Nine pack-fit military personnel participated in two heat-stress tests to exhaustion, one in an arid environment (44°C, 21% humidity) and the other in a humid environment (33°C, 78% humidity). Participants walked at 5 km.h⁻¹ while physiological, cognitive and perceptual measures were recorded. Tests were terminated volitionally, or by excessive core temperature or heart rate.

Results

The operational environments induced similar physiological stress, resulting in no difference in time to exhaustion ($p = .155$). The humid environment saw a greater elevation in core temperature (+0.3°C, $p < .001$) and heart rate (+5 b.min⁻¹, $p < .001$). Skin temperature was greater in the arid environment (+0.4, $p < .001$) as was sweat evaporation (+0.3 L.h⁻¹, $p = .045$). Baseline performance predictors only provided moderate predictions of performance, whereas changes in perceptual measures provided the best performance predictors during the exercise, specifically perceptions relating to thermal sensation ($\beta = -.65$ --.80) and sleepiness ($\beta = -.79$ --.87). While no differences in cognitive performance were observed, greater cognitive stress was reported by participants over time, regardless of environment (all $p < .011$).

Conclusions

The humid operational environment elicited a greater thermal strain that may threaten safety, and impair performance, to a greater degree than the arid environment. Perceptual measures of thermal sensation and sleepiness were the best predictors of test termination and could likely be used to monitor thermal tolerance in field settings.

Introduction

Military personnel deployed abroad are often exposed to different environments from that which they typically live and train in (Parsons, Stacey et al. 2019). Regions with tropical climates are predisposed to conflict as weather patterns that affect food production can lead to civil unrest, which in extreme cases leads to conflict and international military intervention (Humphreys 2005, Koubi 2019). Climate change is already exacerbating resource competition and conflict and will worsen. Therefore, military operations in

extreme environments are expected to rise (CNA 2007, Reuveny 2007, Smith 2007, Brzoska and Fröhlich 2016).

Hot environments pose a unique challenge to military operations as military-specific factors, such as carrying heavy loads and wearing protective gear, increase endogenous heat production and restrict heat loss (Taylor 2015), thereby impairing work capacity and predisposing military personnel to exertional heat illness (Casa, Armstrong et al. 2012). Exertional heat illness can present as heat syncope, heat exhaustion, and in extreme cases heat stroke, which can cause organ damage, and in some cases death (Carter, Chevront et al. 2005, Howe and Boden 2007, Goforth and Kazman 2015). Therefore, understanding the effects and mitigation of heat stress is important for military performance and safety in such environments.

Hot environments are typically characterised by either very high ambient temperatures and low humidity (i.e., arid), or high ambient temperatures and high humidity. Arid conditions are typical of desert environments and have been encountered recently by numerous international militaries in Afghanistan and the Middle East (Armed Forces Health Surveillance Branch 2019). Humid environments are often found in jungle environments, and have been encountered in tropical regions of Asia (Forster 1951, Haisman 1972). Heat stress differs between these environments, with the high ambient temperature in arid environments causing heat gain via sensible exchanges (Nadel 1979), while the vapour pressure in humid environments minimises sweat evaporation (Gonzalez, Pandolf et al. 1974, Akerman, Tipton et al. 2016). Given that evaporative heat loss is the main avenue for heat loss during moderate and heavy physical activity in humans, a greater thermal challenge is likely to occur in humid environments (Bergeron, Bahr et al. 2012, Maughan, Otani et al. 2012).

In military contexts the environmental characteristics and terrain influence the carried loads and protective clothing requirements of each soldier (Larsen, Netto et al. 2011, Eddy, Hasselquist et al. 2015), which may inadvertently augment the effects of hot environments (McLellan 2001, Boffey, Harat et al. 2018). For example, arid environments consist primarily of open areas where air support is more often available, and soldiers often move alongside vehicles. Consequently, the carried pack is relatively light, but as open conflict is more likely, more body armour is worn, further restricting heat loss from the torso (Johnson, Knapik et al. 1995). Conversely, a humid jungle environment often requires self-sufficiency, requiring a larger pack. However, as camouflage and stealth play a greater role, less body armour may be worn.

Given the environmental differences in the presentation of heat and the expected mission objectives dictating a unique gear loadout it is likely that the environments place different physiological strain on soldiers. Understanding these differences allows training plans prior to deployment to be tailored for each environment. Additionally, identification of physiological variables that influence or predict subsequent performance in the heat is important to help inform safety outcomes and assist both deployment selection and real-time monitoring of military personnel in the field. Therefore, the aims of the current study were two-fold. Firstly to determine physiological responses to military activity in arid and humid

environments. And secondly, to determine factors that may predict performance both prior to, and during, exercise in arid and humid environments.

Methods

Experimental Design and Overview

A randomised crossover design was used, with 9 participants completing two heatstress tests (HSTs); one HST in a humid environment (33°C, 75% relative humidity (RH) (27 g.m⁻³ absolute humidity)) and the other in an arid environment (46°C, 10% RH (7 g.m⁻³ absolute humidity)). Temperatures were matched on wet-bulb globe temperature (~ 30°C WBGT). During each HST several physiological, perceptual, and cognitive assessments were conducted (Fig. 1). Each HST was conducted at least one week apart. University (AUTEC: 17/420) and New Zealand Defence Force (6755/1) ethical approval was obtained, and informed consent obtained in writing from all participants as per the *Declaration of Helsinki*.

Participants

Nine packfit military personnel (8 males, 1 female) volunteered to participate in the study (age 32.6 ± 9.4 y, body mass 81.1 ± 10.0 kg, 2.4 km run time 9:40 ± 1:11 min:s, estimated $\dot{V}O_2$ 54.2 ± 6.1 mL.kg⁻¹.min⁻¹).

HeatStress Tests

Heatstress tests were conducted at the same time of the day for each participant. Participants were asked to avoid strenuous activity for the 24 h preceding each HST and were asked to record their food intake so that it could be replicated for the subsequent trial. Each HST was carried out in an environmental chamber (Design Environmental, Simultech Australia, Australia), beginning with 10 min of seated rest, followed by walking on a treadmill (Platinum Club Series, Life Fitness, Illinois, USA) at a fixed speed of 5 km.h⁻¹ for 2 h or until termination criteria were met. Termination criteria were voluntary termination or ethical end points being reached for core temperature (> 39.3°C) (Aoyagi, McLellan et al. 1995) or heart rate (> 95% age-predicted maximum for 1 min) (Tanaka, Monahan et al. 2001). Time to exhaustion (TTE) was taken as the time at test termination. Participants were dressed according to the environment they would be operating in. For the arid environment participants wore body armour (~ 10 kg), a small backpack (~ 15 kg), helmet, and hiking shoes (total ensemble 31.1 ± 2.3 kg) (Fig. 2). For the humid environment participants wore load-carrying webbing (~ 8 kg), a large backpack (25 kg), a jungle hat, and jungle boots (total ensemble 36.4 ± 2.1 kg) (Fig. 2). In both environments participants also carried a rifle (~ 3 kg, included in total ensemble weights) and wore military uniform comprised of long-sleeved shirt and trousers. Fluid intake was allowed *ad libitum* up to a maximum of 2 L.h⁻¹, as per military rations, and was recorded.

Baseline measures

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Prior to the start of each trial, a resting urine and a blood sample were obtained from each participant. Urine was used to assess hydration status from urine specific gravity (USG) (Atago, Japan). Blood was obtained by venepuncture of an antecubital vein, without stasis, into a 6 mL K₂EDTA vacutainer (Becton Dickinson and Co, USA). Vacutainers were then centrifuged (1500g for 15 min at 4°C) and the separated plasma was stored at -80°C until heat-shock protein analysis. Body fat was assessed via ultrasound (12L, Vivid S5, GE Healthcare, Chicago, IL) of the abdomen, 2 cm lateral to the umbilicus (Mike Marfell-Jones and Lindsay 2006, Leahy, Toomey et al. 2012), given that subcutaneous adipose tissue thickness at the abdomen has been shown to correlate strongly with body fat measured by DEXA (Leahy, Toomey et al. 2012, Wagner 2013). Participants were weighed both semi-nude and fully dressed (i.e. all protective equipment on), pre- and post- HSTs, for calculation of wholebody sweat rate ($(\text{semi-nude weight change} + \text{fluid consumption}) \div \text{walking time}$) (Buono, Martha et al. 2009) and evaporated sweat rate ($(\text{semi-nude weight change} - \text{fully dressed weight change}) \div \text{walking time}$) (Amos, Hansen et al. 2000).

Continuous measures

Core body temperature was recorded rectally, using a flexible thermistor (Hinco Instruments, Australia) self-inserted ~ 10 cm beyond the anal sphincter. Skin temperature was measured on the righthand side of the body at the chest, bicep, thigh, and calf using skin temperature probes. Rectal and skin temperature were logged at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). In preparation for analysis, rectal and skin temperature readings were filtered due to noise caused by connections with the logger and occasional skin temperature probes losing contact with the skin due to the humid microenvironment. A filter was applied to remove readings that changed by more than $0.1^{\circ}\text{C}\cdot\text{s}^{-1}$. Then a low-pass Butterworth filter of 0.02 Hz was applied to the data. Missing data were filled with linear interpolation.

Mean skin temperature was calculated using the following formula (Ramanathan 1964):

$$T_{\text{Sk}} = 0.3T_{\text{Chest}} + 0.3T_{\text{Bicep}} + 0.2T_{\text{Thigh}} + 0.2T_{\text{Calf}}$$

If a thermistor became askew or off the skin, the equation was modified to proportionally compensate the weights of the three remaining sensors to maintain the summation of coefficients to 1.0, as has been done previously (Ashworth, Cotter et al., 2021).

Cardiac frequency was measured from ventricular depolarisation using a heart rate monitor (Polar RS800CX, Kempele, Finland), with values recorded every 5 min.

The slope of each continuous measure was calculated by the change from walking onset to exercise termination divided by walking time.

Periodic measures

Several measures were taken periodically throughout each HST. Perceptual measures were taken every 15 min, involving ratings of perceived exertion (RPE) (15point scale ranging 620 arbitrary units (AU)), thermal Loading [MathJax]/jax/output/CommonHTML/fonts/TeX/fontdata.js (5 +5 AU) and sleepiness (19 AU). Respiratory

gas analysis was conducted for 4 min every 15 min with participants breathing through a mouthpiece connected to a calibrated, automated system (Trueone 2400, Parvo Medics, Utah, USA). Change scores for these measures were taken as the difference between the first and last measurement of the variable within each participant within each session. Due to the greater carried load, walking in the humid condition was predicted to incur a 6% higher metabolic rate (and therefore also rate of heat production), based on published calculations (Pandolf, Givoni et al. 1977).

Cognitive Testing

A series of cognitive assessments were completed during each HST. Each battery lasted ~ 10 min and commenced at 10, 40, 70 and 100 min, unless test termination occurred prior. Simple reaction time was assessed using an electronic tablet (Nova 2 Lite, Huawei, Shenzhen) application (Reaction Time Tests for Science, Andrew Novak, 2016), which required participants to respond to a red circle appearing on a screen. Discrimination reaction time was assessed in a similar manner, with participants again responding to a red circle, but also avoiding responding to blue and black circles that appeared. A serial arithmetic task was used to assess cognitive throughput (Kase 2009) to determine information processing speed. This required subtracting either 7 or 9 from a 4digit number as many times as possible within one minute. A digit span task was used to assess working memory (Hocking, Silberstein et al. 2001). Participants were required to memorise a series of numbers read out to them, and then repeat them back, but in the reverse order. The test began with 3 digits being read out and increased by 1 digit after correctly recalling numbers twice at a given level, with the test ending once an incorrect sequence was repeated twice at the same level. Due to a lack of familiarisation, the first test for all non-reaction time cognitive tasks was removed from analysis. Following completion of this cognitive testing battery a NASA task-load index (TLX) was given to participants to indicate how they perceived the tasks to be, specifically in relation to mental, temporal and physical demands, as well as performance, effort and frustration (21-point scale).

Furthermore, a declarative memory task was also conducted using a memory map. The task involved memorising a simplified, fictional urban town plan, regarding a predefined route, the roads travelled along, landmarks and directions. The task was presented to participants at 25 and 85 min for 2 min, alongside a list of predetermined questions they would be required to answer. Following removal of the memory map participants were required to retain the information for ~ 30 min. At 55 and 115 min the predetermined questions were read aloud, and participants answered orally.

Blood Analysis

Thawed plasma samples were analysed for extracellular heat-shock protein 70 (HSP70) using a commercially available HSP70 High Sensitivity Enzyme-Linked Immunosorbent Assay (ELISA) kit (ab133061, Abcam, Cambridge, UK). The kit was run according to the manufacturer's instructions, and for all incubations the plate was covered and incubated on a gentle plater shaker (200–300 rPm) at room temperature (22°C). In brief, 100 µL of HSP70 standards and plasma samples (1:4 dilution) were added

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washed, and 100 µL of HSP70 antibody was

added and incubated for 1 hour. The plate was washed again, and 100 μL HSP70 conjugate was added and incubated for 1 hour. Following the final plate washing, 100 μL of TMB substrate was applied and the plate was incubated in the dark for 30 minutes. Subsequently, 100 μL of stop solution was added and the absorbance of individual samples were immediately determined spectrophotometrically at 450 nm on an automated absorbance plate reader (Multiskan Go, Thermo Fisher Scientific, Massachusetts, USA). The intra assay coefficient of variation for HSP70 was 4.9%.

Data Analysis

Data analysis was conducted in two phases: the first compared the change in physiological variables over time between the two environments, while the second involved a linear regression for each variable and performance in each environment. All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria).

To compare variables between environments, linear mixed models were fitted for each variable. Environment, time, and order (whether the arid or humid heat-stress test was conducted first) were used as fixed effects, with participant as the random effect. The model-generated estimated means are reported, with either standard deviation or 95% confidence intervals and p-values where appropriate. The alpha level was 0.05. For data with multiple time points, *post hoc* tests, with Bonferroni correction, were conducted using a time by environment interaction.

For regression analyses, predetermined variables of interest were selected and inputted into a linear regression model along with the performance outcome; walking time. Before running regression analysis each variable was checked for normality using a Shapiro-Wilk test, and homoscedasticity by plotting residuals. Data that did not meet normality were either log transformed or reciprocated prior to regression analysis, which overcame issues of non-normality. The `lm.beta` function, from the `QuantPsyc` package, was used for analysing each regression. Data are reported as both standardised (β) and unstandardised (B) regression coefficients, with a 95% confidence interval shown. The strengths of the standardised regressions were classified by the following correlation guidelines: very weak < 0.2 , weak $0.2-0.4$, moderate $0.4-0.6$, strong $0.6-0.8$, and very strong $0.8-1.0$ (Evans 1996).

Results

Environmental Differences

The actual temperature and humidity during the humid trials was $33.4 \pm 0.6^\circ\text{C}$ and $78 \pm 2\%$ RH (28 $\text{g}\cdot\text{m}^{-3}$ absolute humidity), while in the arid trials it was $44.3 \pm 0.5^\circ\text{C}$ and $21 \pm 2\%$ RH (13 $\text{g}\cdot\text{m}^{-3}$ absolute humidity), providing WBGTs of 31.1°C and 31.5°C , respectively. Baseline characteristics of body mass, body fat, USG and sleep quality were not different between environments (all $p > .262$).

No differences were observed in TTE between the two environments (Humid: 73.1 ± 12.8 min; Arid: $82.3 \pm$ environment, 5 (56%) were terminated due to rectal

temperature rising beyond the ethical threshold limit, one due to heart rate, and the remaining three were voluntarily terminated. In the arid environment HST, 4 (44%) were terminated due to rectal temperature, one due to heart rate, and the remaining four were voluntarily terminated.

Physiological Differences Between Environmental Conditions

While no significant differences were evident at rest or in the slope of rectal temperature between environments, during exercise rectal temperature was higher in the humid environment ($p < .001$; Table 1, Fig. 4). When extrapolated to determine how long it would be before rectal temperature reached 40°C , exercise in the humid environment was projected to last 95 min, compared to 120 min in the arid environment (Fig. 4). Conversely, the arid environment had a $\sim 0.5^{\circ}\text{C}$ higher skin temperature across the trial, despite no baseline differences, or differences in the rate of rise in skin temperature (Table 1). Heart rate in the humid environment was elevated by a time-averaged $\sim 5 \text{ b}\cdot\text{min}^{-1}$ in comparison to the arid environment, although other differences in heart rate were minimal (Table 1). Although overall sweat rate was not significantly different between conditions, evaporated sweat rate was $\sim 40\%$ greater in the arid environment (Table 1). No differences were observed in any measure of hydration (Table 1).

The $\dot{V}\text{O}_2$, $\dot{V}\text{CO}_2$ and \dot{V}_E all increased significantly throughout the trial (all $p < .001$). Between conditions, a 10% greater $\dot{V}\text{O}_2$ was present in the humid condition (Humid: $19.8 \pm 2.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; Arid: $18.0 \pm 2.2 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$; $p < .001$), which was close to the 6% predicted, and was supported higher \dot{V}_E (Humid: $47.0 \pm 12.1 \text{ L}\cdot\text{min}^{-1}$; Arid: $42.6 \pm 9.8 \text{ L}\cdot\text{min}^{-1}$; $p < .001$) and $\dot{V}\text{CO}_2$ (Humid: $1.40 \pm 0.21 \text{ L}\cdot\text{min}^{-1}$; Arid: $1.28 \pm 0.18 \text{ L}\cdot\text{min}^{-1}$; $p < .001$). Estimated substrate partitioning was comparable between conditions, based on respiratory exchange ratio (Humid: 0.88 ± 0.04 ; Arid: 0.88 ± 0.05 ; $p = .848$), and showed a trend for faster oxidation of carbohydrate in humid conditions (Humid: $1.2 \pm 0.3 \text{ g}\cdot\text{min}^{-1}$; Arid: $1.1 \pm 0.4 \text{ g}\cdot\text{min}^{-1}$; $p = .063$).

Perceptual Differences

All perceptions worsened throughout each condition (all $p < .001$). RPE was slightly but significantly elevated in the humid environment compared to the arid environment (Humid: 12.9 ± 2.6 ; Arid: 12.4 ± 2.8 ; $p = .040$). However, there were no differences between environments for thermal discomfort, thermal sensation, sleepiness or feeling state (all $p > .186$).

Cognitive Differences

No differences in cognitive performance existed between environments (all $p > .220$) or over time (all $p > .075$). Similarly, cognitive perception was not different between the environments in the task-load index (all $p > .075$), although increases in mental, physical, and temporal demand, as well as effort and frustration all occurred over time in both environments (all $p < .011$) (Fig. 5).

Regression

Both standardised and unstandardised regression coefficients between individual measures and walking TTE are presented in Table 2. Baseline measures were generally poor/weak predictors of TTE, although lower body fat in the arid environment and high body mass in the humid environment both provided moderately strong predictions of performance (longer TTE; Table 2). The slope of skin temperature also had a moderately strong negative relationship with walking TTE in the arid environment but not in the humid environment. The change in heart rate during exercise was strongly associated with walking TTE in the humid environment (Fig. 6C). Sweat rate (Fig. 6A) had a moderate relationship with performance in the humid environment, whereas only a trivial association was observed in the arid environment (Table 2). The change in perceptual measures of thermal sensation and sleepiness (Fig. 6D) were strong or very strong predictors of performance in both conditions, although perceived effort had a much weaker relationship (Table 2).

Discussion

The first aim of this study was to compare the physiology of each environment, results showed the humid environment to be marginally more stressful, with higher core temperature, higher heart rate and a greater oxygen requirement. The understanding of these differences allows for specific preparation ahead of deployment, including heat acclimation, equipment design and mission planning. The second aim was to assess the strength of physiological variables at predicting performance in hot environments. To this end several factors were found in each environment that predicted performance, including factors unique to each environment.

Performance

Despite differences in environmental conditions, gear loadouts and physiological responses, there was no difference seen in performance between arid and humid environments (Fig. 3), with minimal differences in the reasons for test termination. Together these similarities indicate the overall thermal strain in both environments was similar, likely due to the comparable WBGT, originally developed to quantify heat stress (Yaglou and Minard 1957). However, the WBGT does not account for the difference in clothing and protective equipment worn by soldiers. It was expected that the larger and heavier pack carried in the humid environment would exacerbate endogenous heat production while also impairing evaporative heat loss and thereby cause earlier test termination (Dorman and Havenith 2009). However, it is possible that the combination of body armour and backpack in the arid environment may have comparatively restricted heat loss from the chest (Johnson, Knapik et al. 1995), helping to nullify the effects of a heavier pack in the humid condition.

Body Temperatures

Higher rectal temperatures were observed in the humid environment than the arid environment (Table 1, Fig. 4). While this is likely partially accounted for by the additional metabolic heat production caused by the heavier carried load (Dorman and Havenith 2009), there was also a reduced evaporated sweat rate, with the same absolute sweat rate, suggesting reduced evaporative heat loss. Despite no statistical difference in the rate of rise in rectal temperature, extrapolation of the data revealed that rectal temperature would reach 40°C 25 min faster in the humid environment (Fig. 4). While military personnel can likely still perform beyond this threshold safely (Ely, Ely et al. 2009, Lee, Nio et al. 2010, Veltmeijer, Eijsvogels et al. 2015), it represents a limit at which heat stroke is known to occur, and therefore safety guidelines suggest that exercise should be restrained beyond this threshold (Goforth and Kazman 2015, Smith, Jones et al. 2016). Indeed, reducing core temperature below 40°C rapidly after exercise drastically reduces the mortality risk (Casa, Armstrong et al. 2012). However, in real-world military contexts, heat stress is often not alleviated and rectal temperature continues to rise even after the cessation of exercise, placing soldiers in danger, even if exercise is stopped (Giesbrecht, Jamieson et al. 2007, Smith, Withnall et al. 2017). In the humid environment a 40°C rectal temperature would have been seen only 20 min after the average termination time, highlighting the imminent danger of exercise in humid environments. However, it should be noted that the 95 min mark where rectal temperature is calculated to reach 40°C in the humid condition falls outside of the 95% confidence interval (Table 1), suggesting internal cues can help reduce risk by terminating exercise in both environmental conditions. Therefore, when operating in these environments, particularly humid environments, continuous physiological monitoring of soldiers may be valuable to ensure activities are conducted safely (Tharion, Buller et al. 2013, Buller, Welles et al. 2017, Parsons, Stacey et al. 2019), as is understanding methods for rapidly cooling individuals (Carter, Rayson et al. 2007, Casa, Armstrong et al. 2012, Epstein, Druyan et al. 2012).

The strength of the relationships between rectal temperature and performance is strengthened by the ethical termination of trials when core temperature exceeded 39.3°C, although, as mentioned above, internal cues such as central fatigue likely also lead to test termination (Nybo and Nielsen 2001, Tucker, Rauch et al. 2004, Hargreaves 2008). The stronger relationship between rectal temperature slope and performance in the humid environment may also be explained by this, where 56% of heat-stress tests were terminated due to high core temperature, compared to only 44% in the arid environment. Nonetheless, this ethical limit was put in place as it was deemed unsafe for core temperature to rise any further, and is the point where physical activity should be restrained in the field, if possible (Taylor, Patterson et al. 1997, Goforth and Kazman 2015). High rates of rise in core temperature have previously been identified to increase hyperthermia risk and heat-illness symptoms (Armstrong, Johnson et al. 2010, Maughan, Otani et al. 2012), highlighting the desire for a reduced rate of rise in core temperature (Hunt, Billing et al. 2016). Therefore, to prioritise safety, core temperature should be monitored. Although less practical, the ability to monitor core temperature during exercise, either using a heat tolerance test prior to departure or real-time monitoring of soldiers in the field (Buller, Welles et al. 2017, Epstein, Shapiro et al. 2017), provides a much stronger predictor of performance (Table 2).

The arid environment induced a higher skin temperature (Table 1), likely through heat gain from the Loading [MathJax]/jax/output/CommonHTML/fonts/TeX/fontdata.js (Nadel 1979). Elevated skin temperature

impairs heat loss as it minimises the core-to-skin temperature gradient (Chou, Allen et al. 2018). However, as the humidity gradient is ~ 50% lower in the arid environment, evaporative heat loss is facilitated (Akerman, Tipton et al. 2016), explaining the lower rectal temperature despite a higher skin temperature. The higher skin temperature in the arid environment likely explains the stronger relationship with performance, which was of moderate strength, compared to only a weak relationship in the humid environment. Furthermore, skin temperature may directly influence the perceptual relationships with performance, which were among the strongest predictors of performance in both environments (Table 2), consistent with previous findings (Schlader, Perry et al. 2013, Flouris and Schlader 2015). Whether the higher skin temperature in the arid environment partially explains the stronger relationships between perceptual changes and performance in the arid environment, however, is uncertain as a lack of perceptual differences existed between environments (Table 1). Perceptions are produced by the brain integrating numerous physiological signals to generate behavioural responses to help cope with environmental stress (Morante and Brotherhood 2008, Schlader, Simmons et al. 2011, Fleming and James 2014, Periard, Racinais et al. 2014). Therefore, as a response to exercise becoming uncompensable, thermoregulatory behaviour leads to the termination of the test (Pimental, Cosimini et al. 1987, Cheung and McLellan 1998, Gonzalez-Alonso, Teller et al. 1999). Thereby having a lower skin temperature could delay the rate at which perceptual feelings worsen, allowing prolonged performance before voluntary termination, although there were only marginally more voluntary terminations in the arid environment. The absence of relationship between rating of perceived exertion and performance may highlight military mental toughness, hypothesised to place individuals in danger as they disregard internal cues to cease exercise (Howe and Boden 2007, Epstein, Druyan et al. 2012, Buller, Welles et al. 2017, Parsons, Stacey et al. 2019). If valid, overcoming these internal cues exacerbates the danger of these environments as continuing to exercise further elevates core temperature which can ultimately be fatal (Parsons, Stacey et al. 2019). Understanding that in these environments the accumulated heat gain from both endogenous and exogenous sources, and not simply exercise intensity alone, is the primary cause of fatigue and casualties, may help develop monitoring strategies (Macpherson 1962). The data in the current study found that directly addressing heat in perceptual monitoring, by enquiring of how hot or sleepy individuals are feeling, provides an indication of how much longer an individual can safely exercise for.

Cardiovascular

Cardiovascular differences were apparent between the two environments, with a higher heart rate during the heat-stress test in the humid environment (Table 1). Furthermore, cardiovascular variables were better predictors of performance in the humid environment, whereas aerobic fitness, which is often cardiovascular dependent, was a better predictor in the arid environment (Table 2). While aerobic fitness and heart rate were expected to have a similar relationship with performance, it is possible that in the humid environment the heavier carried load, and subsequent increase in cardiovascular demand, accounts for part of this discrepancy. Furthermore, fitter individuals are known to be able to tolerate a higher core temperature (Cheung and McLellan 1998), therefore the withdrawal of participants due to

having a high core temperature, which occurred more frequently in the humid environment, limits aerobic fitness influencing the time to exhaustion.

During exercise, elevations in cardiac output, facilitated by an increase in heart rate, are required to ensure both cutaneous and skeletal muscle circulations receive adequate blood supply (Gonzalez-Alonso and Calbet 2003, Cramer and Jay 2016). A larger underlying blood volume facilitates higher stroke volume and a more widespread distribution of blood, allowing heat loss while maintaining performance (Gonzalez-Alonso, Calbet et al. 1998, Taylor 2000). A greater blood volume may be more important in humid environments as sweat evaporation is restricted by high humidity (Maughan, Otani et al. 2012), thereby causing insensible fluid loss, where dehydration occurs without beneficial heat loss (Eichna 1943, King, Clanton et al. 2016, Taylor 2017). As central blood volume declines a greater stress is placed on the cardiovascular system (Gonzalez-Alonso, Calbet et al. 1998, Charkoudian 2016), limiting peripheral blood flow. As the perfusion of cutaneous circulations is reduced, heat transfer becomes limited, thereby causing increases in core temperature (Nadel, Fortney et al. 1980, Gonzalez-Alonso, Calbet et al. 1998, Kenefick, Chevront et al. 2010, Casa, Armstrong et al. 2012). Alternatively, a greater reliance may be placed on convective heat loss mechanisms, thereby requiring an increased cardiac output to elevate cutaneous blood flow (Kenney, Stanhewicz et al. 2014, Chou, Allen et al. 2018, Tebeck, Buckley et al. 2019), shown by an elevated heart rate in the humid environment (Table 1). The importance of limiting the cardiovascular demand is further illustrated by the strong ability of the change in heart rate to predict performance (Fig. 6C). When the cardiovascular system can no longer increase cardiac output to support perfusion of both skeletal muscle and cutaneous circulations blood flow is reduced, first to cutaneous, and then to skeletal muscle circulations (Gonzalez-Alonso and Calbet 2003, Gonzalez-Alonso, Crandall et al. 2008, Kenney, Stanhewicz et al. 2014). Without the muscular blood flow to sustain oxygen requirements for exercising muscle intensity is reduced (Tucker, Rauch et al. 2004), which in this experiment meant test termination. Heart rate monitoring is one of the simplest real-time monitoring methods available (Eggenberger, MacRae et al. 2018), and by assessing the rate of rise in heart rate it allows evasive steps to be taken to prevent exhaustive limits being reached by the individual.

Sweat Rate

No differences in sweat rate were seen between the environments, although evaporated sweat was significantly reduced in the humid environment (Table 1), likely due to the vapour pressure gradient being reduced by the humidity, preventing sweat evaporation (Maughan, Otani et al. 2012). As sweat is unable to evaporate, core temperature rises (Sawka, Wenger et al. 1993, McLellan and Aoyagi 1996), underlying the elevated rectal temperature in the humid condition (Fig. 4), whereas the evaporation of sweat in the arid environment would have helped maintain a lower rectal temperature (Fig. 4) (McLellan, Meunier et al. 1992). Sweat rate changes were closely linked to performance in both environments (Table 2). In the humid environment sweat rate strongly predicted performance (Fig. 6A), while evaporated sweat rate had a weak negative relationship. This suggests sweating facilitates performance, but only if the sweat evaporates. If sweat does not evaporate then heat is not lost from the body, and water loss merely adds

evaporation of sweat, the arid environment had only a moderately strong relationship between sweat rate and performance, (Table 2). As sweat could more readily evaporate, it is likely that this was not a limiting factor, and therefore other variables were more directly linked to performance.

Metabolic

The metabolic strain during the heat stress test was greater in the humid environment, illustrated by larger oxygen uptake and carbon dioxide production. The greater pack weight in the humid environment likely accounts for some of this difference as more muscular work is required to carry the pack (Knapik 1997). Indeed, the relatively greater $\dot{V}O_2$ in the humid environments occurred close to the expected relative value based on load carrying energy expenditure predictions (Pandolf, Givoni et al. 1977). Furthermore, lighter individuals are known to have a greater relative metabolic demand when carrying heavy absolute loads (Bilzon, Allsopp et al. 2001). Therefore, the increased oxygen requirement from the additional relative workload likely creates a strong relationship between body mass and performance, as this would also add to metabolic heat production (Table 2).

No relationship was found between HSP70 and performance (Table 2), although most participants showed minimal plasma concentrations that were often below the detection limit of the ELISA assay. Low serum concentrations of HSP70 are not uncommon, especially at rest (Njemini et al. 2011, Walsh et al. 2001), with some studies reporting wide variations in concentrations between individuals (Lee et al. 2015). It is acknowledged that the practicality of measuring HSP70 in a real-world military context is limited due to the cost, invasiveness and laboratory expertise required to obtain results. Therefore, based on these constraints, the large variability, and our non-significant findings, HSP70 does not appear to be a worthwhile or accessible measure for predicting soldier performance in the heat.

Cognitive

Minimal changes in cognitive performance existed both within and between environments. Many of the tasks used in the cognitive assessments were relatively simple, which have been shown to be largely unaffected by heat (Hancock and Vasmatazidis 2003, Mazloumi, Golbabaie et al. 2014). However, research has shown load carriage (Caldwell, Engelen et al. 2011, Eddy, Hasselquist et al. 2015) and physical fatigue (Vrijlkotte, Roelands et al. 2016) to impair simple cognitive processes. Despite the self-reported mental demand of tasks increasing across the trial (Fig. 5), no differences in cognitive performance existed. It is possible participants felt more strained when doing the tasks, but could still allocate sufficient cognitive resources to the task to complete them accurately (Lambourne and Tomporowski 2010). In real-world military contexts, soldiers may experience greater thermal stress, physical fatigue and more complex tasks, which could impair cognition.

Conclusion

While physiological responses to military specific physical activity in humid and arid environments share

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ould be accounted for. Specifically, the expected

environmental parameters and gear loadout of the humid environment appeared to increase heat production, while also impairing cooling due to limited sweat evaporation resulting in increased core temperature and heart rate, which lead to impairments in soldier performance. While many physiological variables predicted performance, perceptual variables were the strongest predictors. The lack of relationship between the difficulty of exercise and performance suggests monitoring questions should focus on the heat, not the exercise, to ensure soldier safety and wellbeing. Understanding the dangers of heat and improving coping mechanisms and monitoring strategies will help minimise soldier casualties.

Abbreviations

AU
arbitrary units
HST
heat stress test
HSP
heat shock protein
RH
relative humidity
RPE
rating of perceived exertion
TTE
time to exhaustion
USG
urine specific gravity
WBGT
wet bulb globe temperature

Declarations

Ethics approval and consent to participate

Consent to publish was approved by both the Auckland University of Technology (17/420) and the New Zealand Defence Force (6755/1) Ethics Committees, and given by participants in writing prior to their participation.

Consent for publication

Consent to publish was provided by participants in writing, and by the New Zealand Defence Force

Availability of data and materials

Data and materials can be requested through the corresponding author

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Competing interests

N/A

Funding

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Authors' contributions

EA, JC and AK designed the experiment

EA and LK collected and analysed the data

EA drafted the manuscript

LK, JC and AK reviewed the manuscript

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Tables

Due to technical limitations, table 1 and 2 is only available as a download in the Supplemental Files section.

Figures

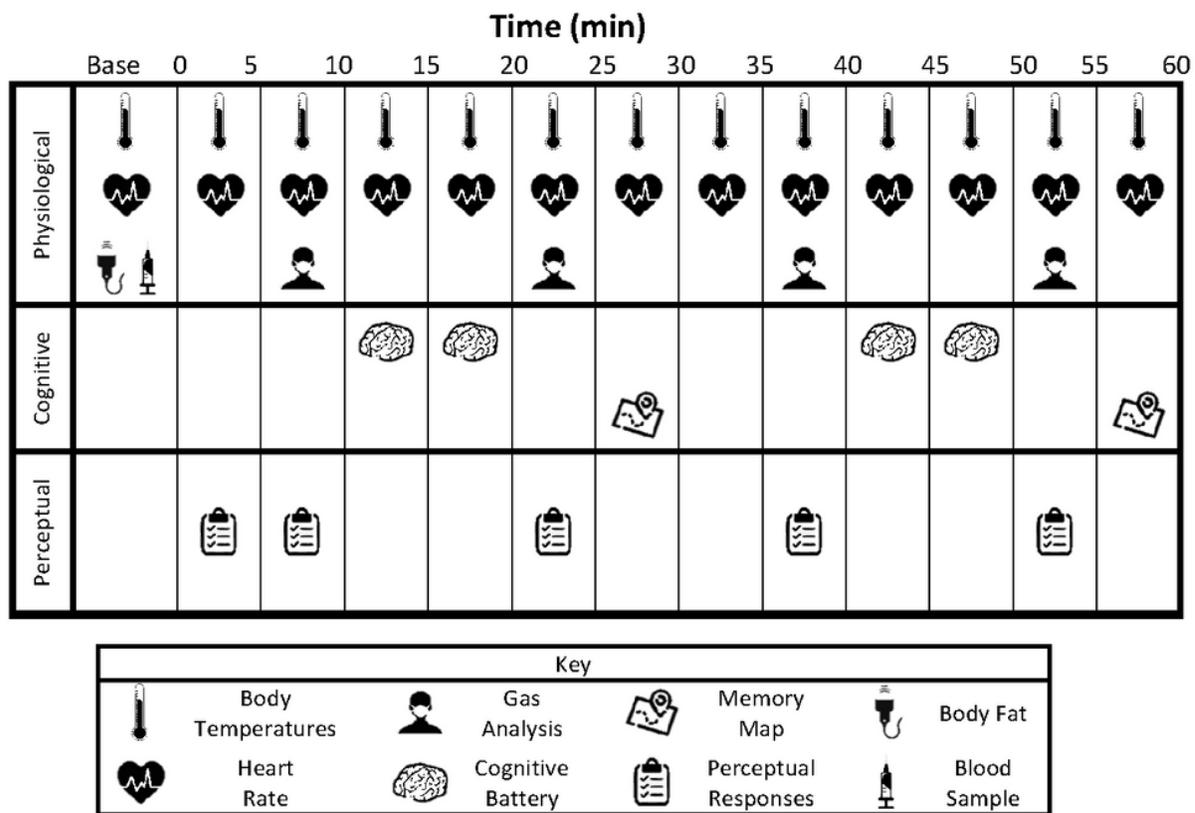


Figure 1

Schematic of tests conducted over the first 60 min in each heat-stress test. From 60 to 120 min measures were taken in the same order.



Figure 2

Gear loadouts for the humid (left) and arid (right) environments for each heat-stress test.

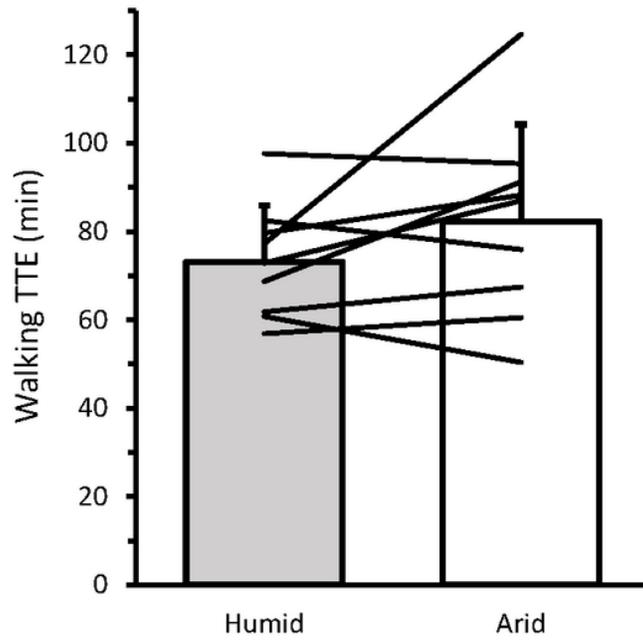


Figure 3

Walking time to exhaustion (TTE) in a simulated pack march in humid and arid environments in full military protective equipment. Individual responses are displayed by individual black lines.

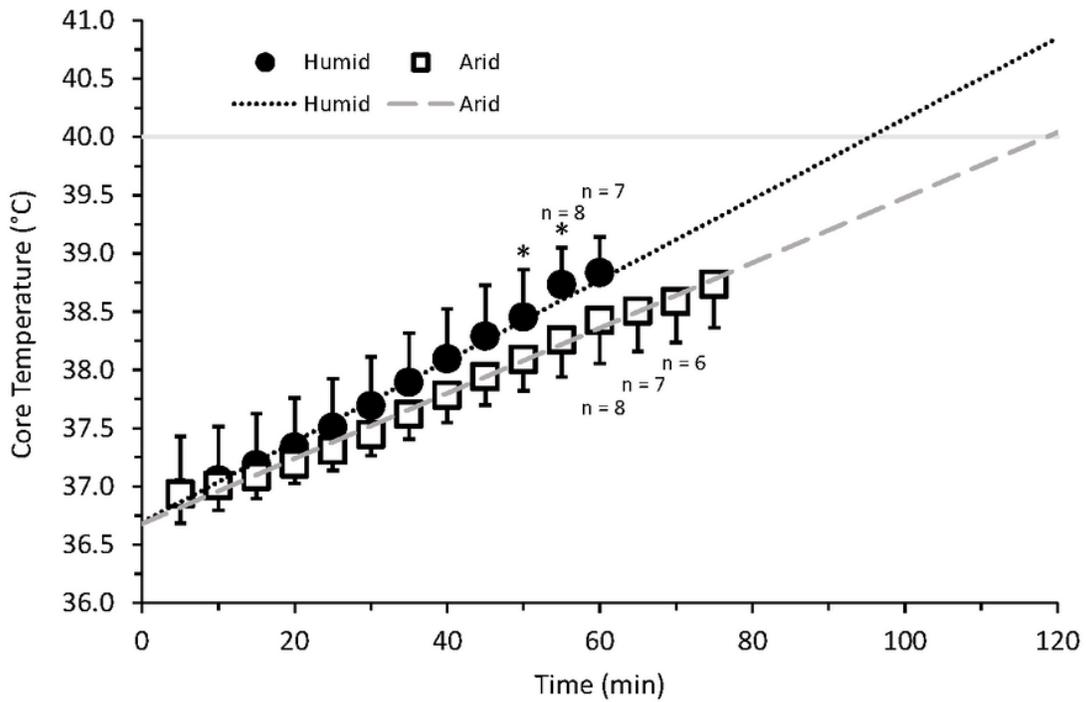


Figure 4

Rectal temperature during a simulated pack march in either a humid (33°C, 78% RH) or arid (44°C, 21% RH) environment. Trendlines display the predicted means based on recorded data, only for when n = 9. Data are plotted as mean ± standard deviation for n = 9 unless otherwise stated (data are stopped once n < 6 and is noted when it changes). *p < .05 between conditions at individual time points

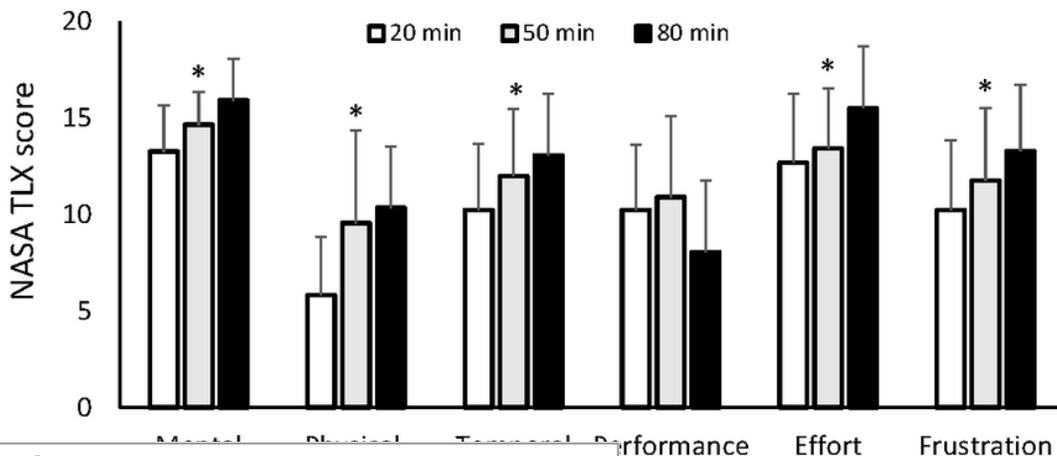


Figure 5

Pooled responses from both humid and arid heat-stress tests to the NASA task-load index following completion of a cognitive battery. Higher scores indicate. *indicates a significant effect of time, regardless of the environment.

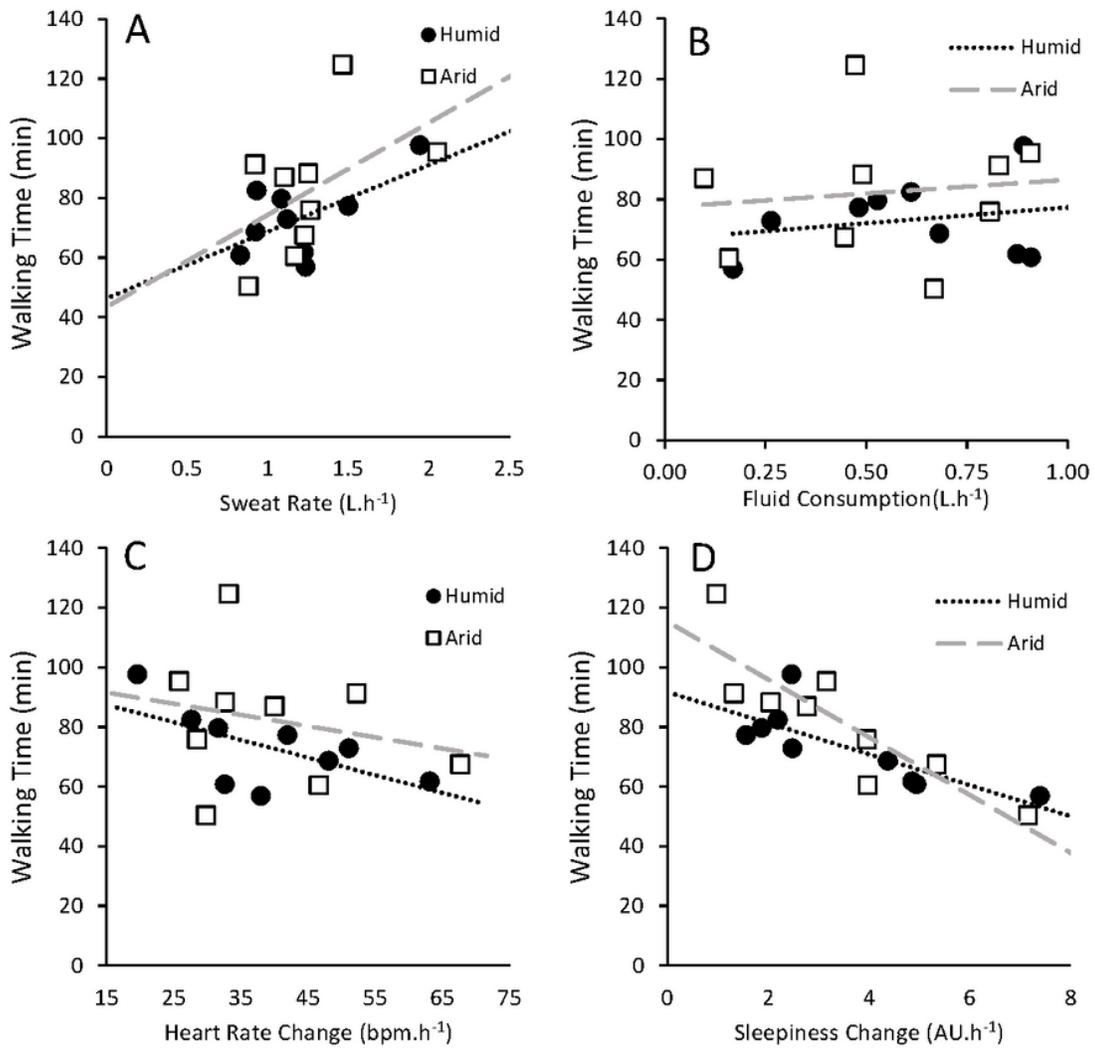


Figure 6

Regression analysis between physiological variables and performance (walking time) during a simulated pack march in humid (33°C, 78% RH) and arid (44°C, 21% RH) environments. Individual data points are plotted, with linear trendlines for each condition. AU – arbitrary units. Regression coefficients can be found in Table 2.

Supplementary Files

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This is a list of supplementary files associated with this preprint. Click to download.

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