January 2011

The interaction of body armor, low-intensity exercise, and hot-humid conditions on physiological strain and cognitive function

Joanne N. Caldwell
University of Wollongong, joc@uow.edu.au

Lian Engelen

Charles van der Henst

Mark J. Patterson

Nigel A.S Taylor
University of Wollongong, ntaylor@uow.edu.au

Recommended Citation

Caldwell, Joanne N.; Engelen, Lian; van der Henst, Charles; Patterson, Mark J.; and Taylor, Nigel A.S: The interaction of body armor, low-intensity exercise, and hot-humid conditions on physiological strain and cognitive function 2011, 488-493.
https://ro.uow.edu.au/hbspapers/1067

The interaction of body armor, low-intensity exercise, and hot-humid conditions on physiological strain and cognitive function

Abstract

Objective: This project was aimed at evaluating the impact of combat armor on physiological and cognitive functions during low-intensity exercise in hot-humid conditions (36°C and 60% relative humidity). Methods: Nine males participated in three trials (2.5 hours), walking at two speeds and wearing different protective equipment: control (combat uniform and cloth hat); torso armor with uniform and cloth hat; and full armor (uniform, torso armor, and helmet). Results: As time progressed, core temperatures increased and deviated significantly among trials, rising at 0.37°C h −1 (control), 0.41°C h −1 (torso armor), and 0.51°C h −1 (full armor). Heart rates also progressively diverged, and subjects lost significantly more sweat during the two armored trials. However, cognitive-function tests revealed neither significant main effects nor time by treatment interactions. Conclusion: The combat armor and helmet significantly increased thermal and cardiovascular strain, but these were unlikely to lead to either exertional heat illness or impaired cognitive function during uneventful urban, military patrols in hot-humid conditions.

Keywords

intensity, low, armor, body, interaction, humid, hot, exercise, conditions, physiological, strain, cognitive, function

Disciplines

Arts and Humanities | Life Sciences | Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Caldwell, J. N., Engelen, L., van der Henst, C., Patterson, M. J. & Taylor, N. A.S. (2011). The interaction of body armor, low-intensity exercise, and hot-humid conditions on physiological strain and cognitive function. Military Medicine: international journal of AMSUS, 176 (5), 488-493.

ORIGINAL ARTICLES

MILITARY MEDICINE, 176, 5:488, 2011

The Interaction of Body Armor, Low-Intensity Exercise, and Hot-Humid Conditions on Physiological Strain and Cognitive Function

Joanne N. Caldwell, MSc; Lian Engelen, BSc*; Charles van der Henst, BSc*;*
*Mark J. Patterson, PhD†; Nigel A. S. Taylor, PhD**

ABSTRACT Objective: This project was aimed at evaluating the impact of combat armor on physiological and cognitive functions during low-intensity exercise in hot-humid conditions (36°C and 60% relative humidity). Methods: Nine males participated in three trials (2.5 hours), walking at two speeds and wearing different protective equipment: control (combat uniform and cloth hat); torso armor with uniform and cloth hat; and full armor (uniform, torso armor, and helmet). Results: As time progressed, core temperatures increased and deviated significantly among trials, rising at 0.37°C h^{-1} (control), 0.41°C h^{-1} (torso armor), and 0.51°C h^{-1} (full armor). Heart rates also progressively diverged, and subjects lost significantly more sweat during the two armored trials. However, cognitive-function tests revealed neither significant main effects nor time by treatment interactions. Conclusion: The combat armor and helmet significantly increased thermal and cardiovascular strain, but these were unlikely to lead to either exertional heat illness or impaired cognitive function during uneventful urban, military patrols in hot-humid conditions.

INTRODUCTION

Metabolic heat production and external heat sources are equally capable of elevating the core temperature during work in hot environments. Indeed, heat illnesses in military and industrial personnel are primarily associated with physical exertion (exertional heat illness), rather than heat exposure per se,[1] perhaps with the exception of cases occurring within armored vehicles. However, core temperature elevation can be restricted to a safe and manageable level if heat loss mechanisms (sweating and skin blood flow) can be sustained or supplemented. When the effects of these mechanisms are impeded by the addition of clothing and personal protective equipment, the risk of heat strain is exacerbated. Therefore, the aim of this project was to assess the impact of body armor on physiological and cognitive functions in hot conditions.

When working in hot environments, work–rest guidelines[2] can be used to manage and reduce the risk of exertional heat illness. When clothing insulation is increased, altered rest and work times can be used.[3,4] However, there is a paucity of experimental data upon which such modifications may be based, and this absence may result in increased risk of exertional heat illness and compromised operational capability.[5]

The operational scenario of interest in this project was the urban military patrol, where movements are deliberate and slow. Before undertaking laboratory work, the thermodynamics of such a scenario were modeled using first-principles algorithms.[6,7,8] For instance, the heat transfer for a 75- to 80-kg person dressed in combat fatigues, working at different intensities, and exposed to a wide range of air temperatures may be predicted and illustrated as a three-dimensional surface (Fig. 1). This model provides a mechanism through which combinations of work rate and external temperature that increase the probability of high levels of heat storage can be determined. For instance, all parts of this surface that appear above the zero heat transfer plane represent conditions for which heat storage will be positive. It is apparent that only in the foreground conditions (external work rates <110 W and air temperatures <33°C) will heat storage be zero or negative. The

---

*Human Performance Laboratories, School of Health Sciences, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia.

†Human Protection and Performance Division, Defence Science and Technology Organisation, 506 Lorimer Street, Fishermans Bend, VIC 3207, Australia.

The opinions expressed in this paper are those of the authors and do not reflect the official policy or position of the Defence Science and Technology Organisation or the Australian Government.

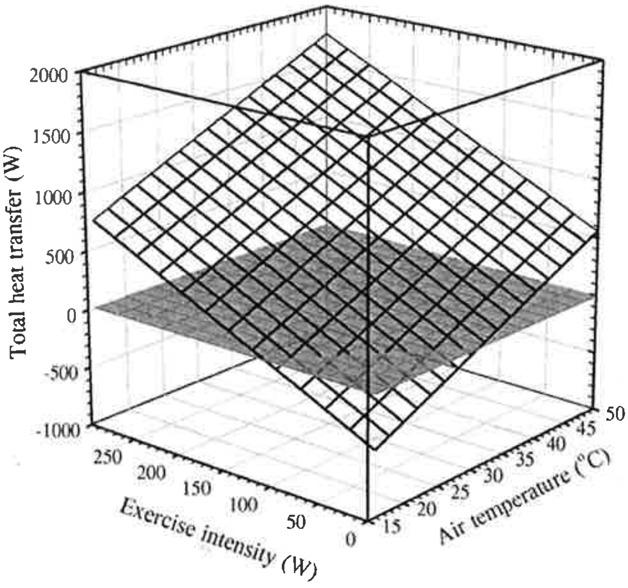

FIGURE 1. A predicted transfer surface for a 78-kg individual wearing a single layer of camouflaged, combat fatigues (insulation 0.29 m^2 K W^{-1}), working at external work loads that may be encountered in the field (rest to 300 W), and exposed to a 35°C ambient temperature range (60% relative humidity). Regions above the zero heat transfer plane represent situations of positive heat storage for combinations of external work rate and air temperature.

upper work rate at the border of this region is relatively light, but is not too dissimilar from that which might be expected during an urban patrol. However, the upper air temperature boundary falls very close to that expected in the tropical climates of northern Australia and Asia, placing personnel close to the cusp of positive heat storage, particularly when work rates increase during heightened operational states, or when body armor is added. Therefore, this analysis has shown that it was necessary to conduct human experiments under these conditions to evaluate the consequences of using armored protection during exercise at intensities anticipated during urban patrolling.

METHODS

Nine active male volunteers (age 27.3 years, SD 5.43; mass 79.4 kg, SD 11.3; height 180.3 cm, SD 5.11) participated in three stress trials in a hot-humid environment (36°C, 60% relative humidity) with a substantial radiant heat source (three infra-red lamps of 500 W, positioned [on average] at 82, 89, and 91 cm from the subject). Subjects provided written, informed consent, and procedures were approved by the Human Research Ethics Committee (University of Wollongong).

Trials differed only in the clothing and personal protective equipment worn: (1) Control trial: disruptive pattern (camouflage) combat uniform with a cloth hat (clothing mass 2.05 kg and insulation ~0.29 m^2 K W^{-1}) and shoes. (2) Torso armor trial: control state plus combat body armor (arimid-lined [Kevlar] vest with ceramic-plate inserts) covering the chest and back (6.07 kg; Hellweg, Australia) and a cloth hat (total ensemble mass 8.12 kg). (3) Full armor trial: control state (minus cloth hat) plus torso combat armor and combat helmet (Rabintex Industries, Herzliya, Israel [1.29 kg]; total ensemble mass 9.41 kg). These body-armor components were in-service items at the time of this investigation.

Within each trial, subjects walked for 2.5 hours on a treadmill at two intensities that were chosen to simulate military patrolling. For the first 1.5 hours, subjects walked 2.0 km h^{-1} (0.56 m s^{-1}) followed by 1 hour at 4.0 km h^{-1} (1.11 m s^{-1}). A large-diameter fan in front of the subject simulated natural airflow at each walking speed.

Trials were performed in a fully balanced order, with subjects refraining from strenuous exercise and the consumption of alcohol and tobacco during the 12 hours before each trial. On the night before a trial, subjects were instructed to drink 15 mL kg^{-1} of additional water before retiring, and to eat an evening meal and breakfast high in carbohydrate and low in fat. Subjects also refrained from caffeine for 2 hours before testing. On arrival, subjects were provided with supplementary water (500 mL). During each trial, subjects consumed a further 500 mL of water at room temperature (36°C) after each 30 minutes of the exercise, for a total fluid consumption of 2.5 L. This standardized consumption was designed to replicate military practice, but it results in some inter-subject variance in hydration state. This was partially offset by using subjects as their own controls. Before leaving, subjects were provided with an iso-osmotic drink equivalent to 150% of the body mass change.

Body core temperatures were measured from the auditory canal and from the rectum (Edale Instruments, Cambridge, United Kingdom). In the former, a thermistor protruded from an ear mould that was snugly located within the helix and into the junction of the auricle and the external auditory canal. A wad of cotton wool was secured over the ear. This wad and the mould shielded the thermistor from the thermal environment and, under the current conditions (36°C), artifactual influences of air temperature are minimal. These procedures result in the auditory canal measurement being a valid, reliable, and very responsive core temperature index.[9,10] Rectal temperatures were used only as back-up measurements in case of data loss, and are not reported in this article. Skin temperatures were measured using thermistors taped to eight sites (Type EU; Yellow Springs Instruments, Yellow Springs, Ohio): forehead, right scapula, right chest, right upper arm, left forearm, left dorsal hand, right anterior thigh, and left posterior calf. All temperatures were sampled at 0.2 Hz using a portable data logger (Grant Instruments, Cambridgeshire, United Kingdom). Mean skin temperature was derived using skin surface area weightings.[11] Thermistors were calibrated over relevant physiological ranges.

Heart rate was monitored throughout each trial using a Polar Electro Sports Tester (0.2 Hz; Polar Electro, Kempele, Finland). Sweat and evaporation rates were determined from gross mass changes, with subjects weighed before and after each trial (A&D Fw-150k scale; A&D, San Jose, California).

The latter were recorded following complete drying of the subject. These data were then corrected for drinking and urination, and also for sweat retained within the clothing and equipment. At the end of each trial, all clothings and some equipment were placed into plastic bags, which were sealed to prevent evaporation before weighing.

Subjects were asked, at 15-minute intervals, to rate perceived work effort (15-point Borg scale[12]), thermal sensation (13-point scale[13]), thermal discomfort (5-point scale[13]), perceived skin wettedness, and skin wettedness discomfort. The last two scales are modifications of the corresponding thermal scales. Subjects were familiarized with these scales and provided with written and oral instructions for each before the experiment.

Cognitive function was evaluated using the Mini-Cog rapid assessment battery[14] administered via a personal digital assistant (PalmOne Tungsten C, Milpitas, California). Subjects performed six cognitive-function tests during each trial, following 8 to 10 hours of preliminary training. This was necessary to ensure that learning effects were no longer present. The baseline cognitive-function tests were administered under resting, thermoneutral conditions before entering the climate chamber and then at 30-minutes intervals throughout the exercise phase. The following tests were used: (1) Vigilance: a series of geometric shapes was randomly presented (500 ms) followed by an inter-trial interval of 1, 2, or 3 s. Subjects responded during this interval and were required to recognize and identify the correct (and incorrect) shape and its orientation as quickly as possible. (2) Three-term reasoning: three simple statements were made, with subjects evaluating whether the third statement was "true" or "false." (3) Filtering: this is a modification of the Stroop test (numbered Stroop), with subjects being presented with arrays of three numbers. The number of digits within a presentation varied, and the subjects chose how many numbers were presented by attending to the total number and not the actual numbers being presented. (4) Verbal working memory: four numbers were presented, and subjects tried to recall whether the digit was the same as that presented two-back in the sequence of digits. (5) Divided attention: this test is part of the vigilance test battery and required subjects to focus on two different (unrelated) stimuli. Subjects were presented with four geometric shapes that appeared in four shades. The two recognition criteria were shape and shade and subjects endeavored to identify either of these states (ignoring all other information). (6) Perceptual reaction time: subjects were given a stimulus that appeared over one of four keys. The subject responded by pressing the corresponding key as quickly as possible.

This project was based on a repeated-measures experimental design, with subjects acting as their own controls, participating in all trials, and wearing each of the clothing ensembles. Between-ensemble differences were analyzed using two-way, repeated measures analyses of variance, with Tukey's HSD post hoc procedure used to identify sources of significant differences. Paired *t* tests were used for pre- and post-experimental comparisons. Alpha was set at the 0.05 level for all statistical comparisons.

RESULTS

Pre-experimental core temperatures were, on average, within 0.1°C across the three trials (Fig. 2). During each trial, thermal strain increased linearly, but diverged over time among the treatments. Accordingly, although a significant treatment (personal protective equipment configuration) effect was not evident ($p > 0.05$), significant time-by-treatment interactions were revealed between the control and torso armor trials ($p < 0.01$), the control and full armor trials ($p < 0.01$), and also between the two armored trials ($p < 0.01$). That is, as time progressed, the core temperatures deviated significantly between each of these trials, increasing at rates of 0.37°C h^{-1} (control), 0.41°C h^{-1} (torso armor was 10.8% faster than control trial), and 0.51°C h^{-1} (full armor was 38% faster than control trial).

Complete armored protection displaced mean skin temperature upward about 0.5°C relative to the control condition ($p < 0.01$), but differences between the two armored conditions were not significant ($p > 0.05$). The skin temperatures also revealed significant time-by-treatment interactions: control versus torso armor ($p = 0.03$) and the control versus full armor trials ($p < 0.01$). These differences were associated primarily with localized changes in torso skin temperatures, reflecting the impact of the armor on the trapping of metabolic heat and the concomitant elevation in core and clothing temperatures. For instance, from 90 to 150 minutes, the scapula skin temperatures differed significantly between the control and full armor conditions ($p < 0.01$), but not for the control and torso armor comparison ($p > 0.05$). The chest skin temperatures revealed significant differences between the control and both of the armored trials ($p < 0.01$).

A clear separation of the heart rate curves was apparent (Fig. 3), commencing from mean pre-experimental values that were within 5 b min^{-1} across trials. The corresponding mean heart rates for each trial were 100.0 ±2.2 b min^{-1} (control), 105.3 ±3.6 b min^{-1} (torso armor), and 110.7 ±2.4 b min^{-1}

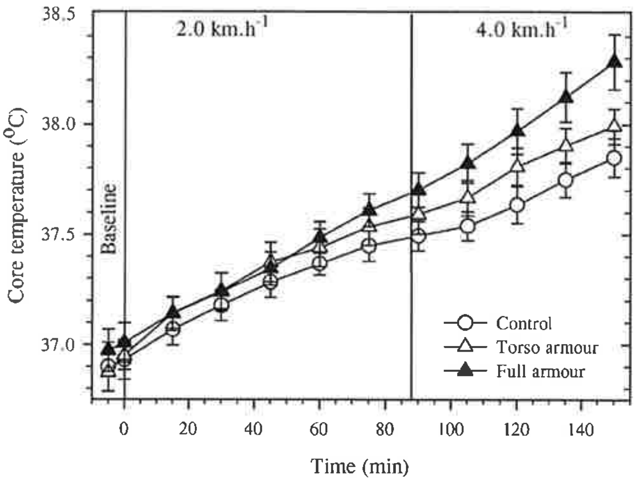

FIGURE 2. Core (auditory canal) temperatures during steady-state walking at two speeds in a hot-humid environment (36°C, 60% relative humidity, and radiant heat ~750 W m^{-2}) wearing three different uniform and combat armor configurations.

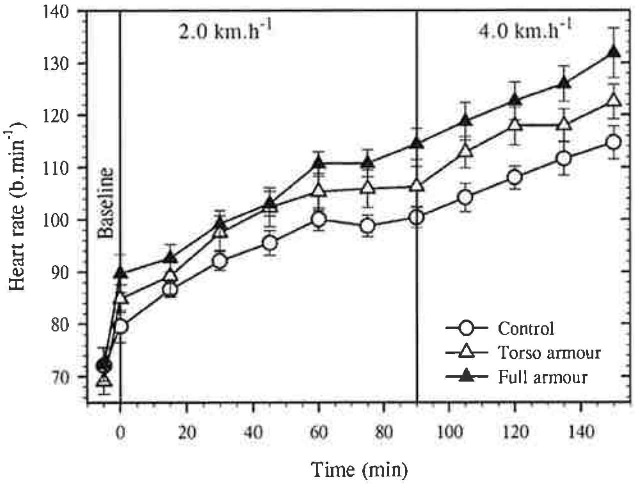

FIGURE 3. Heart rate during steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, and radiant heat ~750 W m^{-2}) with subjects wearing three uniform and body armor configurations.

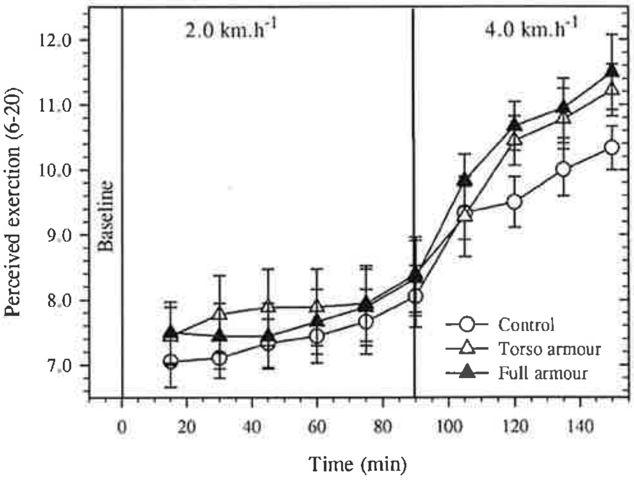

FIGURE 4. Perceived exertion (effort sense) during two intensities of steady-state exercise in hot-humid conditions (36°C, 60% relative humidity, and radiant heat ~750 Wm^{-2}) while wearing different uniform and body armor configurations.

(full armor). Although these differences were not significant ($p > 0.05$), the time-by-treatment interactions differed significantly for the control relative to the torso armor trial ($p < 0.01$), and for the control and full armor trials ($p < 0.01$). Thus, data from each of the armored trials deviated significantly over time from those obtained within the control trial, indicating a progressive divergence in cardiovascular strain.

Subjects lost significantly more sweat during the two armored states, relative to the control condition (1.32 kg versus 1.72 kg [torso armor], $p = 0.04$ and 1.74 kg [full armor], $p = 0.03$). These corresponded to relative mass changes of 1.65% (±0.22), 2.19% (±0.19), and 2.19% (±0.19), respectively. In the two armored trials, significantly more sweat was retained within the clothing and protective equipment relative to the control state ($p = 0.01$). Therefore, as predicted, the combat armor reduced evaporation. However, differences between the two armored states were not significant for sweat secretion, clothing retention or evaporation ($p > 0.05$).

Effort sense increased quite markedly during the second exercise phase, with evidence of a powerful armor effect (Fig. 4), and also a significant treatment effect for the comparison of the control and full armor trials at 120, 135, and 150 minutes ($p = 0.02$). A significant time-by-treatment interaction was also apparent between these trials ($p = 0.01$). The response curves for thermal sensation, thermal discomfort, perceived skin wettedness, and skin wettedness discomfort during the full armor trial were invariably above those for the other two trials, indicating stronger sensations and greater discomfort. However, the between-trial differences were generally not significant ($p > 0.05$). There was one exception, with the time-by-treatment interaction between the control and full armor states revealing significantly greater thermal sensation throughout the second exercise phase in the latter state ($p = 0.01$).

The cognitive-function tests were analyzed in several ways, including determining the number of correct responses and, where appropriate, the reaction time. However, none of these tests and output forms revealed either significant main effects for time or the level of armored protection ($p > 0.05$), or significant time-by-treatment interactions ($p > 0.05$). For simplicity, and for reasons of relevance to the application of this research, the data presented in Figure 5 are limited only to the number of correct responses for vigilance and perceptual reaction time. The absence of a time effect, when combined with the other nonsignificant differences, reinforces the veracity of the pre-experimental training protocol that was designed to remove learning artifacts.

DISCUSSION

The principal aim of this project was to evaluate physiological strain when military personnel are required to wear combat body armor during very light to light workloads in environments typical of the northern Australian summer. It is apparent that core temperatures did not approach levels associated with impending exertional heat illness (Fig. 2). Under these simulated operational conditions, one would, therefore, not expect an individual who was not wearing any body armor to experience a core temperature elevation to 39.5°C, or for heat-associated exhaustion to occur within 7 hours. That is, the risk of developing frank hyperthermia under these conditions was negligible.

However, the temperature curves for each treatment deviated over time. Thus, when the complete combat armor state was used (torso plus helmet), the projected time to 39.5°C declined to slightly <5 hours (a 30% reduction). Approximately 60% of this reduction can be directly attributed to wearing the combat helmet, because the torso armor trial reduced the time to reach 39.5°C to ~6 hours (−12%). That is, adding the combat helmet alone represented a significant thermal load that was not evident when wearing the cloth hat.

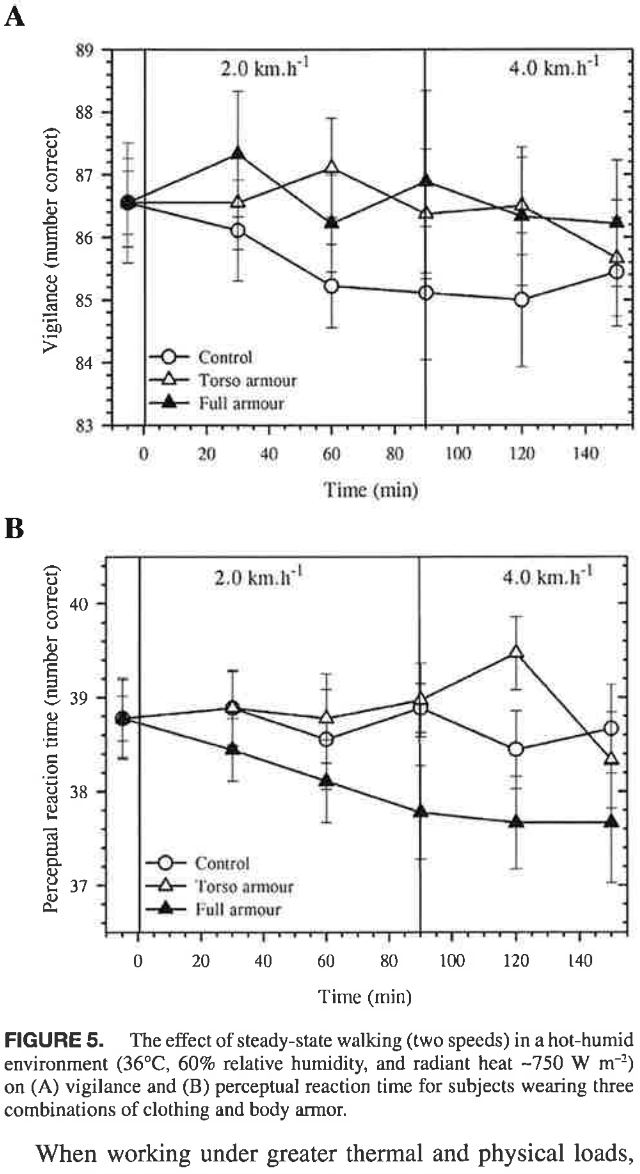

FIGURE 5. The effect of steady-state walking (two speeds) in a hot-humid environment (36°C, 60% relative humidity, and radiant heat ~750 W m^{-2}) on (A) vigilance and (B) perceptual reaction time for subjects wearing three combinations of clothing and body armor.

When working under greater thermal and physical loads, physical exhaustion can occur at much lower core temperatures. Such fatigue is largely of cardiovascular origin, where the combined blood flow demanded by metabolically active tissues and the skin (heat dissipation) overwhelms the cardiovascular system, challenging pressure regulation.[15] Nevertheless, as the work rates of patrolling activities can be regarded as very light to light, the risk of exertional heat illness, even with full combat armor, should remain small in well-hydrated, healthy, and physically active individuals.

Torso armor dramatically reduces heat loss from the torso, trapping heat between the skin and clothing. This effect is reflected in the current differences in mean skin temperature, as previously reported.[16,17,18] In addition, the two armored trials resulted in significantly more sweat being retained within the clothing. As a consequence, evaporative heat loss was impaired and these differences largely account for deviations from the control trial.

For the two armored conditions, the only difference was headwear: cloth hat versus helmet. The addition of an extra 1.3 kg to the head was not likely, on its own, to have a powerful impact, even though this is approximately equivalent to carrying an extra 1.7 kg on the back.[19] It is more likely that it was the combination of the torso armor and helmet loads, and their impact on heat dissipation, that produced the current results.

The cutaneous vasculature of the head and the nasal and paranasal mucous membranes provide effective avenues for heat dissipation,[20] with scalp tissue insulation remaining somewhat constant across a wide range of air temperatures (~0.059 m^2 K W^{-1}).[21] Thus, in temperate conditions (23°C), the head, which contains about 7% of the total body surface area,[22] has a surface area-to-mass ratio 1.6 times that of the torso and loses heat very rapidly. In absolute terms, the resting heat loss from the head is ~45 W, with the rest of the body losing approximately 75 W.[21,23,24] However, when normalized to skin surface area (W m^{-2}), its rate of heat loss is greater than eight times that of the rest of the body. During exercise in temperate states (150 W), this can increase to ~130 W.[24] It is, therefore, not surprising that in clothed and heated conditions, where heat losses from the limbs and torso are impeded, evaporation from the head becomes a dominant means for heat dissipation. Thus, it is possible that the helmet may have further impeded evaporation, above that associated with the cloth hat. Then, in combination with the added mass carried over 150 minutes, it became the straw that broke the camel's back, as indicated by deviations between the two armored trials beyond the first 60 minutes (Figs. 2 and 3).

Cardiovascular strain (Fig. 3) tracked thermal strain. Indeed, a steady state in heart rate was evident only during the last 30 minutes at the lighter work rate. The continual rise in heart rate beyond 90 minutes in each condition was probably due to a cardiovascular drift associated with the prolonged humid-heat exposure. Because hydration state was rigidly controlled (1 L h^{-1}), this drift is unlikely to have been due to progressive dehydration. It is more probable that it accompanied a decline in stroke volume, occurring as a result of increased cutaneous blood flow, perhaps in combination with other physiological responses, such as altered sympathetic tone accompanying rising core temperatures.[25]

If one assumes an arbitrary cardiovascular termination threshold of 180 b min^{-1}, then, on the basis of the current data, one would predict heat-associated fatigue to occur in about 5 hours 45 minutes (control), 5 hours (torso armor), and 4 hours 10 minutes (full armor). Thus, exercise termination due to cardiovascular insufficiency would be predicted to occur about 1 hour earlier than hyperthermia. It may, therefore, be assumed that an exercise- and thermally induced cardiovascular impediment will limit performance, rather than frank thermoregulatory failure, should exercise be continued beyond 4 hours.

A secondary objective of this experiment was to address the possibility that progressive increments in thermal strain associated with body armor, may adversely affect cognitive function and psychophysical status. Neither of the armored conditions affected thermal sensation, perceived skin wettedness, or the corresponding discomfort votes, relative to the control trial. Effort sense was increased when wearing the body armor, but without a separation between the armored trials. Thus, although the current forcing functions permitted a physiological separation of these conditions, the psychophysical indices lacked this sensitivity. Furthermore, although heat strain can adversely affect some cognitive functions,[26] none of the functions currently evaluated demonstrated significant treatment effects. It is, however, quite possible that greater thermal and metabolic strain, as reflected by more severe hyperthermia, dehydration, sleep disturbance, and perhaps even hypoglycemia, may well have elicited such changes. These conditions may arise when the exercise intensity or the air temperature are independently or simultaneously elevated (Fig. 1). However, the current data show that, for the cognitive functions evaluated, the combined influences of low-intensity exercise (urban partol), hot-humid conditions, and combat armor did not have an adverse influence over the 150-minutes experimental period. It may be possible, under more stressful combat conditions in which physiological strain is even further elevated, that cognitive function may be impaired.

It is concluded that the use of torso combat armor, whereas significantly increasing thermal and cardiovascular strain, was unlikely to lead to either exertional heat illness or impaired cognitive function in the current hot-humid conditions, during routine and uneventful patrolling. Furthermore, while the addition of a 1.3-kg combat helmet elicited a further separation of the core temperature and heart rate responses, the risk of hyperthermia or degraded cognitive function and psychophysical status, even with full combat armor, should remain small in well-hydrated, healthy, and physically active individuals. However, if exercise is continued beyond 4 hours, then cardiovascular insufficiency, rather than thermoregulatory failure, is likely to precipitate fatigue.

ACKNOWLEDGMENT

This project was funded by a grant from the Defence Science and Technology Organisation, Australia.

REFERENCES

1. Goldman RF: Introduction to heat-related problems in military operations. In: Medical Aspects of Harsh Environments, Vol. 1. Edited by Pandolf KB, Burr RE, Wenger CB, Pozos RS. In: Textbook of Military Medicine, pp 3–49. Edited by Zajtchuk R, Bellamy RF. Department of the Army, Office of the Surgeon General, and Borden Institute. Washington, DC, 2001.
2. TBMED507: Heat Stress Control and Heat Casualty Management. Technical bulletin medical 507. Air Force Pamphlet 48–152 (I), Department of the Army and Air Force, Washington, DC. Available at www.usariem.army.mil/download/; accessed 2003.
3. Kenny WL: WBGT adjustments for protective clothing. Am Ind Hyg Assoc J 1987; 48: 576–7.
4. Bernard TE, Ashley CD, Schwartz SW, Caravello V: Making heat stress assessment relevant again. National Institute for Occupational Safety and Health. University of South Florida, Florida. 2004.
5. Danielsson U, Bergh U: Body armour: effects on performance and physical load. In: Environmental Ergonomics XI, pp 111–4. Edited by Holmer I, Kuklane K, Gao C. Proceeding of the Eleventh International Conference on Environmental Ergonomics, 2005.
6. Goldman RF: Prediction of human heat tolerance. In: Environmental Stress: Individual Human Adaptations, pp 53–69. Edited by Folinsbee LJ, Wagner JA, Borgia JF, Drinkwater BL, Gliner JA, Bedi JF. New York, Academic Press, 1978.
7. Caldwell JN, Taylor NAS: A first-principles evaluation of auxiliary cooling for ADF personnel. UOW-HPL-Report-020, pp 1–47. Human Performance Laboratories, University of Wollongong, Australia.
8. Taylor NAS: Challenges to temperature regulation when working in hot environments. Ind Health 2006; 44: 331–44.
9. Cotter JD, Patterson MJ, Taylor NA: Topography of eccrine sweating in humans during exercise. Eur J Appl Physiol Occup Physiol 1995; 71: 549–54.
10. Keatinge WR, Sloan RE: Deep body temperature from aural canal with servo-controlled heating of the outer ear. J Appl Physiol 1975; 38: 919–21.
11. ISO 9886: Evaluation of thermal strain by physiological measurements. International Standard Organisation, Geneva, 1992.
12. Borg GAV: Perceived exertion in relation to physical work load and pulse rate. Kunggliga Fysioga Sallsk Lund Forh 1962; 31: 105–15.
13. Gagge AP, Stolwijk JA, Hardy JD: Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res 1967; 1: 1–20.
14. Shephard JM, Kosslyn SM: The MiniCog rapid assessment battery: developing a "blood pressure cuff for the mind." Aviat Space Environ Med 2005; 76(Suppl 6): B192-B197.
15. Taylor NAS, Kondo N, Kenney WL: The physiology of acute heat exposure, with implications for human performance in the heat. In: Physiological Bases of Human Performance During Work and Exercise, pp 341–58. Edited by Taylor NAS, Groeller H. Edinburgh, Churchill Livingstone Elsevier, 2008.
16. Goldman RF: Physiological costs of body armour. Mil Med 1969; 134: 204–10.
17. Bishop PA, Krock LP: Energy costs of moderate work activities in protective clothing. In: Advances in Industrial Ergonomics and Safety III, pp 623–8. Edited by Karwowski W, Yates JW. New York, Taylor and Francis, 1991.
18. Majundar D, Srivastava KK, Purkayastha SS, Pichan G, Selvamurthy W: Physiological effects of wearing heavy body armour on male soldiers. Int J Indust Ergon 1997; 20: 155-61.
19. Soule RG, Goldman RF: Energy cost of loads carried on the head, hands, or feet. J Appl Physiol 1969; 27: 687–90.
20. Zenker W, Kubik S: Brain cooling in humans—anatomical considerations. Anat Embryol 1996; 193: 1-13.
21. Froese G, Burton AC: Heat losses from the human head. J Appl Physiol 1957; 10: 235–41.
22. Hardy JD, DuBois EF: The technic of measuring radiation and convection. J Nutr 1938; 15: 461–75.
23. Clark RP, Toy N: Natural convection around the human head. J Physiol 1975; 244: 283-93.
24. Rasch W, Samson P, Cote J, Cabanac M: Heat loss from the human head during exercise. J Appl Physiol 1991; 71: 590–5.
25. Coyle EF, Gonzalez-Alonso J: Cardiovascular drift during prolonged exercise: new perspectives. Exerc Sport Sci Rev 2001; 29: 88–92.
26. Ramsey JD, Morrissey JJ: Isodecrement curves for task performance in hot environments. Appl Ergon 1978; 9: 66–72.