Heat Strain at High Levels Does Not Degrade Target Detection and Rifle Marksmanship

Peter Tikuisis and Allan A. Keefe

Tikuisis P, Keefe AA. *Heat strain at high levels does not degrade target detection and rifle marksmanship.* **Aviat Space Environ Med 2005; 76:963–9.**

Background: A recent investigation found no degradation in rifle marksmanship due to mild heat strain (up to a 1°C increase in core temperature) even though the subjective sensation of discomfort was significant. The present study was conducted to determine if, and at what level of heat strain would degradation in both target detection and marksmanship (TD&M) occur. ***Hypothesis:*** Degradation in TD&M performance is expected in individuals who reach a level of high heat strain. ***Methods:*** There were 11 subjects (mean ± SD of 28.9 ± 6.0 yr, 177 ± 10 cm, and 81.2 ± 18.8 kg) who participated in 3 counterbalanced trials: control (CN); heat with hydration (HH); and heat without hydration (HD). Core temperature was increased through a combination of exercise and passive heating over 4 h. Measures of shooting performance every half hour included target detection and engagement times, friend-foe discrimination, and shooting accuracy using a small arms trainer. ***Results:*** All physiological measures and indices indicated that a significantly elevated heat strain was attained during HH and HD compared with CN. Mean heart rates and core temperatures approached 150 bpm and 39°C, respectively, at the end of the heated trials. Aside from minor differences in target detection and identification owing to target type, no detrimental impact on TD&M due to heat strain, whether hydrated or dehydrated, was observed. ***Conclusions:*** High levels of heat strain do not adversely affect target detection and rifle marksmanship performance, at least for a period of time not exceeding 4 h in a non-threatening environment.

Keywords: heat exposure, target detection and engagement, vigilance, shooting performance.

HEAT STRAIN IS known to adversely affect physical performance and cognitive function at thresholds specific to the intensity of effort. Shooting performance, or marksmanship, which comprises both components, has been reported to deteriorate with heat exposure (12), although the extent of heat strain (i.e., the consequential rise in core temperature due to heat stress) was not measured. In a more recent marksmanship study that involved mild heat strain where core temperature had increased by up to 1°C prior to shooting, marksmanship was not degraded, and in some measures was found slightly, but significantly better than under a thermoneutral condition (18). This result was attributed to the previously reported observation (7) that sustained attention can improve with an elevated, but not increasing core temperature, as was the case when marksmanship was tested.

This then begs the question: at what level of heat strain, as opposed to heat stress, will marksmanship degrade? Recently, Hancock and Vasmatzidis (9) reported that an increase of 1°C in core temperature is considered detrimental to psychomotor performance. Marksmanship is a psychomotor activity that requires aiming and firing a weapon. Hence, marksmanship can be expected to deteriorate in individuals whose core temperature exceeds 38°C, which is higher than we had previously tested. Targets that appear randomly in time and location add a cognitive challenge to the task. Targets that can also be friendly or foe further challenge the decision-making process. Since cognitive performance is more sensitive to heat strain than manual performance (3), deterioration in target detection and identification might be expected to occur earlier than degradation in marksmanship, especially if detection and identification of a target is more cognitively demanding than firing at it. The intent of this study was to separate the effect of heat strain on these various components of target engagement. It was hypothesized that overall performance will deteriorate when core temperature exceeds 38°C, and that the purely cognitive components (target detection and identification) will be affected sooner than the psychomotor task of marksmanship (aiming and shooting at the target).

METHODS

Subjects

There were 11 military subjects (9 men and 2 women) who were recruited from various local reserve units. Subjects had a mean (± SD) age, height, and weight of 28.9 ± 6.0 yr, 177 ± 10 cm, and 81.2 ± 18.8 kg, respectively. All subjects were rifle-trained, had passed a standard Canadian Forces marksmanship assessment within the previous year, and had prior experience with the small arms trainer used in this study. The subjects were also medically screened and a full explanation of the procedures, discomforts, and risks were given before written informed consents were obtained prior to their involvement. The study was granted approval by

From the Human Modelling Group, SMART, Defence R&D Canada–Toronto, Toronto, ON, Canada.

This manuscript was received for review in May 2005. It was accepted for publication in August 2005.

Address reprint requests to: Peter Tikuisis, Ph.D., Defence Scientist, DRDC Toronto, P.O. Box 2000, 1133 Sheppard Ave. West, Toronto, ON M3M 3B9, Canada; Peter.Tikuisis@drdc-rddc.gc.ca.

the Human Ethics Review Committee for Defence R&D Canada.

Protocol

Subjects were asked to attend four sessions. The first involved medical clearance, basic anthropometric measurements, and familarization with the heating protocol and shooting task. Sessions 2 to 4 were the experimental trials to investigate target detection and marksmanship (TD&M) performance under the control (CN) condition and under heat strain with (HH) and without hydration (HD). These trials were counterbalanced (to the extent possible with 11 subjects) and held 1 wk apart. Subjects arrived at the laboratory at 07:30 in a normal restive state, having refrained from alcohol consumption and heavy exercise 24 h prior to arrival. Caffeine consumption was not monitored but subjects were asked to adhere to their habitual use (i.e., without over- or under-consuming caffeine before a trial) to avoid confounding effects.

The subject underwent the following procedure prior to each trial including familarization: 1) zeroing and grouping the rifle and scope (i.e., standard calibration procedure) that was used during the shooting session; 2) having nude body mass measured; 3) self-inserting a rectal probe (Pharmaseal® 400 Series, Baxter Healthcare Corporation, Irvine, CA) 15 cm beyond the anal sphincter for core temperature (T_{co}) measurement; 4) strapping a heart rate monitor (Polar Accurex Plus, Polar Electro Oy, Kempele, Finland) around the chest for continuous heart rate (HR) measurement; 5) donning undergarments, tube-laced shirt and pants for liquid circulation (Cool Tube Suit, Med-Eng Systems Inc., Ottawa, Canada), and a Canadian Forces nuclear, biological, and chemical protective overgarment (i.e., heavy semi-impermeable fabric with hood, but with the face and hands uncovered) to minimize evaporative heat loss; and 6) completing questionnaires on their subjective sensation of heat strain and perceived exertion.

The subject then assumed a standing position on the treadmill and began a 30-min cycle of walking for 25 min at a 3 $km \cdot h^{-1}$ pace, which included shooting during the latter 15 min, and resting in a seated position for 5 min. During the familarization and heated trials (HH and HD), room temperature was 28–30°C and water at 42°C was circulated continuously through the tube suit at a flow rate that was adjusted to ensure a steady rise in core temperature (calibrated during the familarization trial); no water was circulated during the control trial held at a room temperature of 22°C. The rationale for combining exercise and passive heating was to attain higher core temperatures than would otherwise be tolerated by passive heating alone due to hypotension associated with cutaneous blood pooling. The subject was given unlimited water at room temperature to drink during the rest break each half hour in the CN and HH trials, but not in the HD trial.

The trial ended when one of the following occurred: 1) subject core temperature reached 39.5°C; 2) 4 h elapsed since the start of the trial (2 h for the familarization trial); 3) subject complained of dizziness/nausea, or requested withdrawal; or 4) on the discretion of the investigating team or medical officer. Following the trial, the subject completed additional subjective questionnaires on task performance and heat illness, was offered cold water for rehydration and cooling down, was de-instrumented and dry nude-weighed, and was released. Dehydration level was determined from the subject's before and after nude weights, corrected for any water ingested at the end of the trial prior to weighing.

Shooting Session

De-militarized C-7A1 rifles with C79 optical sights and pneumatically activated recoil and authentic blast audio were used in a simulated patrol scenario using the FATS IV Combat Firing Simulator (FATS Inc., Suwanee, GA). A high-resolution projector/hit detection assembly provided hit/miss assessment of each round fired. A digital video camera was also used to capture the timing of each round fired. The subject faced a 2.2 × 3.0 m screen 5.8 m away (horizontal viewing angle of 29°) that displayed a moving landscape synchronous with the subject's walking pace. The subject advanced in an open semi-wooded field for the first 5 min toward a village, traversed through the village (consisting of several low-lying buildings and scattered debris) over the next 5 min, and exited through the field taking a different path from the inbound patrol during the remaining 5 min. During each 5-min segment, 12 targets, 8 foe and 4 friendly, would appear at ground level randomly in time and location. This randomization was different for all segments within and across all trials. Targets were, however, located along an arc 60 m away from the subject to standardize target size, and they were evenly divided left and right of center. Target detection difficulty, on the other hand, varied with the obstacles and background of the terrain that the subjects traversed.

There was an even number of standing and kneeling targets, and all were visible for 6 s. Foe targets were identified by a disruptive dark green patterned uniform in a standing posture or disruptive light green patterned uniform in a kneeling posture; friendly target uniforms and postures were the opposite of the foes. Although arbitrary, these target designations were chosen to challenge the subject with non-obvious presentations. On sighting a target, subjects were instructed to immediately squeeze the trigger of the rifle away from the screen to signal target detection. If deemed to be a foe, subjects were required to quickly step onto a slightly elevated and inverted U-shaped stationary platform that straddled the treadmill to facilitate a stable shooting position off the treadmill. They would then take deliberate aim at the target and fire when they perceived to have the best chance of a direct hit. Following engagement of the target, subjects stepped down onto the treadmill and resumed walking. Stepping off the treadmill on friendly target sightings was optional, but rarely exercised.

Target detection and marksmanship performance was based on target detection time (from target appearance to first trigger squeeze), friend/foe discrimination (percentage of successful identifications based on fires at foe targets and fire-holds at friendly targets, and sensitivity of discrimination), foe target engagement time [TET; from target appearance to engagement (second trigger squeeze) whether the target was hit or not, but not including late shots (i.e., taken after the target disappeared)], and shooting accuracy (percentage of successful foe hits). Sensitivity of target discrimination was assessed according to d′, an index that comprises all possible responses and indicates greater than moderate discrimination when values exceed unity (13).

Questionnaires

Subjects were queried on their subjective assessments of heat strain (HS) and level of perceived exertion (PE) at the beginning of the trial and during each rest break every 30 min. HS is a modified version of the Gagge et al. (5) rating of thermal sensation from comfortable to intolerably hot on a scale from 0 to 10. PE is a modified version of the Borg (1) rating of perceived exertion from not tired to extremely tired, which was deemed as an appropriate strain index of effort, also scaled from 0 to 10. These ratings were combined to generate an index of perceived strain (PeSI; 20) to be compared with the physiological strain index (PSI; 15); both are scaled from 0 (no strain) to 10 (maximum).

Subjects also completed detailed self-assessment questionnaires on task performance [NASA Task Load Index (TLX)] and on their sensation of heat illness during the trial (USARIEM Environmental Symptoms Questionnaire) at the end of each trial. The NASA TLX (10) comprises six questions involving mental demand, physical demand, temporal demand, performance, effort, and frustration. Subjects were instructed to mark their responses on a continuous line labeled low and high on opposite ends, and these responses were assigned a numerical value based on a linear scale in 0.1 increments from 0 to 10. The subjective heat illness (SHI) component of the Environmental Symptoms Questionnaire (version IV; 17) comprises 22 questions involving the presence of various symptoms (e.g., headache, weakness, blurry vision, etc.) and subjects were instructed to choose either 0 = not at all, 1 = slight, 2 = somewhat, 3 = moderate, 4 = quite a bit, or 5 = extreme to each question.

Statistical Analysis

Dehydration level and the subjective indices of TLX and SHI were analyzed using a single-factor 3-way within-subjects repeated measures analysis of variance (ANOVA) to compare trial conditions. The physiological measures of T_{co} and HR, measured pre-exposure and every 30 min starting 20 min into exposure (during the walk), subjective indices of HS and PE, recorded pre-exposure and every 30 min starting 25 min into exposure (during rest), and the performance scores of target sensitivity to discrimination, foe targets hit, and foe engagement times were analyzed using a 2-factor [3 (condition) × n (time)] repeated measures ANOVA. The three levels of condition pertain to the three trials (CN, HH, and HD), and the n levels of time comprise the initial and number of subsequent 30-min periods of a trial. Target detection and identification metrics were analyzed using a 3-factor [2 (target) × 3 (condition) × n (time)] repeated measures ANOVA where performances on the type of target (i.e., foe vs. friendly) were compared.

A Newman-Keuls test was used for post hoc analyses where main differences were found ($p < 0.05$). Unless stated otherwise, all reported results are expressed as mean ± SD and plotted as mean ± SE. Since the durations of exposure varied due to the early termination of some subjects, data were grouped according to these durations. The first group includes all the subjects' data up to the earliest termination point, the second group up to the next termination point, etc., until the last group that completed 4 h under all trial conditions. Note that data in any one group are contained in all previous groups.

RESULTS

All 11 subjects completed a minimum of 3 h on all trials. One subject lasted 3 and 3.5 h during HH and HD, respectively. Another subject lasted 3 h during HD and two others lasted 3.5 h during HD. The resultant groups for subsequent data analyses were: G180 (n = 11); G210 (n = 9); and G240 (n = 7), where the numeric portion indicates the time in minutes that complete data were available for all trials.

The two-factor ANOVA indicated significant effects and interactions for the physiological measures of T_{co} and HR, and subjective indices of HS and PE. Core temperatures, shown in **Fig. 1A**, were not different between HH and HD, but were higher than CN after 50 min of exposure. Heart rates, shown in **Fig. 1B**, were not completely recorded for two of the subjects that lasted for 240 min of exposure; hence n = 9, 7, and 5 for G180, G210, and G240, respectively, in this analysis. HR was not different between HH and HD, but was higher than CN after 20 min of exposure. Initial and final values of T_{co} and HR are given in **Table I**.

Dehydration level at the end of HD (3.27 ± 1.11%) was higher than CN (0.51 ± 0.64%) and HH (0.96 ± 0.69%), which were not different. The subjective indices of the TLX indicated that overall mental and physical demands and effort were higher for HH and HD than during CN. Temporal demand was higher for HD compared with CN and HH, which were not different. Self-assessment of performance and rating of frustration were not different among the three trials. The end of trial subjective heat illness scores for HH and HD were higher than CN, which was not different from its pre-trial value. Out of a maximum score of 110, SHI rose from pre-trial values of 0.9 ± 1.4, 0.9 ± 0.9, and 0.9 ± 1.3, which were not different, to post-trial values of 7.0 ± 6.0, 27.3 ± 12.8, and 32.7 ± 17.0 for CN, HH, and HD, respectively. Although seemingly low, SHI values largely reflect symptoms of illness vs. heat strain.

Heat strain was less for CN than either HH or HD after 55 min of exposure, and it was less for HH compared with HD after 85 min of exposure. Similarly, perceived exertion was less for CN than either HH or HD after 85 min of exposure, and it was less for HH compared with HD after 85 min of exposure, except at

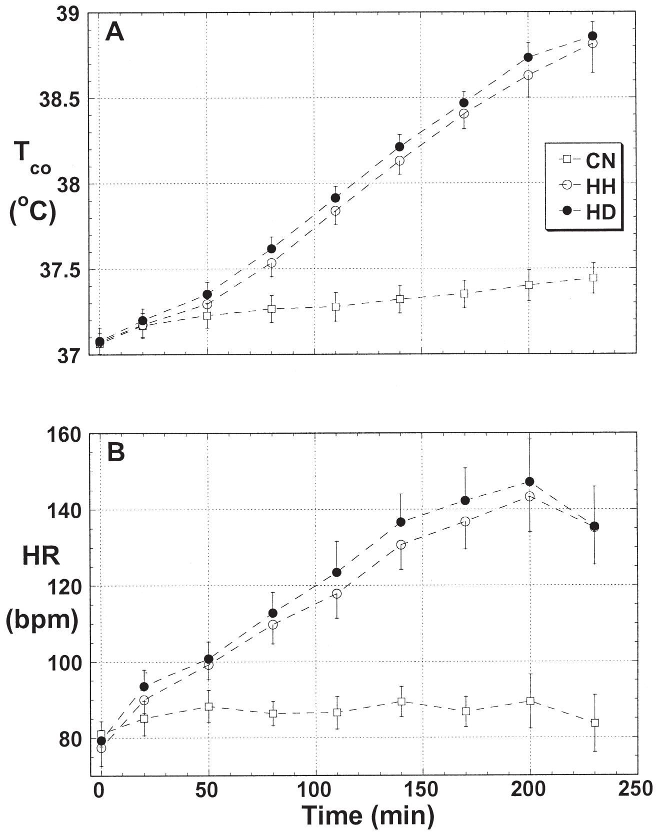

Fig. 1. Mean ± SE of A) core temperature and B) heart rate (HR) of G180 (0 to 170 min), G210 (at 200 min), and G240 (at 230 min).

235 min. Final values of HS and PE are given in Table I. Respective rankings of 2, 5, and 7 pertain to 'warm,' 'hot,' and 'very hot' for HS and to 'slightly tired,' 'tired,' and 'very tired' for PE.

The PSI, which is zero by definition assuming thermoneutrality at the start of the trial, was less for CN compared with either HH or HD after 55 min of exposure, but it was not different between HH and HD. While the PeSI was also less for CN compared with either HH or HD, but only after 85 min of exposure, PeSI for HD was also higher than HH after 115 min of exposure. Final values of PSI and PeSI are also given in Table I.

Several measures of mean TD&M performance during the first and last test sessions of all trials of G180 are provided in **Table II** for an overview among trials and across time. Note the comparison of hit accuracies between all valid foe targets and only those that were correctly detected and engaged within the 6 s of their appearance. The three-factor ANOVA indicated small, but significant effects and interactions for certain of the performance measures of target detection and identification. A marginally lower percentage of friendly targets were detected across all trials (94.5 ± 2.6%) compared with foe targets (96.1 ± 1.3%). This was attributed to a smaller detection rate of friendly targets for G180 during HH (92.4 ± 4.5%) than under CN (94.2 ± 1.3%) and HD (96.9 ± 0.6%), and under all conditions compared with foe targets (range from 95.9 to 96.1%). Findings were similar for G210 and G240, except that the percentage of friendly targets detected under CN was, as under HH, also less than the other combinations of target type and trial condition. Interestingly, there was no effect of time, that is, the percentage of target detections did not change as the subjects' core temperatures rose.

Overall correct target identifications for G180 were not affected by trial condition or time, but averaged 94.8 ± 3.0 and 96.5 ± 3.4% for foe and friendly targets, respectively, which were different. This difference was attributed to the lower percentage of correct foe target identifications during the first two shooting sessions in the first hour (93.2 ± 6.0 and 94.1 ± 3.9%, respectively) compared with friendly target identifications over the

TABLE I. SELECTED INITIAL AND FINAL MEASURES (MEAN ± SD) OF PHYSIOLOGICAL STRAIN.

		G180		G210	G240
Measure	Trial	Initial	Final	Final	Final
T_{co} (°C)	CN	37.07 ± 0.20	37.35 ± 0.26	37.40 ± 0.27	37.44 ± 0.24
	HH	37.07 ± 0.27	38.41 ± 0.29	38.63 ± 0.38	38.82 ± 0.45
	HD	37.08 ± 0.25	38.47 ± 0.22	38.73 ± 0.26	38.86 ± 0.22
HR (bpm)	CN	81 ± 10	87 ± 12	89 ± 19	84 ± 17
	HH	77 ± 15	137 ± 22	143 ± 25	135 ± 22
	HD	79 ± 8	142 ± 26	147 ± 29	135 ± 23
HS	CN		1.8 ± 1.2	2.1 ± 1.5	2.2 ± 1.5
	HH		5.3 ± 1.7	5.6 ± 1.7	5.9 ± 2.3
	HD		6.2 ± 2.0	6.7 ± 1.9	7.0 ± 2.3
PE	CN		1.8 ± 1.8	2.2 ± 1.8	2.1 ± 1.8
	HH		4.3 ± 1.6	5.1 ± 2.0	6.0 ± 2.5
	HD		5.4 ± 2.2	6.7 ± 2.5	7.1 ± 2.5
PSI	CN		0.9 ± 0.5	1.2 ± 0.9	1.1 ± 1.0
	HH		5.7 ± 1.5	6.6 ± 1.7	6.6 ± 1.4
	HD		6.0 ± 1.5	6.8 ± 1.8	6.5 ± 1.2
PeSI	CN		1.8 ± 1.4	2.1 ± 1.6	2.2 ± 1.6
	HH		4.8 ± 1.4	5.3 ± 1.8	5.9 ± 2.4
	HD		5.8 ± 2.0	6.7 ± 2.2	7.1 ± 2.4

CN = control; HH = heat strain with hydration; HD = heat strain without hydration; T_{co} = core temperature; HR = heart rate. Initial values of heat strain (HS) and perceived exertion (PE) were not recorded, and those of the psychological strain index (PSI) and index of perceived strain (PeSI) are zero by definition.

TABLE II. INITIAL AND FINAL MEASURES (MEAN ± SD) OF TARGET DETECTION AND MARKSMANSHIP PERFORMANCE FOR G180 (N = 11).

		Trial		
Measure	Time	CN	HH	HD
% foe detected	Initial	94.7 ± 4.6	96.4 ± 3.9	96.2 ± 4.4
	Final	95.2 ± 5.7	96.1 ± 4.0	95.8 ± 3.7
% friendly detected	Initial	96.7 ± 6.1	93.9 ± 8.4	95.9 ± 6.3
	Final	95.0 ± 6.5	97.0 ± 4.2	94.1 ± 6.2
% foe identification	Initial	94.8 ± 6.1	89.9 ± 12.3	94.8 ± 3.8
	Final	92.5 ± 5.5	96.3 ± 4.6	96.8 ± 2.8
% friendly identification	Initial	97.5 ± 8.2	98.4 ± 3.5	98.0 ± 6.7
	Final	99.3 ± 2.3	95.1 ± 11.0	90.5 ± 8.7
d′	Initial	3.22 ± 0.66	3.05 ± 0.52	3.22 ± 0.39
	Final	3.19 ± 0.37	3.27 ± 0.50	3.06 ± 0.43
foe TDT (s)	Initial	1.19 ± 0.26	1.27 ± 0.19	1.22 ± 0.23
	Final	1.28 ± 0.24	1.17 ± 0.27	1.15 ± 0.24
friendly TDT (s)	Initial	1.14 ± 0.32	1.09 ± 0.25	1.14 ± 0.26
	Final	1.33 ± 0.26	1.41 ± 0.31	1.24 ± 0.22
foe TET (s) (excludes late shots)	Initial	4.65 ± 0.42	4.65 ± 0.40	4.75 ± 0.40
	Final	4.68 ± 0.31	4.64 ± 0.34	4.62 ± 0.37
% HIT of all foe targets	Initial	65.4 ± 17.1	59.9 ± 11.0	64.3 ± 17.4
	Final	61.4 ± 14.9	64.6 ± 16.5	66.5 ± 13.7
% HIT (excludes undetected foe targets and late shots)	Initial	75.1 ± 14.4	76.9 ± 12.8	74.5 ± 15.6
	Final	75.4 ± 17.5	71.2 ± 14.9	77.3 ± 10.3
% late shots (excludes incorrect foe identifications)	Initial	4.2 ± 5.7	9.1 ± 9.3	6.4 ± 8.1
	Final	7.1 ± 7.4	2.5 ± 3.8	7.2 ± 13.9

CN = control; HH = heat strain with hydration; HD = heat strain without hydration; TDT = target detection time; TET = foe target engagement time; % HIT = percent successful foe hits.

same period (98.0 ± 3.3 and 97.9 ± 3.6%). No significant effects were found for G210 and G240.

Target detection time for G180 were not affected by trial condition or time, but averaged 1.16 ± 0.16 and 1.29 ± 0.17 s for foe and friendly targets, respectively, which were different. This difference was attributed to a faster detection of foe targets (1.10 to 1.13 ± ~ 0.17 s) than friendly targets (1.34 to 1.36 ± ~ 0.21 s) during most of the three consecutive shooting sessions following the first half-hour of the trials. Findings were similar for G210 and G240, except that foe detection times were also faster during the last shooting session in both groups.

The two-factor ANOVA of target discrimination (d′), TET, and percentage of foe targets hit (HIT) did not indicate any effect of trial condition or time. Overall mean d′ for G180 were 3.30 ± 0.40, 3.14 ± 0.37, and 3.18 ± 0.34 for CN, HH, and HD, respectively. Overall respective mean percentages of correctly identified foe targets that also excluded late shots were 73.2 ± 8.6, 74.6 ± 5.3, and 72.3 ± 9.1%. Late shots averaged 4.4 ± 3.9, 4.8 ± 4.5, and 5.7 ± 5.1% for CN, HH, and HD, respectively, which were not different. Overall mean TET were 4.66 ± 0.38, 4.64 ± 0.31, and 4.67 ± 0.39 s for CN, HH, and HD, respectively. Overall mean %HIT of all foe targets, whether detected or not, were 64.6 ± 9.9, 64.0 ± 7.4, and 62.2 ± 9.4% for CN, HH, and HD, respectively, and excluding unidentified foes and late shots were 73.2 ± 8.6, 74.6 ± 5.3, and 72.3 ± 9.1%. Overall mean values of all the above performance metrics were similar for G210 and G240.

DISCUSSION

Unquestionably, the lack of any serious detrimental impact on TD&M performance due to heat strain is surprising. Differences that did occur were related to target type where a slightly higher percentage of foe vs. friendly targets were detected, although less accurately, and foe targets were detected more quickly than friendly targets. Whether this latter difference is truly a difference in detection per se or an unconscious delayed response in identifying a friendly target before signaling remains to be determined through further investigation. Nevertheless, these differences were attributed to the hydrated heat strain condition in the former case and to the first half of the trial period in the latter case. Even these results defy expectation since the hydrated heat strain condition was subjectively less stressful than HD (heat strain and perceived exertion were generally both lower for HH than HD after 85 min of exposure), and mean core temperatures were still below 38°C in the first 2 h of heat exposure.

In a previous study (18), we found no decrements in marksmanship performance in subjects whose mean core temperatures ranged from 37.5 ± 0.3 to 38.0 ± 0.3°C. The core temperature range of the previous study was exceeded by about 1°C in the present study; peak individual core temperatures exceeded 39°C in three subjects in both the HH and HD trials. Further, one HH and three HD subjects reported extreme/intolerable heat strain at the end of their trials, and three others requested early withdrawal due to discomfort. Yet, target detection and identification, and shooting accuracy were not eroded, suggesting that TD&M performance can be maintained at baseline levels under a condition of high heat strain with the addition of light exercise (i.e., walking as conducted herein).

Various reports would have suggested the opposite, as hypothesized in this study. Wyndham et al. (22) categorized the effort of physical work as "easy" and "difficult" when core temperature is less than 38.1°C, and between 38.1 and 39.1°C, respectively, and inferred that performance is likely to be compromised in the latter zone. Hancock and Vasmatzidis (9) also stated that degradation in vigilance and tracking should occur when the rate of increase in core temperature exceeds 0.055 and 0.88°C · h^{-1}, respectively, which encompasses the rate we measured in the heated trials (0.45°C · h^{-1}). Hancock and Vasmatzidis further published threshold performance times for various tasks as a function of wet bulb globe temperature. We estimate that our subjects experienced a wet bulb globe temperature of at least 37°C based on the saturated micro-environment they were exposed to. Consequently, predicted maximum performance threshold times are 8 and 122 min for vigilance and tracking tasks, respectively, and 230 min for physiological tolerance. The latter prediction concurs with our findings, whereby some of our subjects had requested withdrawal by this point. Yet, TD&M performance was not adversely affected, contrary to this expectation for vigilance and tracking tasks. It is conceivable that changes in performance might be so task-specific as to render extrapolations of typical cognitive and motor performance measures (e.g., vigilance and tracking) inappropriate for TD&M. Interestingly though, in the exploratory study to develop the exercise-passive heating protocol used herein, we found no detrimental effects of heat strain on an intensive 7-min vigilance task and on three demanding 1-min tracking tasks (21).

Another possibility for the present lack of performance degradation is that operators with high skill and interest levels are less susceptible to performance degradation under heat strain (8). The military subjects used in the present study were well trained to focus on shooting tasks and they enjoyed this activity. Precedents for similar situations can be found in other activities, such as auto racing, where competitors routinely experience high levels of physiological strain (11,16), yet must maintain a sufficiently high constant proficiency in cognitive and motor performance. On the other hand, elevated heat strain has been correlated with an increased incidence of helicopter pilot error (4). This undercores the considerable variation in performance due to heat strain stemming from other intervening factors such as task duration and intensity (2,9). While task duration and operator skill and interest were high in our study, task intensity was arguably less than in other critical tasks, and thus TD&M performance was less susceptible to heat strain. Indeed, there is also the possibility that the level of attentiveness was not as intense as would occur if our subjects faced lethal danger, in which case sensitivity to heat strain on TD&M performance might be different. It appears that the combination of task duration and intensity, and compensatory operator skill and interest in the present study was such that TD&M performance could be maintained above a currently unknown degradation threshold.

The ~20% decrement in marksmanship accuracy during 2 h of exposure to 35°C with chemical protective clothing (similar to that used herein), as reported by Johnson and Kobrick (12), is, on first inspection, difficult to reconcile with our findings. While both studies used non-moving targets, they were continually present (i.e., zeroing targets) in the former whereas they appeared suddenly and for only 6 s in our study. Further, our subjects were challenged with a wider angular field of target appearances (29 vs. 16°), and were required to shift from a moving to stationary posture for engagement, which is a seemingly more difficult task. However, there are two major explanatory differences between the two studies, namely, the protective clothing worn by the subjects and the criterion for assessing performance. The protective clothing in the Johnson and Kobrick study included gloves, mask, and a hood, which our subjects did not wear and are known to significantly degrade marksmanship (12). Johnson and Kobrick also measured the closeness of shots to the target's center of mass whereas we applied a simple hit or miss criterion (i.e., % HIT) to quantify shooting accuracy. This latter difference suggests that the task measurement criterion is an additional important consideration when analyzing the effects of any stressor, such as heat strain, on marksmanship performance.

The subjects' attentiveness under the heat strain condition was amply demonstrated by the rather high target detection rates (> 90%) and high sensitivity to target discrimination (d′ averaging > 3). This attentiveness, however, differs from previously reported results of a delayed reaction owing to fatiguing exercise (6) and sleep deprivation (19), which emphasizes the specificity of stressor as an important determinant of performance degradation.

The reported mean target engagement time of about 4.7 s was also remarkably tight across all trial conditions. In a separate follow-up investigation, engagement times were measured in 12 rifle-trained subjects standing on a stationary treadmill and when dismounting a moving treadmill, as conducted herein. A difference of approximately 0.7 s emerged, suggesting that true engagement time for foe targets used in this study lies approximately between 4 and 4.7 s, depending on whether soldiers were stationary or walking.

A final interesting observation can be made from the reported heat strain metrics. While a difference between HH and HD was found for the perceptual strain (PeSI) that comprises subjective scores of heat strain and perceived exertion, no difference was found for the PSI that comprises core temperature and HR. The latter is also contrary to the findings of Moran et al. (15), who reported a significantly higher PSI in hypohydrated vs. euhydrated subjects. However, their subjects were not encapsulated in vapor-impermeable clothing, which would have prevented evaporative heat loss (14). The consequence of restricted evaporative heat loss, as our subjects experienced, was similar to increases in core temperature and heart rate during HH and HD. Hence, the PeSI, in this case, was a more accurate assessment of physiological strain than the PSI.

The present study has demonstrated no major degradation in TD&M performance due to high heat strain. There is little doubt, however, that performance degradation would occur in the "excessive" zone, defined by a core temperature exceeding 39.1°C (22), when physiological collapse is imminent with unchecked heat storage. Whether additional investigation is warranted to precisely titrate the TD&M performance threshold is a decision that must be weighed against the risk of physiological collapse. Also, whether the operational consequences of high heat strain are negligible with respect to TD&M remains to be ascertained in the presence of lethal danger either through well-documented case histories or increasingly realistic simulations.

ACKNOWLEDGMENTS

The authors express their gratitude to the subjects who endured the discomforts of this study. In addition, the expert technical assistance of A. Shin, M. Ponikvar, and J. Pope is gratefully acknowledged. This work was kindly sponsored by Thrust 12sa of the Department of National Defence (Canada) through L.Col. M. Bodner.

REFERENCES

1. Borg GAV. Perceived exertion as an indicator of somatic stress. Scan J Rehab Med 1970; 2:92–8.
2. Enander AE. Effects of thermal stress on human performance. Scand J Work Environ Health 1989; 15(Suppl. 1):27–33.
3. Enander AE. Thermal stress and human performance. Scand J Work Environ Health 1990; 16(Suppl. 1):44–50.
4. Froom P, Caine Y, Shochat I, et al. Heat stress and helicopter pilot errors. J Occup Med 1993; 35:720–4.
5. Gagge AP, Stolwijk JAJ, Hardy JD. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res 1967; 1:1–20.
6. Gillingham RL, Keefe AA, Tikuisis P. Acute caffeine ingestion improves target detection and rifle firing speed following fatiguing exercise. Aviat Space Environ Med 2004; 75:865–71.
7. Hancock PA. Task categorization and the limits of human performance in extreme heat. Aviat Space Environ Med 1982; 53:778–84.
8. Hancock PA. The effect of skill on performance under an environmental stressor. Aviat Space Environ Med 1986; 57:59–64.
9. Hancock PA, Vasmatzidis I. Effects of heat stress on cognitive performance: the current state of knowledge. Int J Hyperthermia 2003; 19:355–72.
10. Hart SG, Staveland LE. Development of the NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock PA, Meshkati N, eds. Human mental workload. Amsterdam, North Holland: Elsevier; 1988:139–83.
11. Jacobs PL, Olvey SE, Johnson BM, et al. Physiological responses to high-speed, open-wheel racecar driving. Med Sci Sports Exerc 2002; 34:2085–90.
12. Johnson RF, Kobrick JL. Effects of wearing chemical protective clothing on rifle marksmanship and on sensory and psychomotor tasks. Mil Psych 1997; 9:301–14.
13. MacMillan NA, Creelman CD. Detection theory. Mahwah, NJ: Lawrence Erlbaum Assoc.; 2005.
14. McLellan T, Cheung C, Tenaglia S. The thermophysiology of uncompensable heat stress. Sports Med 2000; 29:329–59.
15. Moran DS, Montain SJ, Pandolf KB. Evaluation of different levels of hydration using a new physiological strain index. Am J Physiol 1998; 275:R854–60.
16. Oswaldo L, Rodrigues C, de Castro Magalhaes F. Car racing: in the heat of competition. Rev Bras Med Esporte 2004; 10:216–9.
17. Sampson JB, Kobrick JL, Johnson RF. Measurement of subjective reactions to extreme environments: the environmental symptoms questionnaire. Mil Psych 1994; 6:215–33.
18. Tikuisis P, Keefe AA, Keillor J, et al. Investigation of rifle marksmanship on simulated targets during thermal discomfort. Aviat Space Environ Med 2002; 73:1176–83.
19. Tikuisis P, Keefe AA, McLellan TM, et al. Caffeine restores engagement speed but not shooting precision following 22 h of active wakefulness. Aviat Space Environ Med 2004; 75:771–6.
20. Tikuisis P, McLellan TM, Selkirk G. Perceptual versus physiological heat strain during exercise-heat stress. Med Sci Sports Exerc 2002; 34:1454–61.
21. Tikuisis P, Shin A, Keefe AA, et al. Vigilance and tracking performance during uncompensable heat stress. In: Holmer I, Kuklane K, Gao C, eds. Environmental ergonomics XI. Sweden: Lund University; 2005:205–7.
22. Wyhdham CH, Strydom NB, Morrison JF, et al. Criteria for physiological limits for work in heat. J Appl Physiol 1965; 20(1):37–45.