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The interaction of transcutaneous heating and helicopter flight simulation performance

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Abstract
It is well known that elevations in body temperature can impair both physical and cognitive performance. For helicopter pilots, the major heat source during flight originates from solar radiation. However, when nuclear, biological and chemical (NBC) protective clothing is worn, metabolic heat generated during the pre-flight period, and during the mission, is trapped, exacerbating thermal strain. In this project, the hypothesis that elevations in body heat content would degrade flight performance was tested. Helicopter pilots completed three, two-hour flight simulations under three levels of thermal strain, administered in a balanced order. Thermal strain was induced using a water-perfusion gannent, worn under flight and NBC clothing, and supplied with water that would elicit skin temperatures of 33°C (control), 37°C (moderate) and 39°C (hot). Each sortie was programmed and controlled by the simulator flight officer (blind to treatment order), and was comprised of eight flight circuits, each involving takeoff and landing exercises. During each circuit, the pilots were required to identify and solve two operational problems, graded as "easy", "moderate" and "hard". In this report, we present preliminary data from four pilots. Terminal core temperatures for each trial were: 37.5°C (±0.17; control), 38.6°C (±0.14; moderate) and 38.8°C (±0.19; hot). This strain was also reflected within the terminal heart rates: 87.8 b.min-1 (±9.6; control), 127.8 b.min-1 (±9.1; moderate) and 150.8 b.min-1 (±6.1; hot). The simulator officer independently graded pilot performance, and while the moderate trial resulted in slightly reduced performance scores, relative to control ($P>0.05$), scores were significantly lower in the hot trials ($P<0.05$). Strong correlations existed between the thermal load and both the effort needed to sustain the appropriate flight performance, and the pilots' own assessment of performance quality. From these data, it appears that mean body temperature has the most powerful impact upon perceived performance quality, whilst mean skin temperature appears to largely determine effort perception. In both instances, the explained variance currently exceeds 65%.

Keywords
heating, performance, transcutaneous, flight, helicopter, simulation, interaction

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ABSTRACT

It is well known that elevations in body temperature can impair both physical and cognitive performance. For helicopter pilots, the major heat source during flight originates from solar radiation. However, when nuclear, biological and chemical (NBC) protective clothing is worn, metabolic heat generated during the pre-flight period, and during the mission, is trapped, exacerbating thermal strain. In this project, the hypothesis that elevations in body heat content would degrade flight performance was tested. Helicopter pilots completed three, two-hour flight simulations under three levels of thermal strain, administered in a balanced order. Thermal strain was induced using a water-perfusion garment, worn under flight and NBC clothing, and supplied with water that would elicit skin temperatures of 33°C (control), 37°C (moderate) and 39°C (hot). Each sortie was programmed and controlled by the simulator flight officer (blind to treatment order), and was comprised of eight flight circuits, each involving takeoff and landing exercises. During each circuit, the pilots were required to identify and solve two operational problems, graded as "easy", "moderate" and "hard". In this report, we present preliminary data from four pilots. Terminal core temperatures for each trial were: 37.5°C (±0.17; control), 38.6°C (±0.14; moderate) and 38.8°C (±0.19; hot). This strain was also reflected within the terminal heart rates: 87.8 b.min^{-1} (±9.6; control), 127.8 b.min^{-1} (±9.1; moderate) and 150.8 b.min^{-1} (±6.1; hot). The simulator officer independently graded pilot performance, and while the moderate trial resulted in slightly reduced performance scores, relative to control (P>0.05), scores were significantly lower in the hot trials (P<0.05). Strong correlations existed between the thermal load and both the effort needed to sustain the appropriate flight performance, and the pilots' own assessment of performance quality. From these data, it appears that mean body temperature has the most powerful impact upon perceived performance quality, whilst mean skin temperature appears to largely determine effort perception. In both instances, the explained variance currently exceeds 65%.

Key words: Thermal strain, cognitive performance, flight simulation, military, skin temperature

1. INTRODUCTION

When the air temperature exceeds skin temperature (critical temperature), heat is gained from the environment. Exercise and clothing lower this critical temperature, since clothing impedes heat exchange. When wearing military clothing and working at a moderate exercise intensity, the critical air temperature can be as much as 10°C lower than for an unclothed, resting person (Caldwell and Taylor, 2005). Exercise in such conditions is physiologically uncompensable, even when wearing minimal clothing.

It is well known that elevations in body temperature can impair physical and cognitive performance. For helicopter pilots, the major heat source during flight is from solar radiation, where cabin temperatures can exceed 45°C. Yet, under times of nuclear, biological or chemical (NBC) threat, personnel must wear appropriate protective clothing. Such NBC garments substantially impede evaporative cooling. Furthermore, metabolic heat generated during the pre-flight period, and during the mission, is trapped, exacerbating thermal strain. The combination of these states places personnel at risk of elevated thermal strain, even during light work, with the possibility of a reduced operational capability and heat illness (Caldwell, 2005).

A progressive elevation in thermal strain impacts upon physiological function, but our understanding of the affect of heat strain upon cognitive function is less certain. While the literature contains a wide range of experimental observations concerning this relationship, there is no consistent trend within those observations. This is due largely to previous design limitations. Nevertheless, changes in physiological or cognitive function can have a catastrophic impact upon personnel, equipment and operational capability. The focus of the current project was upon the impact of the thermal loading of helicopter pilots on flight performance (Caldwell *et al.*, 2005b). We hypothesised that elevations in body heat content, as reflected by skin and core temperatures, would degrade flight performance.

2. METHODS

Preliminary trials

Prior to the flight simulations, trials were undertaken to determine the upper, but realistic, mean skin temperature that a pilot may reasonably be expected to experience during mid-summer flights, in a hot climate (>40°C), with a solar load. This temperature was taken as the steady-state, mean skin temperature observed over the last 15-20 min of exposure. Five subjects, wearing the full NBC ensemble and military clothing, were exposed to a hot-dry environment (48°C, 20% relative humidity). Three 350 watt infra-red lights were directed onto each subject, who performed 90 min of low-intensity cycling (~30 watts This workload closely approximates that of a helicopter pilot. It was established that this steady-state, mean skin temperature would be about 39°C.

Experimental protocol

Six helicopter pilots will be tested. However, to date, just four pilots have completed the full protocol. Pilots completed three, two-hour flight simulations (SK50A Simulator, Link-miles, Somerset, U.K.) under each of three levels of thermal strain. Pilots were tested in pairs, with each wearing a water-perfusion garment, flight and NBC clothing. Thermal strain was induced by modifying the temperature of water supplied to the perfusion garment, such that three target skin temperatures could be achieved: 33°C (control), 37°C (moderately hot) and 39°C (hot).

Prior to each trial, subjects performed 10 min of bench stepping (18 steps.min-1, step height: 18 cm) to replicate typical pre-flight physical activity (~400 Watts). Subjects then moved into the simulator. Each flight sortie was comprised of eight different simulated circuits, with circuits lasting 4-18 min, but were among pilots, and involved separate takeoff and landing exercises. These simulations were programmed, and controlled, by the simulator flight officer, who was blind to the order of experimental treatments.

During each circuit, the pilots were required to identify and solve two operational problems, graded in difficulty as "easy", "moderate" and "hard". Both the simulated circuits and the operational problems were presented in a different order for each of the three trials, to minimise learning effects. Between circuits, a 5-min rest allowed pilots to answer psychophysical questionnaires, under supervision, and to drink water (*ad libitum*).

Standardisation

Subjects were instructed to refrain from strenuous exercise, and alcohol and tobacco consumption during the 12 h prior to testing. Before testing, subjects ate an evening meal and breakfast, high in carbohydrate and low in fat, and drank 20 $ml.kg^{-1}$ of water before retiring. Caffeine was avoided for 2 h prior to testing. After the completion of each trial, subjects were rehydrated, with an iso-osmotic drink equivalent to 150% of the body mass change: 100% was consumed in the laboratory and 50% taken away.

Measurements

The following measurements were recorded: (1) core temperature: radiotelemetry (gastric pill: HQ Inc, U.S.A. and receiver: FitSense, U.S.A.), (2) heart rate: from ventricular depolarisation (Polar Electro Sports Tester, Finland), (2) skin temperatures: using thermistors (Edale Instruments Ltd, U.K. and portable data logger (Grant instruments Ltd., 1206 Series Squirrel, U.K.), (3) gross mass changes (fw-150k, A&D scale), and (4) psychophysical measures at the completion of each simulated flight circuit: (a) thermal sensation, (b) thermal discomfort, (c) perceived flight performance effort, and (d) perceived flight performance quality.

The simulator officer independently graded overall pilot performance for each circuit, and on problem solving within each circuit. Performance scores ranged from 0-8.

3. RESULTS AND DISCUSSION

When averaged across the entire experimental period, the mean skin temperatures for each of the three treatments were: control: 33.7°C (SD 0.16); moderately hot: 36.8°C (SD 0.24); and hot: 38.0°C (SD 0.20). Each of these temperatures differed significantly from one another ($P<0.05$). Two key observations are immediately apparent from these data. First, based upon the distribution of temperatures across both trials and subjects, the clamping of the skin temperature was successful. Second, the attainment of the control and moderately hot targets (33°C and 37°C, respectively) was also successful. However, while skin temperatures differed significantly, we were unable to obtain the desired separation between the moderately-hot and hot (39°C) trials, due to the attainment of a lower than desired target temperature, possibly due to differences in perfusion suit fit across the subjects, and the interaction with cockpit cooling. This affect was most pronounced when the target perfusion temperature was at its highest.

Examination of the time series data for skin temperature (Figure 1), again revealed the stability of the control trial. This is not surprising, since 33°C is very close to the thermoneutral skin temperature of a resting person. The significant separation of the treatment effects is evident, but so too is the approximately exponential rise in mean skin temperature in both the moderate and hot trials. That is, a steady-state temperature had not been obtained prior to the commencement of each sortie. This was not an unexpected trend, and there was no attempt to prevent its occurrence.

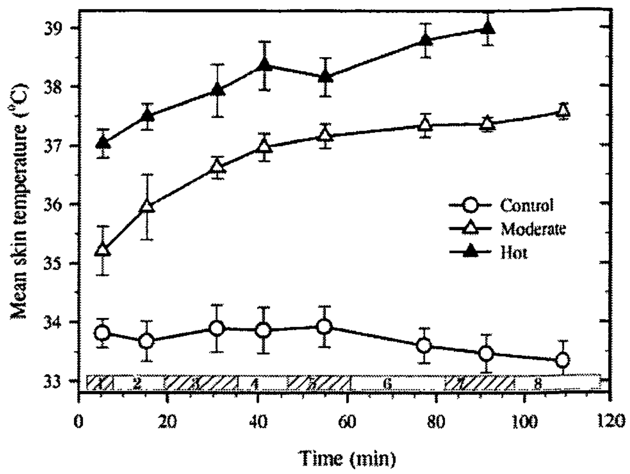

Fig. 1. Mean skin temperatures during helicopter flight simulations (eight circuits: 1-8), performed under three levels of thermal strain. Data are means with standard errors of the means.

All pilots completed the control and moderately-hot trials. However, every hot trial was terminated prematurely, due to physiological strain or subject discomfort. The terminal core temperatures were: 37.5°C (±0.17; control), 38.6°C (±0.14; moderate) and 38.8°C (±0.19; hot). This strain was also reflected within the terminal heart rates: 87.8 b.min^{-1} (±9.6; control), 127.8 b.min^{-1} (±9.1; moderate) and 150.8 b.min^{-1} (±6.1; hot).

Whilst clear separation was evident for the mean skin temperature, this was not apparent for either the heart rate or core temperature (Table 1), though significant differences existed between treatment conditions.

These physiological trends were also reflected within the subjective sensation of body heat content, and the associated thermal discomfort. Nevertheless, when analysed over the complete trial, neither thermal sensation nor discomfort differed significantly between the two hot treatments ($P<0.05$). At this stage of the experiment, these trends would indicate that, once a significant thermal load had been applied to the subjects, there was a reduction in the resolution with which they were able to differentiate between significantly different, but qualitatively similar, thermal loads.

Table 1: Physiological responses during helicopter flight simulations. Data are means with standard errors of the means derived across each entire trial.

Variable	Control	Moderate	Hot
Heart rate	85.1 (8.48)^{M,H}	110.5 (10.02)	120.0 (12.40)
Core temp.	37.6 (0.14)^{M,H}	38.0 (0.25)	38.1 (0.30)

Note: Significant differences (P<0.05): M (different from moderate), H (different from hot trial).

All pilots indicated that the thermal load had adverse effects upon perceived flight performance quality, such that, beyond 40 min, performance quality decrement ranged from "reduced" to "dramatically reduced" (Figure 2). At no time did thermal loading enhance performance quality perception. However, differences between the two hot treatments were not significant (P>0.05). In parallel, pilots reported that a greater effort ("moderate" to "considerable") was required to sustain the desired performance quality (Figure 3). This has significant implications when pilots must direct attention to many different tasks.

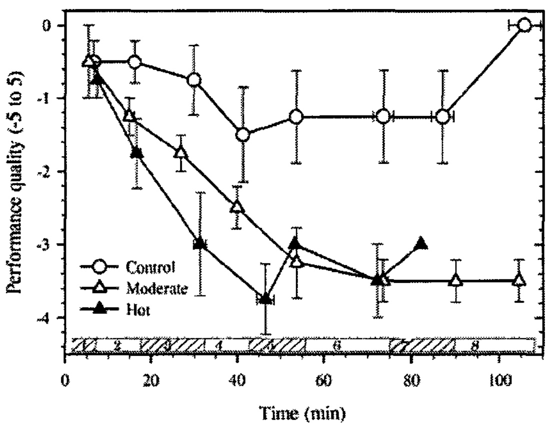

Fig. 2. Perceived flight performance quality during helicopter flight simulations (eight circuits: 1-8).

During each sortie, the simulation officer (blind to the treatment order) rated pilot performance as the operational problems were identified and solved (Figure 4). Moderate heating slightly reduced performance scores (P>0.05), relative to the control state, while differences between the control and hot trials were significant (P<0.05). Thus, thermal loading not only impacted upon the pilots' perception of performance (Figures 2-3), but actual performance decrements were apparent to an experienced flight officer (Figure 4).

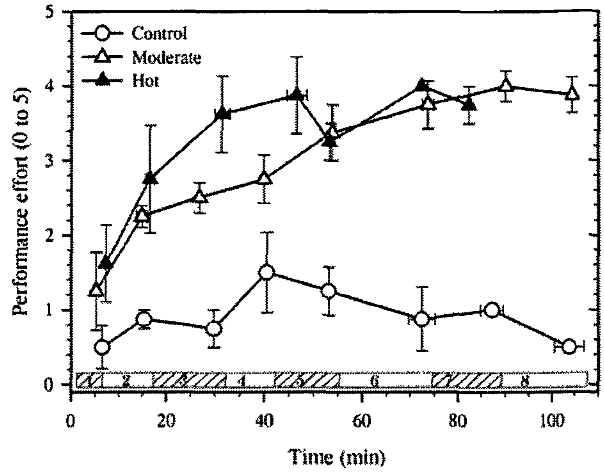

Fig. 3. Perceived flight performance effort during helicopter flight simulations (eight circuits: 1-8).

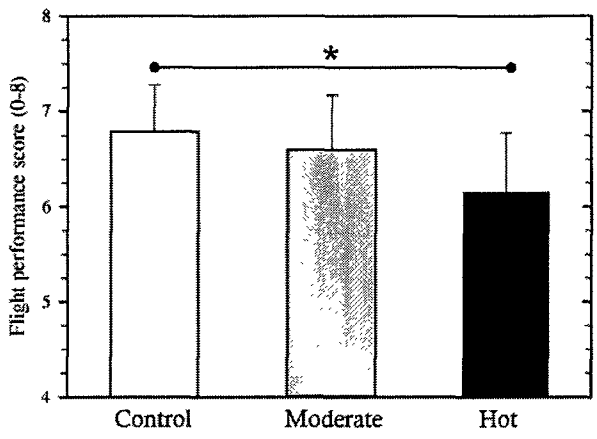

Fig. 4. Flight performance scores during three helicopter flight simulations.

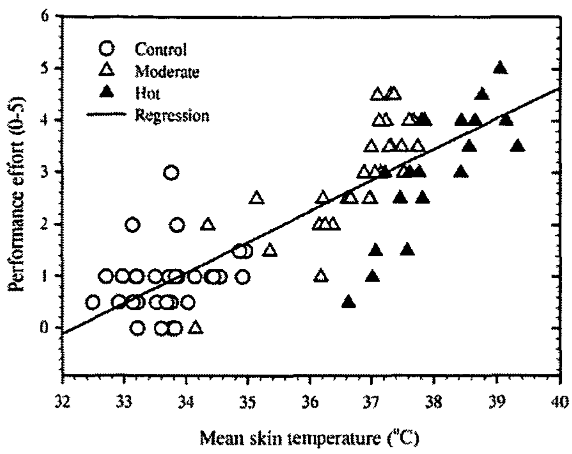

Fig. 5. Correlation between performance effort and mean skin temperature.

At this stage of the experiment, it is apparent that strong correlations exist between the magnitude of the thermal load, and both the effort needed to sustain the appropriate flight performance, and the pilots' assessment of performance quality. These observations are illustrated in Figure 5, with correlation coefficients provided in Table 2.

Table 2: Correlation coefficients (linear regression) for flight performance quality and effort during helicopter flight simulations

Variable	Quality	Effort
Skin temp	-0.13	0.84
Body temp.	-0.81	0.80

4. CONCLUSION

The thermal loading of helicopter pilots reduces flight simulator performance, and adversely affects perceptions of performance effort and quality. It appears that mean body temperature has the most powerful impact upon perceived performance quality, whilst mean skin temperature appears to largely determine effort perception (Figure 5). In both instances, the explained variance currently exceeds 65%. However, the relationship with actual flight performance, as independently assessed, was weak. These preliminary data may indicate that cognitive function during simulated flight has been modified via transcutaneous (external) heating. To evaluate this possibility, we are currently undertaking research in which six different cognitive functions (Shephard and Kosslyn, 2005) are being compare during the progression from the thermoneutral state through to profound hyperthermia (Caldwell *et al.*, 2005a), with and without the use of auxiliary cooling (Caldwell, 2005).

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6. ACKNOWLEDGMENTS

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