Thermal Burden During Safety Helmet Use in Hot Conditions and a Conceptual Cooling System Design

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Abstract: This study assessed helmet-related burden in hot conditions and used the findings to motivate a cooling-device concept. Twenty-four healthy adult males completed Helmet and No-helmet conditions at 35 ± 1 °C and 70 ± 5% relative humidity. Helmet temperature rose from 35.0 to 42.8 °C. Helmet wearing was associated with small heart-rate increases, more psychomotor vigilance task (PVT) lapses (7.71 versus 6.29; p = 0.012), longer median reaction time (287.08 versus 283.00 ms; p = 0.014), greater Stroop interference (p = 0.015), and higher post-task subjective burden (11.67 versus 10.83; p = 0.022). A thermoelectric cooling system coupled to a proposed in-helmet heat-exchange circuit is introduced as a conceptual response. The experiment identifies assessment outcomes for future device testing; it does not establish cooling effectiveness. Thermal capacity, power demand, wearability, and physiological and cognitive benefits remain to be evaluated.

Keywords: Safety helmet; Heat exposure; Thermoelectric cooling; Head cooling; Cognitive performance

1. Introduction

Occupational heat exposure can increase physiological strain, discomfort, and performance demands. Safety helmets provide essential head protection, but their enclosed structure can restrict heat exchange and alter the local microclimate. Reviews of headgear ergonomics and experimental work on industrial helmet ventilation identify heat dissipation as a design concern [1,2]. Thermal performance therefore needs to be considered alongside mechanical protection.

Previous helmet studies have examined ventilation, heat stress, and comfort, whereas heat-exposure studies have investigated cognitive function in workers and laboratory participants [3–5]. These lines of evidence leave a practical question: under the same hot conditions, does wearing a safety helmet add measurable physiological, cognitive, and perceived burden? Helmet microsensor studies and heat-exposure experiments provide complementary approaches to local and functional assessment [6,7].

This study compared Helmet and No-helmet conditions within participants in a controlled hot and humid environment. Helmet microclimate, heart rate, vigilance, interference control, and subjective ratings were assessed using the protocol in Figure 1. We hypothesized that helmet wearing would increase burden. The findings also motivate a thermoelectric cooling concept for use with a safety helmet, presented separately from the experimental results.

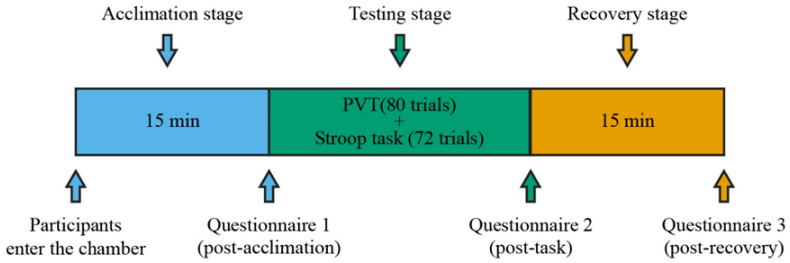


Figure 1: Experimental protocol. Questionnaires 1, 2, and 3 correspond to T0, T1, and T2.

2. Methods

2.1 Environment and Study Design

A within-subject crossover experiment was conducted in a university environmental laboratory in China. Each participant completed Helmet and No-helmet conditions in randomized, counterbalanced order. Ambient temperature was maintained at 35 ± 1 °C and relative humidity at 70 ± 5%, without forced airflow. An air-conditioning unit in heating mode and an auxiliary electric heater regulated temperature; a humidifier regulated humidity. The room was stabilized for 10–15 min before each session.

Ambient conditions were monitored continuously using an Elitech RC-4HC temperature–humidity logger at 10-s intervals. The same cognitive tasks and subjective assessments were administered under both conditions. Helmet microclimate measurements characterized local conditions during helmet wearing; they were not measurements of core body temperature.

2.2 Participants and Preparation

Thirty healthy adult males aged 18–35 years were recruited. Data from six participants were excluded for personal reasons, leaving 24 participants for analysis. Screening excluded cardiovascular, respiratory, and metabolic diseases, hypertension, heat intolerance, and other conditions that could compromise safety during heat exposure. Participants were instructed to avoid caffeine and alcohol for 12 h, refrain from strenuous exercise on the test day, and obtain adequate sleep. All provided written informed consent; participation was voluntary, and anonymity and data confidentiality were maintained.

2.3 Experimental Procedure and Outcomes

Each session comprised 15 min of acclimation in the hot environment, a testing stage, and 15 min of seated recovery in a neutral environment. Testing consisted of an 80-trial PVT followed by a 72-trial color-word Stroop task. Heart rate and helmet microclimate temperature and relative humidity were recorded continuously during acclimation and testing. Heart rate was summarized separately for acclimation and testing. PVT outcomes were lapse count, median reaction time, and mean reaction time; the Stroop task assessed interference between congruent and incongruent trials.

Subjective ratings were obtained after acclimation (T0), after testing (T1), and after recovery (T2). Five items assessed head thermal sensation, overall thermal sensation, thermal discomfort, fatigue, and thermal acceptability. The two sensation items used seven-point scales (−3 to +3), while the remaining items used five-point scales (1–5). Sensation scores were shifted to 1–7, and acceptability

was reverse-coded so that higher values represented greater burden. The five recoded items were summed. This composite was used as an exploratory summary rather than a validated diagnostic measure.

2.4 Outcome Reporting

Results summarize the 24 retained participants. Microclimate and PVT values are presented as means ± standard deviations. Comparisons concern paired Helmet and No-helmet observations. Standardized paired effect sizes are expressed as Cohen's dz, with positive values denoting higher heart rate, poorer task performance, or greater subjective burden under Helmet. Reported p values are presented alongside the magnitude of each difference; they should be interpreted cautiously given the number of outcomes examined.

3. Results

3.1 Helmet Microclimate

Helmet temperature increased from 35.0 ± 0.2 to 42.8 ± 0.6 °C (change: 7.8 ± 0.7 °C), reaching its maximum at 933.8 ± 34.1 s. Relative humidity increased initially from 69.9 ± 0.9% to 71.3 ± 0.9% at 66.3 ± 16.9 s, then declined to 52.2 ± 0.5% (change: −17.8 ± 1.3 percentage points; Figure 2).

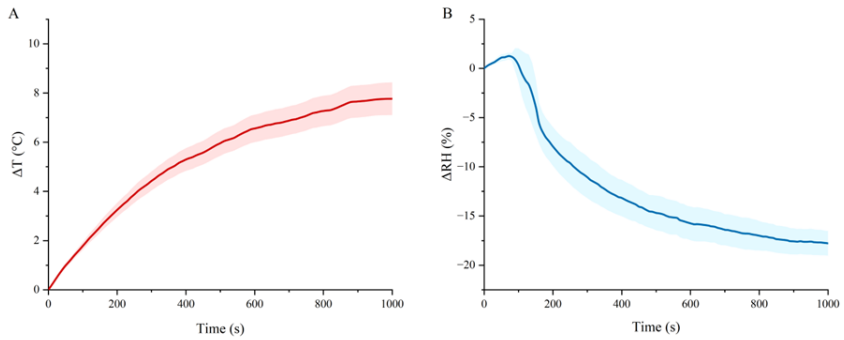


Figure 2: Helmet microclimate changes relative to baseline: (A) temperature and (B) relative humidity. Shading indicates SEM.

3.2 Physiological, Cognitive, and Subjective Outcomes

Helmet wearing was associated with higher heart rate, more PVT lapses, longer reaction times, and greater Stroop interference (p = 0.015; dz = 0.59). Heart-rate differences were below 1 beat/min. Subjective scores peaked after testing; the condition difference was significant at T1 but not at T0 or T2 (Table 1).

Table 1: Outcomes under No-helmet and Helmet conditions

Outcome	No-helmet	Helmet	p	dz
Heart rate, acclimation (bpm)	84.32	84.95	0.038	0.45
Heart rate, testing (bpm)	86.36	87.34	0.024	0.49
PVT lapses	6.29 ± 2.35	7.71 ± 2.60	0.012	0.59
PVT median RT (ms)	283.00 ± 6.87	287.08 ± 8.81	0.014	0.54
PVT mean RT (ms)	317.19 ± 14.10	325.87 ± 11.90	<0.001	—

Subjective total, T0	8.83	9.25	ns	—
Subjective total, T1	10.83	11.67	0.022	0.50
Subjective total, T2	8.13	8.38	ns	—

n = 24. RT, reaction time; ns, not significant. PVT values are mean ± SD. Heart-rate and subjective entries are means. T0, post-acclimation; T1, post-task; T2, post-recovery. —, not reported.

4. Discussion

Helmet wearing was associated with local heat accumulation and less favorable cognitive and subjective outcomes, consistent with earlier heat-exposure research [4,5,8]. Heart-rate increases were below 1 beat/min, and local temperature does not establish systemic hyperthermia. Declining relative humidity also does not establish reduced moisture content. The small male sample, one helmet configuration, and laboratory setting limit generalization. These findings motivate cooling research but do not establish the effectiveness of the proposed cooling system. A future intervention should therefore retain the thermal, cognitive, and subjective assessments used here.

5. Conceptual Cooling System for Safety Helmets

The experimental findings motivate a cooling concept focused on the helmet microclimate (Figure 3). The proposed system combines a power supply, pulse-width modulation (PWM) unit, thermoelectric cooler (TEC), water block, pump, reservoir, fan-assisted heat sink, and an in-helmet heat-exchange circuit. The cooling unit is envisaged as a backpack that would supply cooled water to the helmet circuit. This paper proposes the concept without reporting prototype fabrication or cooling-effect evaluation.

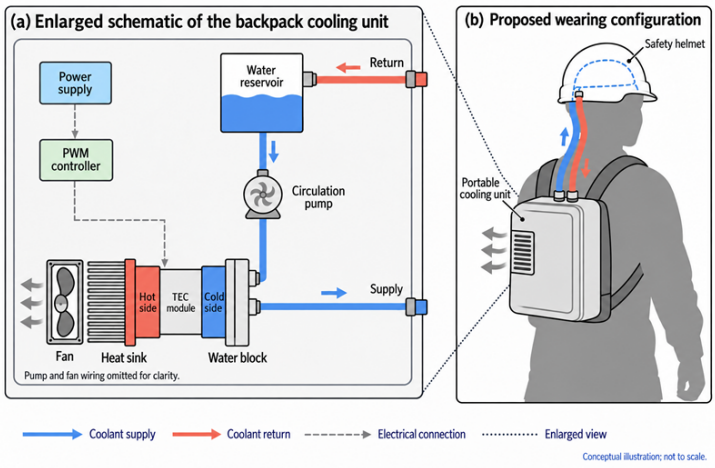


Figure 3: Conceptual helmet cooling system: (a) enlarged schematic of the proposed backpack cooling unit; (b) proposed wearing configuration. Blue and red lines indicate coolant supply and return. Not to scale.

5.1 Operating Principle

Water would circulate from the reservoir through the pump and cooled water block, pass through the in-helmet heat-exchange circuit, and return to the reservoir. The helmet circuit is intended to remove heat from the head region and local microclimate. Its placement, tubing geometry, contact arrangement, and flow rate remain design variables. The TEC cold face would cool the water block, while a fan-assisted heat sink would reject heat from the hot face. The hot side must dissipate

both the extracted heat and the electrical input [9]. PWM is proposed for adjusting the electrical drive; temperature feedback and controller settings require specification. Cooling capacity and achievable water temperature have not been established.

5.2 Conceptual Scope and Future Work

The contribution is limited to proposing a helmet-cooling concept. The existing Helmet versus No-helmet comparison does not test a cooling intervention or establish that the observed burden was caused by the absence of cooling. Further design should preserve helmet fit, suspension clearance, and protective function while addressing tube routing, contact comfort, condensation, and leakage. Future bench tests could assess cooling capacity and power demand. A subsequent helmet-only versus helmet-plus-cooling comparison could evaluate microclimate, heart rate, PVT, Stroop performance, and subjective burden. These are future research directions, not experiments conducted in this paper.

6. Conclusion

Helmet wearing in hot and humid conditions was associated with local heat accumulation and less favorable physiological, cognitive, and subjective outcomes. A thermoelectric cooling system serving an in-helmet heat-exchange circuit is proposed at the conceptual level. The experiment provides a rationale and an assessment framework, while device effectiveness remains unverified.

Disclosure Statement

The authors report no competing interests.

Data Availability Statement

The data are not publicly available because they contain potentially identifiable participant physiological information. Data may be available from the corresponding author upon reasonable request, subject to ethical approval and institutional requirements.

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