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Cooling strategies for firefighters: effects on physiological, physical, and visuo-motor outcomes following fire-fighting tasks in the heat

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abstract

Objectives: Due to the nature of firefighting, most effective cooling interventions to reduce heat strain and optimise performance are not practically viable. This study quantified the effects of two practical cooling strategies, co-designed with subject-matter experts, on physiological strain and physical, perceptual, and visuo-motor performance during simulated firefighting in the heat.

Design: Randomised cross-over

Methods: On three occasions 14 firefighters completed an 80-min simulation in a hot-humid environment (32.0[0.9]°C, 59[3]%RH) including two 20-minute firefighting tasks in full protective clothing, each followed by 20-minutes seated recovery. Recovery involved removal of protective clothing and one of three interventions – control (CON; ambient-temperature water consumption), basic (BASIC; cool-water consumption, ambient-forearm immersion/towels, fan), and advanced (ADV; ice-slushy consumption, cool-forearm immersion/ice packs, misting-fan). Thermal (core temperature) and cardiovascular (heart rate, arterial pressure) responses were measured throughout, whilst physical (handgrip/balance), visuo-motor (reaction time/memory recall) and perceptual (fatigue/thermal sensation/comfort) measures were assessed pre- and post-trial.

Results: Compared to CON, core temperature was lower in BASIC and ADV following the second task (ADV: 37.7[0.4]; BASIC: 38.0[0.4]; CON: 38.3[0.4]°C) and recovery protocol (ADV: 37.5[0.3]; BASIC: 37.7 [0.3] CON: 38.3[0.4]°C). This was paralleled by lowered heart rate, rate pressure product, and thermal sensation following the recovery protocols, in the ADV and BASIC condition compared to CON ($p<.05$). No physical or visuo-motor outcomes differed significantly between conditions.

Conclusion: Whilst these observations need to be extended to field conditions, our findings demonstrate that two novel cooling interventions developed in collaboration with subject-matter experts offered benefits for reducing thermal strain and optimising firefighter safety.

Introduction

Contemporary firefighting is often conducted in hot and potentially catastrophic conditions (Taylor et al., 2021) such as large structural fires and bush/forest fires, which are projected to increase in frequency and severity due to global climate warming (Phillips et al., 2012). When coupled with the requirement to perform repeated physically demanding tasks (e.g., personnel rescues) whilst wearing heavily insulated and non-permeable protective clothing (Payne & Kinman, 2019), these conditions can cause excessive elevations in body core temperature (thermal strain) that can compromise performance and blood pressure regulation (Walker et al., 2015), and lead to heat illness (Larsen, Snow, Williams-Bell, et al., 2015; Yu et al., 2020). Further, sustained physical work in the heat can alter mood and stress hormones, and impair cognitive functioning and decision making (Pilcher et al., 2002), which in turn likely increase the risk of fatalities (Hand et al., 2015). Thus, during training or active duties, logistically manageable heat-mitigation strategies are critical for improving physical and cognitive performance and reducing heat-related injury in firefighters (Brearley & Walker, 2015).

One of the primary methods to reduce thermal strain, and thus, heat illness risk in firefighters is the implementation of cooling strategies (Brearley & Walker, 2015). These include forearm/wrist cooling (Barr et al., 2009; Schlicht et al., 2018), ice-slushy ingestion (Walker et al., 2014), and partial or whole-body cold-water immersion (Walker et al., 2014), which all show small to moderate effectiveness in reducing core temperature and recovery of physiological parameters following simulated firefighting activities. For example, Walker et al. (Walker et al., 2014) found cold-water immersion to be quicker at cooling body core temperature than a passive rest control condition (0.093 vs. 0.058 $°C \cdot min^{-1}$). However, the delivery of whole-body immersion strategies is logistically difficult, especially at remote fireground operations requiring repeated firefighting bouts. To counter logistical difficulties of whole-body cooling, whole body fanning (Barwood et al., 2009), part-body cooling via hand (Barwood et al., 2009) and forearm immersion are supported by previous evidence (Colburn et al., 2011), inexpensive and simple to implement at incidents (McEntire et al., 2013), however their effectiveness is limited when delivered individually compared to passive cooling strategies (Hostler, Bednez, et al., 2010). Ingestion of 7.5g/kg -1ºC ice slurry has been shown to reduce core temperature better than a cold (4ºC) or warm sports drink (37ºC) (Onitsuka et al., 2015). More practically, a recent study showed the application of a cooling vest, forearm immersion, or both, improved decision making following live-fire training compared to a control, without differences between cooling interventions (Hemmatjo et al., 2018). These mixed-method or combined strategies show promise via both benefits to firefighters (i.e., lowering physiological demands during exercise heat stress (Minett et al., 2012)), whilst being easier to deliver at incidents than whole-body immersion. However, the appropriate dose and combination of mixed-method cooling techniques, as based on available resources for firefighters remains to be further explored.

Despite the reported benefits of cooling methods, many are logistically difficult to deliver at typical fire incidents and generally remain unused or not deployed. For instance, in a recent study of Australian firefighters (Fullagar et al., 2021), most (~90%) reported using simple recovery methods ('sit in the shade', 'cold water ingestion (drinking)' and 'removing your helmet, flash hood, and jacket'). Comparatively, <15% of these firefighters reported using more advanced strategies that might offer additional benefit for cooling (e.g., ice packs, ice slushy consumptions, fans). These findings point to the lack of cooling strategy use during active duty, partly due to availability and resource logistics to provide feasible cooling whilst on duty (Fullagar et al., 2021). Hence, a trade-off exists between what is most effective and what is practically available for use at incidents. Further research needs to examine firefighter responses when little or no recovery interventions are available (i.e., water consumption and removal of clothing) versus situations where progressively more advanced strategies are present (i.e., ice and/or fans). Additional considerations need to be given what fire agencies can resource. For instance, whilst novel whole body personal cooling systems offer effective means to ameliorate symptoms of heat stress (Lu et al., 2015), the cost to develop and purchase these may limit their efficacy for some agencies. Indeed, insights into the balance between cooling intervention efficacy with logistical needs should guide the development of operational and policy directives to aid firefighters' recovery at incidents.

Therefore, the aim of this study was to quantify the magnitude of benefit provided by two, practically viable cooling protocols relative to current practice (control) on the physical, perceptual, and visuo-motor performance following stressful firefighting tasks in the heat. To achieve this objective, career firefighters completed three recovery protocols that were progressively incremental in both the resources/equipment required and cooling power provided – control (CON; ambient temperature water consumption), basic (BASIC; cool water consumption, ambient temperature forearm immersion/towels, fan), and advanced (ADV; ice-slushy consumption, cool forearm immersion/ice packs, fan with moisture). The cooling protocols involved were co-designed in collaboration with firefighter stakeholders and feedback from a previous study (Fullagar et al., 2021) on recovery use and availability to ensure they were logistically manageable in live incidents. That is, all strategies were chosen to fall within the agency's potential resourcing remit, involve minimal personnel requirements on the ground and be easily transportable, delivered and deployed during a variety of fire incidents. Since this experiment was directed at quantifying the magnitude of benefit offered by each of these recovery interventions, no formal hypotheses were tested.

Materials and methods

Fourteen firefighters (mean [SD]; 42.6 [8.4] years, 84.1 [13.1] kg, 176 [7] cm, 11 M, 3 F) from one Australian state firefighting agency (Fire and Rescue New South Wales; FRNSW) completed four visits to the university laboratory separated by at least five days. All firefighters were full-time, trained metropolitan firefighters with 14.8 [10.8] years of service. Informed written consent was obtained from all participants prior to testing, and were deemed safe for inclusion in the study if they were a full-time permanent firefighter, 18-65 y old, willing to comply to the study, and did not have a history of a psychological illness or condition such as to interfere with their ability to understand the requirements of the study, or a diagnosed injury that was likely to interfere with the evaluation of their safety and of the study outcome. All procedures were approved by the institutional Human Research Ethics Committee (ETH20-4578) and agree with the latest version of the *Declaration of Helsinki*, except for registration in a database. The study was registered with the Australian New Zealand Clinical Trials Registry (ANZCTR; ID: ACTRN12620001314910).

Overview

On separate days (separated by >48 h), participants completed one familiarisation session and three randomly ordered experimental trials (control and two recovery protocols). Prior to each trial, participants were instructed to refrain from strenuous exercise and the consumption of alcohol and tobacco during the 12-hr period prior to each trial, as well as no caffeine for a 2-hr period prior to each trial which were clarified verbally by the lead researcher.

During the familiarisation visit, participants' age and height were recorded, before performing an abridged version of the study protocol, practicing the simulated physical tasks, and physical, perceptual, and visuo-motor measures, as well as the recovery strategies inside a heated climate chamber. For each experimental trial, participants performed two bouts of simulated firefighting tasks, each followed by a recovery period (Figure 1) within a climate controlled chamber with minimal air flow (<0.3 m/s) regulated to the mean maximum temperature and humidity for summer in the Sydney region (32.0 [0.9]°C, 59 [3]% RH) to replicate field-based firefighting conditions. The protocol and recovery conditions were co-designed by the research team and FRNSW, guided by a survey of workforce perceptions of physical and cognitive demands faced in extreme environments and how firefighters preferred to recover from these tasks (Fullagar et al., 2021). Together, the group (comprising of four researchers and six agency members, three of which had firefighting experience) finalised the protocol and intervention conditions to highlight realistic operational procedures and access to resources (see *Recovery Conditions*). In summary, these conditions addressed targeted areas of the body where heat stress was reported as highest. Further, the interventions were informed by development (resource availability), deployment (location, time) and education (operations, uptake) considerations. Throughout trials, firefighters wore duty wear (standard undergarments), full personal protective clothing (PPC), breathing apparatus, helmet, radio, and boots (total weight ~20 kg) as per agency procedures.

Protocol

Participants performed each trial at the same time of day (within participant). All participants were tested in the Australian summer period and we were well accustomed to exercising in the heat. After confirming euhydration (defined as a urine specific gravity ≤1.025), participants were instrumented in a temperate room before having their baseline measures recorded (see *Measures*). Participants then completed two simulated work bouts in the climate chamber. Each bout was designed to represent the metabolic demands of structural, rescue, and bushfire firefighting as these were the most demanding (physically and mentally) and hottest perceived tasks identified in previous research (Fullagar et al., 2021; Taylor et al., 2015) and, where possible, reflected current agency operational procedures (e.g., firefighters were trained and familiar with these tasks and loads). Overall, each bout lasted 20 minutes to replicate the duration of an average breathing apparatus wear, which firefighters perform in the field prior to taking mandated "rehabilitation/recovery" breaks (FRNSW, 2010). Briefly, each bout included: level-ground walking (see Fig. 1, Task a); walking (4km.h^{-1}, 0% gradient) single-arm load carriage (26 kg jerry can; Fig. 1-b), step-up single-arm load carriage (17.5 kg jerry can at 70 steps per min; 15 cm step; Fig. 1-c); motor vehicle rescue tool isometric holds (19.5 kg) at head- (Fig 1-d1), waist- (Fig. 1-d2), and knee-height (Fig. 1-d3); alternating-arm battling ropes (Fig. 1-e1); incline walking (4km.h^{-1}, 3.5% gradient; Fig. 1-e2); and, finished with level-ground walking (4km.h^{-1}, 0% gradient; Fig. 1-f). A 30-second rest was provided between any changes in task equipment. Speeds and cadences were chosen to replicate standard operational procedure work rates. The series of tasks was repeated after the mandatory 'rehabilitation/recovery' period between bouts (Figure 2) as per standard firefighting agency procedures (i.e., 40 min total task performance [two breathing apparatus wears]). Three separate recovery conditions were undertaken (control [CON] and two recovery protocols; basic [BASIC] and advanced [ADV]) inside the climate chamber.

--------INSERT Figure 1 about here--------

Recovery conditions

Following each 20-minute work bout, firefighters moved to a designated recovery corner within the climate chamber and commenced one of three recovery conditions (Fig. 2-G). For each condition, these were repeated within each trial (i.e., Baseline [rest] measures – Task 1 – Recovery 1 – Task 2 – Recovery 2 – Post measures). All recovery conditions lasted for 20 minutes.

--------INSERT Figure 2 about here--------

Control condition (CON). Firefighters completed passive, seated rest with top layer of PPC/breathing apparatus removed in an armchair whilst consuming + 7 g·kg^{-1} BW (e.g., ~600 mL for an 85 kg person (Ihsan et al., 2010)) *ambient temperature* water (sealed bottle; 20 °C) which contained a dissolved hypotonic solute (150 mOsmol·L^{-1}; Aqualyte, Point Health Pty Ltd., Australia) as per previous protocols (Walker et al., 2014).

Basic condition (BASIC). Firefighters removed top layer of clothing as per control, before commencing passive seated rest in a designated Coola™ armchair with *ambient temperature* water present for forearm immersion (20 °C). In addition, wet towels (100% cotton, 40 x 60 cm) soaked in *ambient temperature* water were placed on the neck, trunk, and thigh areas (20 °C). A motorised fan also provided air flow to the seated firefighter (2.5 m·s^{-1} at head position), with the fan adjusted to have a centralised aim towards the participants' head. Whilst they remained seated firefighters consumed +

7 g·kg^{-1} BW (Ihsan et al., 2010) *cold* water (refrigerated, sealed bottle; 13 °C) which contained a dissolved hypotonic solute as per CON.

Advanced condition (ADV). Firefighters removed top layer of clothing as per control before commencing passive seated rest in a designated Coola™ armchair with *cold* water present for forearm immersion (13 °C). The motorized fan provided air flow as per BASIC with the addition of cool moisture (16 °C) using the fan's misting function. In addition, ice packs were placed on the neck, trunk, and thigh areas, whilst firefighters consumed an ice slushy (7 g·kg^{-1} BW (Ihsan et al., 2010)) drink (–1 °C; 8.5 g carbohydrate per 100 mL), containing a dissolved hypotonic solution as per previous protocols (Walker et al., 2014).

Physiological measures

Core-temperature pills were ingested at least 8 h before exercise and recorded continuously (°C; 1-minute intervals; BodyCap e-Celsius Performance, France) using a wireless data logger worn by the participants. Ingestible pill thermometers are a validated measure of core temperature (Gant et al., 2006). Pills were consumed >8 h prior to the commencement of the trial to minimise the potential confounding influence of food or fluid on the pill (Wilkinson et al., 2008). Confirmation of pill consumption and timing was verified by the lead researcher. One core temperature pill was passed prior to commencement of the experiment, thus our analysis of core temperature was performed on a reduced sample (n=13). Heart rate (beats per min, HR; Polar Systems, Kempele, Finland) was monitored continually throughout the protocol via chest strap. For data analysis, core temperature and HR were focussed on the two min at the end of each stage. Arterial pressure (mmHg; Omron, Kyoto, Japan) was measured at baseline (following 10 min of seated rest), and the start and end of each recovery period (see Figure 1) on the non-dominant arm. Rate pressure product (RPP), a surrogate measure of myocardial oxygen demand and cardiac workload, was derived as the product of systolic blood pressure (SBP) and HR, which was calculated at the commencement and ending to each seated recovery period where SBP and HR were calculated (Figure 1). Mean arterial pressure (MAP) was also derived at the same time points as the sum of diastolic blood pressure (DBP) and the product of 1/3 and the difference between SBP and DBP ($MAP = SBP + 1/3(SBP – DBP)$). Body mass (nude) was measured during a baseline and post-trial to calculate required drink volume and fluid loss (kg; Kunshan Lightever LTP-150, Jiangsu, China). Participants used a dry towel to remove residual sweat and fluid from their body prior to post-trial body mass measurement. Pre-trial urine specific gravity (USG) was measured with a refractometer (MISCO Palm Abbe PA202, Ohio, USA). Participants who presented with a USG > 1.025 consumed ~500 mL ambient temperature water before commencing measures.

Physical measures

Grip strength (kg) from a handgrip dynamometer (Smedlay's, Tokyo, Japan) was collected during baseline (15 mins prior to heat chamber entry) and post-trial (immediately after end of Recovery 2) testing via standardised procedures (standing, maximal strength from three attempts, supervised by a research assistant) on the dominant hand. Balance was assessed using the Balance Error Scoring System (BESS; Chapel Hill, NC) which has moderate to good reliability to assess static balance and the effect of fatigue (Bell et al., 2011). BESS scores were assessed by same three researchers each trial and scores achieved via consensus.

Perceptual measures

Perceptual measures were collected every 10 minutes during exercise and recovery periods. Rating of perceived exertion (RPE, arbitrary units; 6 = no exertion at all, 20 = maximal exertion) was collected during exercise (Borg, 1998). Thermal sensation was evaluated using a subjective scale from 1 (extremely cold) to 13 (extremely hot), modified after Gagge et al. (Gagge et al., 1967) "How does the temperature of your body feel?". Thermal discomfort was assessed using a second scale (1 = comfortable, 5 = extremely uncomfortable) "How comfortable do you feel with the temperature of your body?" (Gagge et al., 1967). Perceptual fatigue (1 = no fatigue, 10=fully fatigued) and gastrointestinal comfort (VAS 1-10; 1 = no symptoms, 10 = extremely severe symptoms) were also collected (Gaskell et al., 2018). Finally, each firefighter provided a predictive (immediately prior to heat chamber entry; "How ready are you to perform your job today?" 0 = not ready at all, 100 = completely ready) and reflective (immediately prior to heat chamber exit; "How well do you think you performed your job today?"; 0 = not well at all, 100 = maximal performance) rating of their own task performance.

Visuo-motor tasks

One of the outcomes of previous research within this fire agency was the mental demand and fatigue placed on firefighters during active duty (Fullagar et al., 2021). As such, the research and agency group sought to assess the effect of the intervention on visuo-motor demands. Firstly, they completed a precued reaction time paradigm (Beavan et al., 2019) to assess firefighters' ability to use or suppress congruent and incongruent information that was presented as a brief precue, with seconds of reaction time recorded for each source. Secondly, firefighters completed a multiple object tracking task (MOT; sustained selective attention task developed using the MOT paradigm (Pylyshyn & Storm, 1988)), where participants were required to track a subset of identical items designated as target items, while all items move randomly and independently. Here, the number of errors for each task were collected for congruent, incongruent, and no precue tests.

Statistical analysis

All statistical analyses were performed in SPSS (version 27; Chicago, IL). Data are presented as mean [SD]. Data were checked for normality through Shapiro-Wilk's test of normality and through a visual inspection of QQ plots. A two-way repeated measures Analysis of Variance (ANOVA; time x condition) was used to identify differences between six time points (baseline/rest), post-task 1 (20 min from the commencement of the task), post-recovery 1 (40 min), post-task 2 (60 min), post-recovery 2 (80 min), and performance testing (100 min), and between conditions (CON, BASIC and ADV) for core temperature and heart rate. The same procedures were used for blood pressure and perceptual scales, however the time points slightly altered as per methods (see methods). Repeated measures Multivariate Analysis of CoVariance (MANCOVA) was conducted to compare the differences in physical and visuo-motor measures between conditions across their respective time points (age and experience used as covariate in MANCOVA – no effect). Handgrip strength and balance scores, and congruent and incongruent pre-cued response times, and multiple object tracking scores were entered as dependent variables for physical and visuo-motor performance, respectively, for pre-post time point measures and conditions (CON, BASIC, ADV) were entered as within-subjects factors given that these same measures were collected across conditions and time points. When a covariate was introduced, it was only retained when a significant influence of the covariate in the linear model was observed. If the covariate was not significant, it was removed to retain a more parsimonious model. The alpha threshold for significance was set at $p < 0.05$. Bonferroni corrections were used for multiple comparisons to adjust the alpha threshold and 95% confidence intervals (CIs) were reported. Partial eta-squared effect sizes (ES; η_p^2), were considered to represent “small” ≤0.009, “medium” 0.010–0.059, “large” 0.060–0.138, and “very large” ≥0.139 effects according to thresholds (Cohen, 1988). Due to the breadth of results, only large and very large ES are reported herein.

Results

Core temperature: Overall, there was a condition (p=.001, η_p^2 =.433) and time effect (p = <.001, η_p^2 =.867), as well as an effect of condition*time (p = <.001, η_p^2=.454). At post-task 2, ADV (37.7 [0.4] °C; p = <.001, η_p^2 =.694) and BASIC (38.0 [0.4] °C; p=.010, η_p^2 =.436) were significantly lower than CON (38.3 [0.4] °C; Figure 3). There were also significant differences present for reduced temperature in ADV compared to BASIC (p=.031; η_p^2 =.334). At post-recovery 2, ADV (37.5 [0.3] °C; p = <.001, η_p^2 =.656) and BASIC (37.7 [0.3] °C; p=.001, η_p^2 =.638) were significantly lower than CON (38.3 [0.4] °C), with a very large ES (η_p^2 =.260) for reduced temperature in ADV compared to BASIC (p=.063). At performance testing, ADV (37.5 [0.4] °C; p=.002, η_p^2 =.549) and BAS (37.7 [0.4] °C; p=.001, η_p^2=.441) were significantly lower than CON (38.1 [0.4] °C), with a very large ES (η_p^2 =.257) for reduced temperature in ADV compared to BASIC (p =.064). At all other time points there was no significant differences (p>0.05) between conditions, although a very large ES existed at post-task 1 for reduced temperature in ADV compared to CON (η_p^2=.185) and BASIC (η_p^2=.143).

Body mass: There was significantly greater fluid loss in CON (1.81 [0.63] L) compared to BASIC (1.12 [0.22] L) and ADV (1.01 [0.19] L; both p<.001; η_p^2 =.639 and .742) and a very large ES for a greater loss in BASIC than ADV (η_p^2 =.310).

Cardiovascular responses: The cardiovascular responses are presented in Table 1. At post-recovery 1, BASIC (p = 0.01, η_p^2 =.671) and ADV (p = <.001, η_p^2 =.732) were significantly less than CON, with a large ES (η_p^2 = .095) for reduced values in ADV compared to BASIC (p = .264). At post-recovery 2, BASIC (p = <.001, η_p^2 =.728) and ADV (p = <.001, η_p^2 =.901) were significantly less than CON, and ADV was significantly less than BASIC (p = .005, η_p^2 =.471).

For SBP, there were no significant differences between conditions. For DBP, at post-recovery 1, CON was significantly lower than BASIC (p=.008; η_p^2 =.429) and ADV (p=.006; η_p^2=.451). At post-recovery 2, CON was significantly lower than BASIC (p =.001; η_p^2=.578) and ADV (p=.002; η_p^2 =.539). Similar to DBP, significant differences were present for RPP at post-recovery 1, where CON was significantly higher than BASIC (p=.001; η_p^2 =.557) and ADV (p=.001; η_p^2 =.560) and post-recovery 2, where CON was significantly higher than BASIC (p=.001; η_p^2 =.614) and ADV (p<.001; η_p^2 =.829), with ES present at both time points for higher values in BASIC compared to ADV (η_p^2 =.086 and .284, respectively). For MAP, at post-recovery 1 BASIC was significantly greater than CON (p=.014; η_p^2 =.381), whilst both BASIC (p = .004; η_p^2 =.488) and ADV (p = .005; η_p^2 =.465) were significantly greater than CON at post-recovery 2.

Physical and visuo-motor measures: The physical and visuo-motor performance responses are presented in Table 2. No significant differences were present between conditions for any physical or visuo-motor measure (all p>0.05). For handgrip there was a time effect for reduced scores post-exercise (p=.001; η_p^2=.705), although no significant differences were present between conditions (p=.575; η_p^2=.233).

Perceptual measures: The perceptual responses are presented in Table 3. For thermal sensation following recovery 1, ADV (p=.003; η_p^2=.500) and BASIC (p=.001; η_p^2=.573) were significantly lower than CON and at recovery 2, ADV (p<.001; η_p^2=.789) and BASIC (p=.009; η_p^2=.503) were significantly lower than CON. There was also a very large ES for reduced values in ADV compared to BASIC (η_p^2=.416). Whilst time effects were present (all p<.001), there were no significant condition effects for comfort, fatigue, gastrointestinal comfort and RPE (all p>.05).

Discussion

This study provides novel insight on the effects of co-designed, mixed-method cooling strategies on physical, perceptual, and visuo-motor performance following stressful firefighting tasks in the heat. The main finding was a lowered core temperature following the second task and recovery protocol, as well as decreased HR and RPP following the recovery protocols, in the ADV and BASIC condition compared to CON. Seemingly related to the extent of cooling provided, ADV showed greater physiological benefits than BASIC and then CON. Further, firefighters perceived significant improvements in thermal sensation following recovery periods for both BASIC and ADV. Despite these improved physiological and perceptual states, there were no significant differences between any conditions for physical and visuo-motor markers of performance. While there is a need for larger, confirmatory studies in live-fire scenarios, these findings provide novel evidence to support the introduction of practically viable, mixed-method cooling to mitigate thermal strain and cardiovascular demand in contemporary firefighting.

Thermal and cardiovascular strain

The current simulated firefighting task resulted in core temperature values of 38.2-39.0 °C, or ≈1.5 °C, 1.2 °C, and 1.0 °C above baseline (CON, BASIC, and ADV), which is similar to values reported in previous field or laboratory-based firefighting activities (Brearley & Walker, 2015) (~0.9 °C; Table 1 from Horn et al. (Horn et al., 2013)). The rise in temperature for the prescribed workload noted here is attributed to the interaction of the work performed in personal protective clothing within the hot environment, thus representing the carriage weight, restricted movement efficiency and increased metabolic heat production representative of active duty (Dorman & Havenith, 2009; Taylor et al., 2012). As evidence, the rise in temperature in the CON condition exceeds NFPA safe working limits (>38.5 °C (NFPA, 2008)), whilst BASIC and ADV remained within these precautionary limits (Figure 3); although it is acknowledged our study does not include additional radiant heat sources such as live fire. Nonetheless, the distances covered for the walking tasks (approximately 650 m), overall work intensity (65-75% HR^{max}) and perceived exertion (11-14 RPE) in our study align with previous simulated Australian wildland firefighting work (Larsen, Snow, & Aisbett, 2015; N. Taylor et al., 2015).

Regardless, when no recovery protocols are present (e.g., CON), an increased thermoregulatory and perceptual load are present, and risks of re-entering hot environments with unsafe core temperatures exist (Fullagar et al., 2021).

Given the noted responses in the CON condition, both BASIC and ADV cooling strategies alleviated excessive thermal strain, as evidenced by a lowered core temperature (Figure 3), during firefighting activities in the heat. Previous evidence indicates the efficacy of a range of isolated cooling strategies (e.g., cold-water immersion (Walker et al., 2014)) in reducing core temperature in firefighters; however, often these strategies are logistically challenging to deploy to incidents or offer limited benefit compared to mixed-method strategies (Minett et al., 2012). For instance, whole-body immersion involves the removal of all clothing and additional resources to cool large volumes of water, all of which present timing, transport and personnel challenges at incidents where firefighters are expected to produce repetitive work bouts in remote areas. Thus, the co-design of a combination of mixed-methods were developed in our study within the agency's potential resourcing remit whilst also taking into account feasibility for the firefighter. In turn, these involved minimal personnel requirements on the ground and were easily transportable, delivered and deployed during a variety of fire incidents where operational use, combination, and timings were considered (Fullagar et al., 2021).

Of note, core temperatures following the second task and recovery protocols showed a dose-response, with greater reductions in ADV than BASIC or CON, likely due to the type of cooling in ADV (mist fan, ice slushie and ice water) providing greater cooling power. For example, previous evidence shows using just forearm immersion has low cooling rates (~0.01 to 0.05 °C min^{-1}) (Brearley & Walker, 2015), whilst passive cooling, fans, and water-perfused vests alone appear to offer minimal physiological benefit for firefighters engaging in tasks in the heat (Carter et al., 2007; Colburn et al., 2011; Hostler, Reis, et al., 2010). Comparatively, a combination of cooling techniques, is suggested as more effective in obtaining a greater cooling rate and larger reduction in core temperature (Bongers et al., 2017). In the BASIC and ADV conditions, the combination of cold-fluid ingestion (e.g., additional internal heat transfer [due to enthalpy of fusion of ice (334 kJ/kg)] from the increase in heat of the ingested bolus to equilibrate with internal body temperature (Jay & Morris, 2018)) and forearm immersion (e.g., vascularity of blood vessels near skin of the arms and hands (Brearley & Walker, 2015; NFPA, 2008), superior surface area to mass ratio of the hands supporting heat loss (Taylor et al., 2014)), are potential explanatory mechanisms. Given the mixed-method 'mid-job cooling' experimental design, delineating the mechanisms contributing to changes observed in this study is not possible. Nonetheless, our data suggest fire agencies can cool firefighters by employing either BASIC or ADV protocols dependent on resource availability.

An additional explanation for the reduction in core temperature in the BASIC and ADV conditions could include the use of fans, which likely aided sweat evaporation (Lamarche et al., 2015) and subsequently reduced sweat losses by 0.7 and 0.8 L (respectively), compared to CON. This indicates that CON was associated with a greater proportion of dripped (or non-evaporated) sweat, which is problematic if such losses cannot be offset by fluid consumption, since moderate dehydration (>2% body mass loss) can further augment thermal and cardiovascular strain (Sawka et al., 2001). As such, a further benefit of the BASIC and ADV protocols is that they appear to reduce the need for evaporative cooling due to increased conduction (immersion) and convection (fan), which lowers thermal strain and aids conservation of a limited fluid reserve (Walker et al., 2014). The latter may be particularly beneficial during prolonged and remote bushfire suppression where access to (cold) fluid consumption may be difficult or infrequent. Indeed, considering the availability of resourcing and equipment, as well as feasibility for firefighters to use certain recovery strategies is a feature of our study. For instance, the provision of electrical batteries (fans), cold boxes/mini fridges (cold water/slushies) and space on appliances/trucks (chairs) may offer options for fire agencies depending on the incident/environment faced.

These reductions in thermal strain and fluid loss in BASIC and ADV compared to CON were also paralleled by a lowered heart rate, RPP, and MAP during recovery (Table 1). Heart rate has been shown to reduce following exposure to cooling (compard to control or heat) following firefighting work in the heat (Burgess et al., 2012) and is comparable to the results found in our study. While we did not possess the more detailed cardiovascular measurements required to delineate the causative mechanism(s) explaining these findings, they are likely owed to a reduced core temperature, which places lesser demand on the cardiovascular system to increase cutaneous blood flow while perfusing the active musculature. Nonetheless, the significant reduction in RPP is noteworthy, as this measure is associated with myocardial oxygen consumption, in turn providing an estimate of myocardial strain, which relates strongly to risk of adverse cardiovascular events (Gobel et al., 1978). As such, these results would appear to support cooling following strenuous firefighting tasks performed in the heat to protect against a rise in cardiac work, as a reduction in RPP potentially lowers the risk of sudden cardiac death for firefighters (Smith et al., 2016).

Physical and visuo-motor performance

When firefighters perform repeated bouts of firefighting tasks in the heat reductions in muscle force production can occur (Walker et al., 2015). In our study we found that although there were reductions in hand grip and balance following the simulated firefighting tasks in the heat, there were limited differences between conditions. For instance, grip strength showed no significant differences between conditions, which concurs with previous evidence of the effects of cold-water immersion and ice-slushy ingestion (Walker et al., 2014). Since firefighting tasks primarily rely on sustained rather than peak efforts, firefighters in our study likely were able to perform maximal efforts for grip strength regardless of cooling strategy due to the absence of any significant local muscular fatigue. Alternatively, the lack of accuracy of hand grip as a strength measure may also represent a limitation (Walker et al., 2014). In addition, the water temperature of both BASIC (20 °C) and ADV (13 °C) may have been insufficient to result in a change in performance outcomes, whereas temperatures closer to 10 °C are recommended (Versey et al., 2013). However, whilst lower temperatures (<10 °C) may have a beneficial cooling effect, they are more likely to impair manual dexterity, which could impact operational capacity (Cheung et al., 2003).

No significant association between conditions were found for sustained visual attention through multiple object tracking, or the ability to use or inhibit perceptual information in a go/no-go task using implicitly perceived precues (Table 2). While executive functions have not been examined in relation to heat exposure in firefighting, investigations into the detrimental effect of exposure to heat stressors on perceptual motor performance are not new (Teichner, 1954), with known reductions in cognitive function during elevated core temperatures (Faerevik & Reinertsen, 2003). More recent findings have confirmed that heat exposure may not be directly related to decrements in cognitive performance (e.g., reaction time performance related to exercise-related heat stress (Serwah & Marino, 2006)), although some evidence shows that selective attention and reaction time (i.e., Stroop Colored-Word test) is impaired (Mazloumi et al., 2014). Indeed, the conflicting evidence across studies which focus on the impact of heat and cooling on visuo-motor function is likely due to limitations in measurement techniques, along with the confounding effects of exercise, cerebral perfusion, and blood flow redistribution to the skin (Van Den Heuvel et al., 2016). The findings in our study concur with results from Van Den Heuvel et al. (Van Den Heuvel et al., 2016) who showed moderate hyperthermia, significant dehydration, and their combined effects, did not impair cognition within memory and perceptual domains. This may suggest a lack of responsiveness of these markers to heat, exercise, or cooling. Alternatively, it is possible that the lack of demanding cognitive load during fire-fighting tasks may limit the applicability of these findings to those performed in the field (i.e., lack of firefighter-specific decision making or threat to life). Future studies could include more dynamic (attention) stressors related to firefighting tasks (i.e., hazard perception) to investigate these possibilities. Overall, given this conflicting evidence of examining visuo-motor performance as a function of heat stress exposure in relation to different cooling methods, further research is warranted.

Perceptual responses to heat and cooling

In our study firefighters reported lowered thermal sensation (i.e., felt cooler) for both ADV and BASIC compared to CON (Table 3). This is an important finding as previous evidence shows limited improvements in firefighter perceptions when exposed to forearm or head cooling (Yeargin et al., 2016). Rather, it appears a combination of cooling strategies is best suited to maximise feelings of cooler thermal sensation, perceptual fatigue and comfort (Barr et al., 2010). Together, these results support including the perceptions of emergency first-responders when delineating the effects of these cooling strategies on health and performance outcomes. Indeed, firefighters from the same state agency investigated in this study have previously expressed a desire for improved access to cooling ingestion (e.g., ice slushies) and exposure (e.g., ice packs), as well as further recovery aids (e.g., immersion cooling, fans) (Fullagar et al., 2021). It was also important to note that firefighters reported minimal gastrointestinal issue differences between conditions in the current study, specifically with regards to ice slushy ingestion. Combined with the evidence that the combination of strategies used as part of the BASIC and ADV protocols is beneficial for cooling, these collective perceptions would support increasing resourcing or availability to disperse these strategies state-wide (e.g., fridges/ice machines on trucks).

Considerations

While this study is the first to examine practically viable heat-mitigation strategies in Australian firefighters, it is not without limitations. Since we used a mixed-method design for our cooling strategies, understanding what specific modalities within each intervention were effective, as well as explaining mechanisms for the reductions in thermal and cardiovascular strain, is limited. However, the advantage of our experimental design is that it possesses strong ecological validity where practical viability and feasibility for the firefighter are well considered. Similar to previous research (Fullagar et al., 2021), though our results may help guide understanding of firefighter views on heat stress and recovery, they are limited to one state agency and caution should be used when extrapolating our findings to other national or international agencies. Australia is serviced by numerous agencies, where environmental conditions and job requirements can vary and may have nuances which impact their experiences (Fullagar et al., 2021). Nonetheless, efforts were made to design the tasks and recovery protocols with various regions and cohorts in mind to maximise replicability in the field. Unfortunately, we were unable to simulate a live-fire scenario, and thus the additional radiative heat load faced during fire suppression was missing. Further feasibility studies using the methods and results of this study are encouraged. It should also be acknowledged that we did not match the sugar content of the slushy mixture to the water drinks and thus may have affected substrate utilisation during the trial, however this was needed as the slushy mixture has a required sugar percentage to freeze. Of further consideration is that menstrual cycle data were not collected in the study protocol for female participants, and thus could have impacted thermorgulatory responses. Finally, the trial was relatively short in duration compared to a complete firefighter shift (24 h) and hence lacks the dynamic and cumulative attentional demand and fatigue induced during these activities.

Conclusions

This study provides novel insight on the effects of a combination of recovery strategies on the performance of physical, perceptual, and visuo-motor tasks following stressful firefighting tasks in the heat. The significant reduction in core temperature following the second task and recovery protocols in the ADV and BASIC condition, along with decreases in heart rate responses, and proportional reductions in RPP, show the benefits of these cooling strategies for firefighter health and safety. Indeed, whilst there were no significant differences between any conditions for physical and visuo-motor markers of performance, future operational interventions should consider the beneficial effect of cooling on core temperature and physiological responses, which likely lowers the risk of adverse cardiovascular events. Future research could include more detailed measurements of thermoregulatory and cardiovascular function, as well as account for environmental factors such as radiant heat and dynamic psychological stress to maximise replicability in the field. Furthermore, larger cohorts and cross-agency replications of such trials would allow for comparisons across firefighting populations and scenarios. Nonetheless, we hope our findings serve as a foundation for the development of policies and procedures for heat-mitigation in structural and bush/forest firefighting.

Practical Applications

- A combination of “mixed” cooling methods, co-designed by researchers and fire agency personnel and considering logistics of delivery in the field, show significant reductions in core temperature, as well as decreased HR and RPP, following stressful firefighting tasks in the heat.
- Firefighters perceive significant improvements in thermal sensation following recovery periods using basic and advanced cooling strategies. The cost vs. benefits for increasing resources surrounding these cooling methods should be considered by fire agencies. Such information

may also help to design education around disseminating these cooling interventions, as well as availability for these tools to be optimised on trucks or recovery vans/pods.

- Despite an improvement in physiological and perceptual states, there were no significant differences between any conditions for physical and visuo-motor markers of performance. Future research should examine visuo-motor performance as a function of heat stress exposure in relation to different cooling methods, which could include more dynamic (attention) stressors related to firefighting tasks (i.e., hazard perception) to investigate these possibilities.

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Figure 1. Overview of experimental protocol and timeline of Tasks and Recovery modes; each Task (20 min) and Recovery (20 min) bout was performed twice (80 min total); treadmill walking – unloaded (a, f), single-arm carry (b; 26 kg) and at multiple gradients (%; e2); single-arm carry step up (c; 17.5 kg) at 70 steps per minute; motor vehicle rescue tool isometric holds at multiple positions (d1-3); alternating-arm battle ropes (e1).

Figure 2. Examples of firefighter activities within each task and recovery modes. *A*: Walking on treadmill; *B*: Walking on treadmill with 26 kg load single-arm load carriage; *C*: Step ups with 17.5 kg single-arm load carriage; *D*: Motor vehicle rescue tool isometric holds at multiple positions; *E*: Alternating-arm battle ropes; *F*: Multiple object tracking visuo-motor performance testing post-trial; *G*: Advanced cooling intervention.

Figure 3. Firefighters core temperatures (°C) during strenuous firefighter tasks in the heat and subsequent recovery. Trials involved 20-min (baseline/rest), two bouts of work and recovery lasting 20-min each, and a 20-min performance testing battery. All trials were identical with the exception of the recovery, which was Control, Basic, and Advanced (see methods for details). Panel A shows the mean (SD) responses for each condition, while Panel B shows the mean difference [95% CI] from Control with individual responses in semi-transparent lines. Analysis of Variance was used to identify differences between (baseline/rest), post-task 1 (20 min from the commencement of the task), post-recovery 1 (40 min), post-task 2 (60 min), post-recovery 2 (80 min), and performance testing (100 min), and between conditions (Control, Basic, Advanced). Significantly different from Control (*; $p<0.050$). Significantly different from Basic ($^{\#}$; $p<0.050$).

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