FLUID INTAKE, HYDRATION AND PHYSIOLOGICAL STRAIN IN WILDFIRE FIGHTERS

by

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*Fluid intake, hydration and physiological strain in wildfire fighters*

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OUTPUTS OF THESIS

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INVITED PRESENTATIONS


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**CONFERENCE PROCEEDINGS**
- Raines J, Snow R, Drain J, Nichols D, & Aisbett, B. ‘*If our firefighters are arriving on shift dehydrated, why aren’t we making them drink beforehand?*’. Australasian Fire Authorities Council & Bushfire Co-Operative Research Centre Conference, Darwin, September 2010.

**INDUSTRY PUBLICATIONS**
MEDIA INTERVIEWS/PUBLICATIONS


- Crisp, D., Protecting the health and wellbeing of our heroes, in DMag. June 2009 (magazine).

- Bull, S., Whiz study to keep up the fluids, in Berwick Journal. 2009: Melbourne. p. 7 (local paper).


This doctoral thesis consists of three studies: 1) pre-shift fluid consumption, 2) prescribed drinking during the shift, and 3) ad libitum fluid consumption over consecutive shifts of wildfire fighting. The central theme, the influence of fluid intake on key physiological strain parameters and hydration, was investigated in each study.

The first study of the thesis evaluated whether ingesting a bolus of fluid before the shift had any effect on firefighters’ fluid consumption, core temperature, or the time they spent in high heart rate and work activity zones when fighting emergency wildfires. Thirty-two firefighters were divided into non-bolus (ad libitum) and pre-shift drinking bolus (500 ml water) groups. They began work hypohydrated as indicated by urine colour, specific gravity and plasma osmolality (P\textsubscript{osm}) results. After their shift firefighters were classified as euhydrated according to P\textsubscript{osm} and hypohydrated by urinary markers. No significant differences existed between the drinking groups in pre- or post-shift hydration status, total fluid intake, activity, heart rate or core temperature. Leading to the conclusion that consuming a bolus of fluid, pre-shift, provided no benefit over non-consumption as both groups consumed equivalent ad libitum volumes of fluid 2.5 hours into the shift. No benefits of bolus consumption were observed in firefighter activity, heart rate response or core temperature response across the shift in the mild-warm
weather conditions experienced. Of note was that ad libitum drinking was adequate to facilitate rehydration in firefighters upon completion of their emergency firefighting work shift.

The second study of the thesis investigated wildfire fighters’ abilities to consume a prescribed fluid volume (1200 ml·hr⁻¹). Additionally, whether this prescribed volume had an effect above ad libitum drinking on plasma sodium and hydration, heart rate, core temperature and activity during emergency suppression shifts. Thirty-four firefighters were divided into ad libitum (n=17) and prescribed (n=17) drinking groups. Prescribed drinkers did not meet the fluid target, yet consumed over double the volume of ad libitum drinkers. No differences between groups in plasma sodium or hydration were noted. Prescribed drinking resulted in lower core temperature between 2-6 hours. This did not coincide with reduced cardiovascular strain, greater work activity or larger distances covered when compared to ad libitum drinkers. Extra fluid consumption (above ad libitum) did not improve firefighter activity or physiological function (though prescribed firefighters core temperature was lower earlier in their shift). It is apparent from these findings that firefighter can self-regulate their fluid consumption behavior and work rate to leave the fireground euhydrated in mild-warm climatic conditions.

The final study investigated the effect of naturally chosen fluid consumption on physiological strain over consecutive days of work in hot conditions. Specifically, it evaluated firefighters’ pre- and post-shift hydration status across two shifts of wildfire suppression work; documented firefighters’ fluid and food intake during and between two shifts of this work; and assessed any changes in heart rate, firefighter activity, perceived exertion and core temperature. Across the two consecutive days, twelve
firefighters’ hydration status and perceived exertion were measured immediately pre- and post- their work shift. Hydration status was also measured two hours post-shift. Work activity, heart rate, and core temperature were logged continuously during each shift. Ten firefighters also manually recorded their food and fluid intake before, during, and after both fireground shifts. Results showed that firefighters were hypohydrated at all time-points on day one (292 ± 1 mOsm·L⁻¹) and euhydrated across day two (289 ± 0.5 mOsm·L⁻¹). Fluid consumption following the firefighters’ shift on day one (1792 ± 1134 mL) trended (p = 0.08) higher than day two (1108 ± 1142 mL), but daily total fluid intake was not different (p = 0.27), averaging 6443 ± 1941 mL across both days. Core temperature and the time spent in the ‘hard’ heart rate zone were significantly elevated on day one (when firefighters were hypohydrated). Firefighters’ work activity profile was not different between both days of work. In summary, there was no difference in firefighters’ pre- to post-shift hydration within each shift, suggesting ad-libitum drinking was at least sufficient to maintain pre-shift hydration status, even in hot conditions. Firefighters’ relative dehydration on day one (despite a slightly lower ambient temperature) may have led to elevations in core temperature, more time in the ‘hard’ heart rate zone, and a higher post-shift RPE, but was not associated with inter-shift differences in physical activity.

The studies within this thesis have practical significance for firefighters, fire agencies and may be extrapolated, with caution, to emergency services/occupations who share long duration work periods in the heat wearing similar protective clothing.
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CHAPTER ONE: INTRODUCTION

Worldwide the frequency and severity of wildfires are increasing [1, 2]. Furthermore, the urban environment continues to expand into typical fire-prone areas placing more people and property at risk [3] of wildfire. An example of this is the infamous Black Saturday bushfires in Victoria (Australia) where a mass of wildfires destroyed 450 000 hectares of land [4], decimated 78 communities, injured 414 people [5], and killed 173 [6]; indeed this was the data collection arena for the first two studies (Chapters 3 & 4) of this doctoral thesis.

Wildfire firefighters are typically asked to perform physically demanding work, in emergency situations. They are routinely required to wear impermeable protective clothing for long durations often in extremes of heat and over multiple days [7]. Individual characteristics which may predispose firefighters (particularly volunteers) to experience greater levels of physical and/or psychological strain may include: their increasing age; their level of fitness and health (as a large proportion are overweight, smoke and have low levels of fitness); any tiredness (mental or physical) from their employment or other daily activities prior to turning out; any medications; their diet and fluid intake (the availability of which may also be a job-related difficulty); and their level of experience and work-hardening leading into the wildfire season.
Wildfire fighting is physiologically stressful, in particular, it is associated with cardiovascular strain and thermoregulatory challenges [8]. Raising the question: ‘How can the health and performance of firefighters be improved?’ In an ideal world, fitness training programs would be undertaken in the weeks prior by those likely to be engaged in wildfire operations in the immediate future. In career and seasonal firefighter ranks the implementation of such a fitness regimen does occur. However, the majority of wildfire firefighters across Australia are volunteers, from all walks of life [9] (office jobs, farmers, truck drivers etc.). Volunteers (albeit the ACT RFS) are not required to meet fitness selection criteria and have limited pre-fire season time available to prepare physically for the demands of the job. A key element to enhance the health and performance of firefighters is therefore: ‘what can be done the day before, on the wildfire shift, and after the shift to enhance work performance and lower physiological strain?’

Tackling hydration may be one such thing. Dehydration has been repeatedly reported by fire agencies and international wildfire research [10-14]. It can result from reduced fluid ingestion and/or greater fluid loss, mostly via sweat. Sweat loss is markedly enhanced in hot weather and when wearing impermeable protecting clothing. As a result of significant fluid loss, plasma volume drops and heart rate is increased [15]. Dehydration also results in increased core temperatures during work in temperate [16, 17] and hot environments [18-20] with a reported increase of 0.1-0.2°C with each 1% increase in dehydration [21, 22]. Both the rate of rise and level of core temperature reached have been implicated in the development of heat exhaustion [23-26]. The collective efforts of Hendrie et al. [12], Cuddy et al. [11], Ruby et al. [10] and Raines et al. [27] have
established that the wildfire fighting work environment threatens hydration status [10-12]. Accordingly, their research found that firefighters arrived on shift significantly hypohydrated [10, 11, 27] and maintained their level of dehydration [10, 27] or accentuated it [11, 12] upon conclusion of their work shift. Hence fluid intake may impact firefighter work performance and health, provided the level of dehydration is severe enough. Unfortunately, there is limited firefighter specific research and little agreement on how much fluid; how often firefighters should consume fluid before, during, or after their shift; or how the environment (e.g., fire intensity, ambient temperature) affects fluid consumption.

We do not know if increasing a firefighters’ fluid intake will improve hydration status and result in lower core temperatures and/or less time spent in high ‘risky’ heart rate zones, nor if these outcomes could transfer to greater distances covered (ie. greater work productivity). A number of benefits may eventuate from such an outcome: 1) firefighters spend less time exposed to high heart rates, which reduces their risk of having a cardiovascular event (for those displaying risk factors) [28, 29]; 2) lower body temperatures may allow firefighters to perform more work at a higher intensity and leave firefighters feeling perceptually better and recovered for the following shift; 3) improved performance and/or productivity which may transpose to more aggressive fire containment. Whether these potential outcomes eventuate is to be determined.

**Scope of Thesis**

There has been minimal research that specifically looks at the interplay between fluid consumption, hydration and physiological strain in wildfire fighters. This doctorate addresses the issues associated with fluid intakes and physiological strain of Australian
wildfire fighters before, during, after and between day shifts. The specific aims addressed include:

1) To evaluate whether ingesting a bolus of fluid before the shift has any effect on firefighter fluid consumption, core temperature, or the time spent in high heart rate and work activity zones when fighting emergency wildfires.

2) To examine i) wildfire fighters’ ability to consume a prescribed fluid volume (1200 ml·hr⁻¹), ii) the effect of fluid intake on plasma sodium and hydration, and iii) firefighters’ heart rate, core temperature response and activity during emergency suppression shifts.

3) To evaluate i) firefighters’ pre- and post-shift hydration status across two shifts of wildfire suppression work in hot weather conditions, ii) to document firefighters’ fluid and food intake during and between two shifts, iii) to assess any changes in heart rate, firefighter activity, perceived exertion and core temperature across the two consecutive shifts.
CHAPTER TWO: REVIEW OF LITERATURE

This review of literature will discuss the potential for fluid intake to influence hydration and physiological strain during wildfire fighting shifts. It begins with a brief overview of firefighting approaches worldwide and the stresses and strains associated with wildfire fighting. The potential impact fluid intake might have on reducing firefighter strain, and the research that has examined hydration in this population, will then be discussed. The review then systematically presents the data available on fluid intake before the shift, during the shift and between shifts on multiple day work deployments. In some instances manual handling work or intermittent exercise is used as the comparison due to the lack of wildfire fighting specific research in this area.

WILDFIRE FIGHTING

Ideal wildfire conditions require abundant rains and vegetation growth followed by a 6-8 week dry period, and a regional weather pattern that carries winds over a hot dry land mass, resulting in corridors of strong wind, high temperatures and low humidity (<20%) [30]. The south eastern pocket of Australia is regarded as the most fire-prone region in the world, followed by California and southern France [31]. Additionally, the threat and severity of wildfires are on the increase [1, 2]. Each year wildfires threaten structures, mining resources, wilderness zones, logging areas, highways and power lines; leading to extensive property damage, loss of produce and livestock, personal injury and death to residents living in fire affected areas and the firefighters themselves [32].
Two wildfire fighting approaches are employed by Australian fire services; for the purpose of this review they will be referred to as ‘wet’ and ‘dry’ firefighting. The ‘wet’ tanker-based (Figure 1) approach primarily uses water and foam suppressants for the protection of property and extinguishing fires along established breaks [33, 34]. It has been defined as a discontinuous activity which involves brief periods of intense work performed regularly within every two hour window of a 10.2 ± 2.1 hour wildfire fighting shift [35], regardless of the deployment objective. Typical tasks performed by tanker-based ‘wet’ wildfire fighters include; manual lifting, carrying and rolling out lengths of hose, advancing and repositioning hoses and stepping on and off tanker trucks [34].

**Figure 1:** ‘Wet’ firefighting. Tanker based wildfire fighters knocking down a grass fire at the Bunyip State Park fire near Labertouche on Black Saturday, 7th February 2009. Copyright: © CFA Public Affairs. Photographer: Keith Pakenham.
In contrast, ‘dry’ firefighting (Figure 2) primarily involves the creation of fire breaks using earth moving machinery (e.g. Bulldozer, Grader) and seasonally employed fire crews using McLeod (rake-hoe), Pulaski (modified axe) handtools and chainsaws to clear low lying vegetation either around the fire edge or at some distance from the main fire to use as a perimeter for back-burn operations [33, 36]. Dry firefighting methods are more commonly employed in the difficult terrain often encountered in remote areas [31, 33]. Blacking out is then performed by both firefighting groups on burnt ground. This involves using axes and handtools to maneuver and expose burning debris and using hoses to apply water, retardant and foam suppressants to prevent the re-ignition of smoldering embers [37]. In a series of experiments, Brotherhood and colleagues measured the raking productivity, and physiological responses of 27 Australian male ‘dry’ wildfire fighters in simulated [36] and wildfire [12, 36, 38-40] conditions. When the traditional ‘step-up’ method [37] of fire line construction was employed, the work rate was 724 W [41], equating to 67% of the wildfire fighters maximum work capacity which may need to be sustained for many hours [33]. It was concluded that ‘dry’ wildfire fighters responses (physiological and behavioral) when suppressing fires in Australian eucalypt forest, were mainly due to their physical work rather than exposure to the fire itself [12].
The third comparison group of firefighters is the American HotShot ‘dry’ firefighters (Spanish Helitack crews operate similarly to these [42]). As depicted in Figure 3 they fall under the same umbrella as the Australian ‘dry’ firefighters however they have different work and equipment approaches and usually carry everything they need for their shift. This is an important distinction as direct applications of international research across the different firefighting approaches should be made with an appreciation of the differences. The total energy expenditure of seventeen American HotShot ‘dry’ handtool firefighters (Figure 3) during five days of wildfire containment was determined using an isotope dilution technique. Total energy expenditure was found to be $17.4 \pm 3.7 \text{ MJ}$ and $17.5 \pm 6.9 \text{ MJ}$ per day during days one to three and four to five, respectively [43]. Approximately half of the American HotShots total daily expenditure was associated with their physical exertion (days one to three $8.8 \pm 3.0 \text{ MJ}$; and four to five $8.9 \pm 6.1 \text{ MJ}$) [43].
Wildfire fighting is hazardous and demanding [43]. Remote locations, poor sleep, impermeable protective clothing, changes to their diet, and sometimes food and/or fluid restriction [44] are some of the circumstances firefighters are required to cope with. They may also bear significant physical or physiological stress as they perform tasks over long durations (10-15 hour shifts) for multiple days [28]; often under threatening circumstances, with extended exposure to smoke, difficult terrain, and hot weather. Notwithstanding the aforementioned challenges, the population of firefighters operating in the most wildfire prone region of the world (South-Eastern Australia [31]) are aging males [9]. The vast majority of these firefighters are volunteers, from all walks of life, who have no physical fitness selection criteria [45]. Undoubtedly, improving the health
and performance of these firefighters is of upmost importance to the firefighters themselves, their families, and the communities they protect.

**HOW CAN THE HEALTH AND PERFORMANCE OF FIREFIGHTERS BE IMPROVED?**

Reducing the strain experienced by firefighters, by improving their tolerance to the stress imposed by wildfire fighting operations, may improve firefighter health and performance. Stress, in this instance, directly relates to the physical loads imposed on wildfire fighters [46]. This includes the intensity and duration of wildfire fighting work or exposure to heat load from the firefighters own exertion, personal protective clothing, the weather or fire [46]. Obviously, a number of these stressors are impossible to manipulate or eradicate in the wildfire fighting environment.

Strain relates to the firefighters’ physiological and/or psychological response to that imposed load (stress) [46]. Namely, responses such as increased heart rate, sweat rate and subjective ratings of thermal discomfort and perceived exertion [46]. When stress overloads the firefighter by being too severe or prolonged; fatigue, impaired performance, and impaired judgment ensue (Figure 4) [46].
FIGURE 4: INCREASING STRESS AND STRAIN LEADS TO FATIGUE AND GREATER THREATS TO FIREFIGHTER HEALTH AND SAFETY. MODIFIED FROM BUDD ET. AL. [46].

This potential escalation of events, stemming from fatigue, can have devastating effects on a firefighter, their crew, their wildfire fighting objective - the protection of people, property and habitat. Fatigue can quickly migrate the firefighter from safe and productive work practices to unsafe working behaviors, accidents, injury and in severe cases, death (Figure 4) [46]. In athletic and occupational endeavors, accumulated fatigue tends to be the result of mental and physical stress; whereas in firefighters, the additional pressures of sleep deprivation [47, 48], working in environmentally challenging conditions (enduring smoke and dust exposures [47, 49]) and physical danger could also contribute to the level of emotional and physiological fatigue [50]. Further challenges intensifying physiological strain also include: the fire behavior
dictating physical work rates [40], operating in habitually remote locations [47], coupled with dietary changes [47, 51], working closely with new groups of people in a less than hygienic setting which can increase the risks of infection during times of reduced immunity [47, 52, 53]. The very nature of firefighting is sporadic and unpredictable, characterized by long periods of waiting between bouts of intense activity, which can amplify emotional stress and anxiety [54]. These aforementioned factors are likely to apply to all wildfire fighters despite any differences in work pattern, work duration or preferred method of wildfire containment (e.g. wet or dry firefighting).

Being able to improve a firefighters’ tolerance to stress could reduce strain and potentially improve physical work performance on the fireground. Indeed, it has been hypothesized that the personal factors of fitness, fatness, heat acclimatization, dehydration and age could modify the tolerance of an individual to the stresses associated with wildfire fighting (Figure 5) [46].

For example, improvements in fitness are desirable in a firefighting population and may improve physical work performance and reduce fatigue, as may reducing the age of firefighters; however, these factors are either not malleable or they require pre-season intervention and a great deal of available time. Raising the question: what could be done, in the moments before a shift commences, during the shift and between shifts which could improve the physical work performance of firefighters?
Fluid Intake may Reduce Firefighter Strain

Altering the fluid intakes of firefighters to reduce the likelihood of dehydration and its associated consequences, is worthy of investigation. When body water is being lost, and is not matched by fluid intake, the body undergoes dehydration [15]. Dehydration is a dynamic process which leads to a state of hypohydration [15]. This depleted state of body water can be associated with mental, physical, health and safety impairments [55, 56]. The level of dehydration which results in the aforementioned deleterious effects is graded. Minimally dehydrated individuals who lose 1 to 3% of their body mass and display urine specific gravity (USG) results of 1.010-1.020, would be less likely to be affected compared to significantly dehydrated individuals (at -4 to -5% body mass loss and USG 1.020-1.030), who in turn, would be expected to display less mental, physical,
health and safety impairments than seriously dehydrated individuals who have lost more than 5% of their body mass and have USG readings over 1.030 [57].

The increased physiological strain and performance impairment associated with dehydration during exercise has long been recognized [57-59]. Essentially, the greater the degree of dehydration, the greater the impact on human physiological systems and performance [57] and therefore worker productivity and safety. Isolating the physiological changes that contribute to decrements in human performance is challenging as a change in one system (e.g. cardiovascular) can affect the performance of another system (e.g. thermoregulatory, muscular) [57]. In non-firefighting contexts, dehydrated individuals display elevated heart rates during exercise in the heat [60], reductions in physical work capacity [61-66], a decrease in mental performance and decision making abilities [67-71], and elevations in core temperature [60], which can eventually lead to exhaustion or collapse [66, 72-74].

Scientific evidence indicates that work tasks which are strength or power based do not appear to be negatively affected by dehydration [75] until moderate losses greater than 3% [76, 77] or 5% of total body water have been reached [61-63]. The short-duration tasks performed by wildfire fighters, in isolation, are less likely to be affected by dehydration. However, when the tasks are repeated over an extended period, or tasks are performed consecutively in a relatively short period (dependent on the work to rest ratio), there is a greater reliance on aerobic metabolism [78]. The finding that aerobic performance decrements are amplified by greater levels of dehydration and increasing environmental temperature is well supported and depicted in Figure 6 [64-66]. However, it is important to note that there are no units for the measurement of the
performance decrement with “dehydration” [65]. Remembering that Australian wildfire fighters often work in ambient temperatures of 35-45°C [30], it is possible that aerobic performance could decline rapidly when firefighters are dehydrated.

![FIGURE 6: THEORETICAL EFFECTS OF DEHYDRATION ON AEROBIC PERFORMANCE DURING PROLONGED EXERCISE IN ENVIRONMENTS THAT VARY IN TEMPERATURE (5-30°C). TAKEN FROM COYLE [65].](image)

Studies as early as 1960 and 1980 demonstrated that greater dehydration resulted in greater reductions in prolonged exercise performance [64, 79] during field investigations in temperate [80, 81] and warm-hot [82-84] environments. In euhydrated people, climatic heat stress alone has been shown to decrease maximal aerobic power by 7% [74]. Unsurprisingly, the warm-hot environments elicit the most consistent and largest degradations seen in prolonged performance [22].

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Unfortunately there has been limited scientific exploration [10, 12, 85] into dehydration and its proposed ill-effects on wildfire fighters. Previous research identifying dehydration in workers performing physically demanding jobs has focused on structural firefighting [86, 87], forestry [80], and mining [88] settings. Considerably less research attention has been directed toward wildfire fighter hydration. There are great difficulties associated with collecting data on geographically dispersed firefighters performing extended work and varying tasks in wild and undulating terrain [86]. Simulations within the laboratory, while providing some useful information, may not be directly applicable to actual wildfire fighting as they cannot reproduce the complexity of the wildfire environment nor the behavioral responses of firefighters [89]. Despite this, within the small body of research, the effects of dehydration have been investigated during the containment of American [10, 85] and Australian wildfires [12] utilizing ‘dry’ firefighting techniques (namely fire line construction with handtools). Hendrie et al. [12], Cuddy et al. [85] and Ruby et al. [10] have established that the work environment of wildfire fighters threatens hydration status [10, 12, 85] (Table 1). Firefighters were arriving to work with minimal to significant dehydration [10, 11] and maintaining this level [10] or accentuating it by shift completion [12, 85] (Table 1). As mentioned previously, significant dehydration (USG 1.020-1.030) is likely to impair firefighters’ mental and physical abilities [55, 56], hence this is likely to influence their performance on the fireground. However, it is unclear how often firefighters sway from euhydrated, to mild dehydration, to minimal and significant dehydration.

In sporting contexts (e.g. marathon running), fluid restriction has been purported to decrease physical performance [90-92]. Hence avoiding dehydration by consuming
fluids while wildfire fighting, and arriving on shift in a euhydrated state may be of benefit to firefighter physiology and performance. At present there is only a small pool of hydration-focused research in ‘dry’ firefighting, there has been no published data that specifically measures hydration parameters during simulated or live wildfire events using ‘wet’ firefighting techniques.
# Table 1: Three studies investigate hydration in ‘dry’ wildfire fighters. *P<0.05, **P<0.01, ***P<0.001.

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects</th>
<th>Daily Water Turnover</th>
<th>Fluid Intake (g·hr&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Body Mass Changes</th>
<th>Sweat Rates (kg·hr&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Urine Osmolality (mOsm·L&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>Urine Specific Gravity</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australian ‘dry’ Handtool Firefighting with and without fire, Hendrie [12]</td>
<td>n=27</td>
<td>(25.9±6.8 years)</td>
<td>Fire 490±262 (0-1352)</td>
<td>Fire -0.654±337 kg·h&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>1.144±0.373</td>
<td>-</td>
<td>-</td>
<td>Wildfire fighting with handtools causes rapid dehydration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No fire 261±139 (45-802)**</td>
<td>Fire -1.996±35 kg·h&lt;sup&gt;-1&lt;/sup&gt; (peak); No Fire +0.068±133 kg·h&lt;sup&gt;-1&lt;/sup&gt; - 0.158 kg·h&lt;sup&gt;-1&lt;/sup&gt; (peak)</td>
<td>2.139 (peak); No Fire 0.194±0.072, 0.422 (peak)**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American HotShot Firefighting Over a Shift, Ruby [10]</td>
<td>n=14</td>
<td>(29.3±4.7 years)</td>
<td>- 6.7±1.4 L·day&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>-</td>
<td>71.9±10.4 kg before, 70.9±10.2 kg after shift * (-1.4%)</td>
<td>-</td>
<td>562±175 before, 629±216 after shift *</td>
<td>American wildland firefighting environment threatens hydration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.016±0.006 before, 1.018±0.0006 after shift</td>
<td></td>
</tr>
<tr>
<td>American HotShot Firefighting Over a Shift, Cuddy [85]</td>
<td>n=8</td>
<td>(23.0±2.4 years)</td>
<td>- 504±472 water, 285±279 water + electrolyte*</td>
<td>Overall = 78.1±13.3 kg before, 77.3±13.3 kg after shift * (-1.0%) Water - 0.5% and -1.4% water + electrolyte</td>
<td>-</td>
<td>-</td>
<td>Supplemeting water with electrolytes can reduce the amount of fluid necessary to consume and transport during extended activity.</td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>1.019±0.007 to 1.023±0.010 water vs. 1.019±0.005 to 1.024±0.009 for water and electrolyte groups before and after shift, respectively*</td>
<td></td>
</tr>
</tbody>
</table>
Issues with the aforementioned body of firefighter hydration research include the methods chosen to discern hydration status. Changes in body mass is a simple, convenient, and rapid feedback method safe for both laboratory and field use [93, 94] deemed by many as an accurate reflection of an individual’s hydration status [57, 93-95]. This method does, however, rely on the assumption that 1 g loss in body mass is equivalent to 1 ml loss of water [93] which is true for an individual during times of caloric balance (when corrected for the mass of dietary intake, urine and fecal loss, sweat evaporation and sweat absorbed in clothing) as no other body constituents are lost at a matched rate [96]. However, studies show that when body mass measures are required over an interval greater than four hours, (firefighting shifts last 10 - 15 hours [35, 85]) substrate oxidation and respiratory water losses become large enough that the results need to be corrected for these factors [96, 97]. Unfortunately, Hendrie and colleagues [12] did not quantify substrate oxidation or respiratory water losses in their firefighters. Additionally, the exact time interval between body mass measurements during this study requires further scrutiny. It was stated that firefighters were weighed, waited 1-2 hours for favorable lighting conditions during fire-rakes and spent 2.0 ± 0.8 hours (range 0.6-3.7) working with rake-hoes; while during non-fire rakes, work duration was 3.5 ± 1.3 hours (range 1.6 - 7.0 hours). After completing the rake, firefighters were reweighed on average 45 ± 19 minutes after stopping work. Therefore the time intervals for fire-rakes potentially ranged from 2.35 to 6.45 hours and 2.35 to 7.75 hours in non-fire rakes. It is unclear how many of their firefighters were weighed within the four hour period, and hence the accuracy of their hydration results based on body mass change is questionable. From one day to the next, body mass fluctuates 0.51 ± 0.20 kg [98]. Inherently, a baseline measure is required comprising three consecutive
measurements of morning body mass to provide an accurate assessment of daily changes in active men who replace 100% sweat lost during exercise [97]. It has also been stressed that body mass should be used in conjunction with other assessment tools to dissociate gross tissue losses from water losses [98]. Hendrie and colleagues [12] did not perform a three day baseline body mass calculation to improve the validity of their body mass measure as a marker of hydration status, nor did they correlate body mass to any additional markers of hydration. Despite these apparent shortcomings, Hendrie and colleagues did measure dietary intakes and excreted waste in their firefighters which improved the validity of their measure, but on balance, relying on one marker of hydration status is not ideal [57]. From the available data, Hendrie and colleagues concluded that ‘dry’ wildfire fighting with handtools causes rapid dehydration and that research focus should be drawn on drinking practices before, during and after firefighting [12].

The decrease in nude body mass and total body water observed in the American handtool wildfire fighters after the shift was coupled with non-significant increases in urine osmolality and urine specific gravity (USG). Firefighters arrived on shift in a minimally dehydrated state (USG = 1.016 ± 0.0060, Table 1) [57]) and maintained this state after the shift (USG = 1.018 ± 0.0006). Urine specific gravity and urine osmolality have been publicized as sensitive to changes in hydration but lag behind during periods of rapid body fluid turnover [93] where the magnitude of the correlation is small (r=0.10) [99] or moderate (r=0.46) [100] when compared to plasma osmolality during acute dehydration. This time lag (Figure 7) is due to a cascade of events originating from a plasma osmolality change which triggers endocrine regulators to reabsorb water
and electrolytes in the kidney [100]. Dilute urine production can occur even when dehydration is present [99, 100] as urinary markers mimic the volume of fluid consumed rather than the amount retained by the body [101]. Therefore, in situations where rapid rehydration [102], alcohol consumption [103], caffeine ingestion [104], or severe dehydration [105] occur (all possible during the firefighters tour of duty); urine results may be altered independently of hydration level.

**Figure 7:** The discrepancy between blood (plasma osmolality) and urine (urine osmolality and USG) markers of hydration in euhydrated subjects who dehydrated to 5% of their body weight via exercise in the heat (40°C, 20% RH).*Significant difference from baseline euhydrated condition (P<0.05). Figure from Popowski [100].
Additionally, there is no agreed upon ‘euhydrated’ range for urine specific gravity. Further there is little to no evidence that urine specific gravity is sensitive to shifts in hydration status (unlike plasma osmolality) during rapid changes in body water turnover [100]. Scales relating urine specific gravity to particular hydration ratings have been suggested [57, 105], and the reader is referred to Table 2 for an illustration of this relationship.

**Table 2: Body Weight and Urine Specific Gravity as Indices of Hydration Status.**

<table>
<thead>
<tr>
<th>Hydration Status</th>
<th>Body Weight Change (%)</th>
<th>Urine Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Hydrated</td>
<td>+1 to -1</td>
<td>&lt;1.010</td>
</tr>
<tr>
<td>Minimal Dehydration</td>
<td>-1 to -3</td>
<td>1.010 - 1.020</td>
</tr>
<tr>
<td>Significant Dehydration</td>
<td>-4 to -5</td>
<td>1.020 - 1.030</td>
</tr>
<tr>
<td>Serious Dehydration</td>
<td>&gt; -5</td>
<td>&gt;1.030</td>
</tr>
</tbody>
</table>

% Body weight change = [(baseline weight - assessment weight)/baseline weight] x 100. Obtained from Casa [57] who states that the numbers provided are only general guidelines.

Similarly, no universally accepted definition of well hydrated or dehydrated urine osmolality values exist [106]. Urine osmolality has been shown to misrepresent hydration status immediately after exercise [99]. However, when studying day-to-day hydration status in athletes during training in a hot environment or competition in a warm environment; urine osmolality has been regarded as an effective tool by Shirrefs et al. [107]. The American National Athletic Trainers Association currently advocate the use of three techniques: body mass change, urine specific gravity and urine colour, when assessing the hydration status of athletes [57].

As a whole, the three studies in ‘dry’ firefighting support the likelihood that wildfire fighters are under threat of minimal to significant dehydration. The complete physiological consequence is yet to be fully elucidated. However, no scientific studies
have investigated the interplay of fluid intake, hydration and physiological parameters in 'wet' wildfire fighters, although there are some inferences published in local fire agency reports [108]. Despite this lack of information, heat stress and physical over-exertion (which have been linked to dehydration), occur frequently in volunteer wildfire fighters [33]. Black reported that almost all members of the ‘wet’ Warrimoo Volunteer Brigade (NSW, Australia) involved in suppressing uncontrolled wildfire have suffered early symptoms (nausea, headaches, dizziness) of heat stress [33]. Additionally, reports from Australian ‘wet’ fire agencies place dehydration in the top three most frequent injuries/accidents reported, supporting the presence of dehydration among this workforce (Table 3) and its worthiness of further investigation. However, the criteria fire agencies utilized to define dehydration was not specified in their reports.

| TABLE 3: DEHYDRATION RELATED ACCIDENT AND INJURY REPORTING BY SOUTHERN AUSTRALIAN ‘WET’ WILDFIRE FIGHTING AGENCIES [35]. |
|---------------------------------|-----------------|-----------------|
| Tasmanian Fire Service (Tasmania) [109] | Country Fire Authority (Victoria) [110] | Country Fire Service (South Australia) [111] |
| **Years in Report** | **Cases of Dehydration** | **Cases of Heat Stress** | **Cases of Fatigue** |
| 2000-2006 | 4 (2%) | 3 (1%) | - |
| 1995-2004 | - | 57 (1.9%) | - |
| 2003-2006 | 1 (0.2%) | 24 (5.5%) | 6 (1.4%) |
| **Total Cases** | **219** | **3724** | **434** |

While specific cases of dehydration were low 2% and 0.2%; heat stress cases were 1%, 1.9% and 5.5%; and fatigue were 1.4% of total reports from Tasmanian, Victorian and South Australian fire agencies, respectively (note: heat stress and fatigue have been associated with dehydration). The fire agency reports did not detail the severity, nor the complete diagnosis, nor the methods for diagnosis. It is also important to note that the true incidence of dehydration is not likely captured by these data. For instance, it has
been noted in Country Fire Authority (Victoria) occupational health reports that ~300 firefighters presented with dehydration/heat stress in 1997 alone [108]. After regularly attending wildfires (years 2006 - 2009) it is apparent that crew leaders and crew members with first aid qualifications are the primary caretakers dealing with minor medical concerns (including dehydration) on the fireground (Raines, unpublished observations). Auxiliary first aid and ambulance services are also provided at staging areas (base camp) during large scale wildfire events. All the cases of dehydration reported to these service providers do not appear in fire agency injury/accident reports. Anecdotally, there is also a reticence of firefighters to officially report incidents; for reasons including the fear of being taken off the fireground and the effort of completing paperwork. Hence the higher incidence of dehydration reported by Black (almost all members of brigade experienced dehydration/heat stress) [33] may be a more accurate reflection of actual occurrences while wildfire fighting. It is apparent from these limited data, which does support the presence of dehydration that more research is needed to understand the drinking behaviors and hydration status of wildfire fighters and the overall effect on physiology, productivity, safety and health.

**Body Water Balance and the Firefighter**

When hydrated, the human body exists in what is termed a euhydrated state, or a level of normal body water. Water is a major component of the body and is essential for homeostasis, biochemical reactions, lubrication, the transport of nutrients and wastes, temperature regulation, and tissue structure maintenance [15, 112]. When euhydrated, the human body functions better, even in challenging situations [15, 57].
Daily water turnover for a sedentary individual in a temperate environment is 5-10% of their total body water per day via obligatory fluid loss avenues; respiration, urine, and sweat [15, 58]. Resting respiratory losses (1-2 g·min⁻¹ [97]) are usually offset by the amount of water liberated during the oxidation of substrates at rest [58]. However, respiratory water loss is increased (beyond the offset provided via oxidation) during exercise, hyperventilation, fever and low environmental humidity [105] (such as the wildfire environment where relative humidity is often lower than 20% [30]).

Urine output is the primary means by which the body regulates net water balance [58, 75] and approximately 1-2 L·day⁻¹ is lost [75]. This varies remarkably according to the individuals’ fluid consumption and level of activity [58, 75]. The prevalence of caffeine and alcohol in the diet and any pharmaceutical medications that exert a diuretic effect also result in increased urinary output and greater body water losses [55, 113, 114].

Water losses in sweat vary greatly and depend mainly on the intensity and duration of physical work, heat acclimation status, clothing and the surrounding environment [115]. Sweat rates for residents in desert climates performing occupational duties have been recorded at 0.3-1.2 L·h⁻¹ [66]. In the case of wildfire fighting, personal protective clothing is an additional factor which influences heat load and sweat rate, therefore an individual’s water needs [58]. When performing handtool work and wearing wildfire turnout clothing, Australian ‘dry’ firefighters averaged sweat rates of 1.144 L·h⁻¹ with a range of 1-2 L·h⁻¹ [12]. Because sweat losses and fluid intakes vary, some individuals will encounter significant dehydration while others will complete activity with mild levels of dehydration [116].
The total amount of body water for an individual at a given time is influenced by their gender [117-119], aerobic fitness [60, 120-124], body composition [58], level of heat acclimatization [123, 124], and drinking behavior [57, 125-127]. The daily water requirement for sedentary to very active people in temperate conditions ranges from 2-4 L·day⁻¹ and increases to 4-10 L·day⁻¹ in hot climates [128]. This water requirement is increased by high metabolic rates, air temperatures, solar load and low relative humidity [58]. Even a slight reduction in total body water (and accompanying increase in plasma osmotic pressure [129]) is detected by the hypothalamic-pituitary-adrenal axis which signals a thirst cascade, increases arginine vasopressin (AVP, an anti-diuretic hormone) and aldosterone [130]. This process initiates an increase in water consumption and water retention. This interplay between neuro-endocrine and renal systems ensures that changes in total body water and tonicity are minimized in the short term [15, 130].

Prolonged strenuous work in the heat may require fluid replacement in the order of 10-15 L·day⁻¹ [129]. In general, water intakes regulated by hunger and thirst are adequate to offset any daily water losses, provided there is sufficient access to food and beverages [131-134]. However, access to drinking fluids may pose a challenge during remote fire response, although the intermittent work profile of firefighters should enable sufficient time for breaks to consume food and beverages. Additionally, people older than 55 years of age have a blunted thirst sensation compared to 18-29 year olds [135]. This observation is important since total body water decreases with age [136], and the aged have a reduced ability to conserve water and electrolytes in the kidneys when challenged by body water deficits [128]. For these reasons, the aging personnel of the Australian
wildfire fighting services [137], may be at a greater risk of dehydration than their younger counterparts in similarly demanding roles.

When body water losses are incurred, through exercise or environmental exposure, many hours of fluid consumption may be required to re-establish body water balance [138]. One of the difficulties of matching water replacement with losses is that the thirst signal is often a poor indicator of total body water losses [66, 139, 140]. Ad libitum (self-selected) intake directly relates to sensations of thirst which initiates behavioral change to increase drinking and/or reduce exercise intensity [22, 141]. Thirst acts as a conscious perception of cellular disturbance by detecting an increase in plasma osmolality from losses in body water [22] which is perceived at ~2% body mass loss [66, 139, 142, 143]. When ad libitum intake of fluid is inadequate to maintain a hydrated state, an individual experiences ‘voluntary dehydration’ [144, 145]. In these circumstances, when physical performance is required, forced hydration strategies have been advocated to avoid voluntary dehydration [90, 92, 146, 147]. However, progressive dehydration is inevitable in some cases as athletes and occupational workers sweat outputs (1-3 L·h⁻¹ [15] and 1-2.25 L·h⁻¹ [66], respectively) often exceed maximum gastric emptying and absorption rates of ~1.2 L·h⁻¹ during physical work [144, 148]. It is possible that wildfire fighters’ sweat rates could exceed 1.2 L·h⁻¹ during peak workloads due to the many factors which may contribute to dehydration in this workforce. Therefore it is likely that Australian wildfire fighters could experience ‘voluntary dehydration’ across long and repetitive shifts. This is yet to be determined by research.
The food items firefighters consume may also affect the quantity of water ingested. However, higher fluid intakes may not necessarily affect preferences for food items (i.e. foods naturally lower in water content) nor the total quantity of food consumed. As opportunities to eat could be limited during the emergency firefighting shift, firefighters may consume food when convenient to do so, even if they were not hungry. Although, previous work has associated greater food intake with higher fluid consumption [149]. Research is yet to investigate this aspect of fluid intake.

**Fluid Intake Behavior and Hydration**

**Before the Shift**
Little is known about firefighter drinking behaviors before a shift, except that they arrive to work hypohydrated (as determined by USG) [10, 11]. We are not aware of what firefighters consume, how much they consume, nor the timing of fluid consumption in preparation for an emergency firefighting shift. Similarly, little is known about the pre-shift drinking habits of workers in other physically demanding occupations. We do, however, know that these workers often start work with a fluid deficit or become hypohydrated during the workday [58]. To illustrate this point, 60% of mine workers operating under thermal stress (temperature 25.7-35.2°C) reported to work hypohydrated (as determined by urine specific gravity) and their hydration state did not improve throughout the 10-12 hour mining shift [88]. The applicability of mining literature to wildfire fighting may be appropriate given the similar durations and nature of manual handling work. But without studies in actual firefighting, it is difficult to predict whether their pre-shift hypohydrated state will be maintained throughout a wildfire fighting shift. Indeed, pre-exercise dehydration (as measured by body mass and plasma
osmolality) has been shown to increase ad libitum drinking during ninety minutes of low-intensity treadmill walking in the heat (33 ± 0°C, 55.6 ± 2.7% relative humidity) such that hormonal and circulatory measures of exercise-heat stress are indistinguishable from exercise begun in a euhydrated state [150]. How ninety minutes of walking in the heat is likely to reflect the typical intermittent work profile of a wildfire fighting shift is unknown, so the applicability of this finding across ten to fifteen hours is questionable. It does, however, lay credence to the effectiveness of ad libitum drinking in the heat.

With respect to body water balance, for each percentage loss in body mass, heart rate has been shown to increase by four beats per minute [74]. This is imperative for wildfire fighters to understand as arriving at work hypohydrated and/or progressively dehydrating throughout their shift, for example, could result in heart rate increases of 16-20 beats per minute during physical work periods if they lose 4-5% of their body mass [58]. Given that firefighters arrive on shift hypohydrated, and there are potentially negative physiological and/or performance consequences associated with this [66, 72-74]; fire agencies may require practical strategies to counter pre-shift dehydration in their personnel. The American College of Sports Medicine recommends that hypohydrated individuals consume 5-7 ml·kg⁻¹ four hours prior to and, potentially, a further 3-5 ml·kg⁻¹ two hours before exercise [92]. Evidence supporting this specific fluid volume prescription before exercise (or work) is scarce. In spite of this, laboratory studies show that when consuming a pre-exercise bolus of fluid (ranging 100-3500 ml), exercise time until exhaustion [151] is extended and heart rate [72, 151-153] and rectal temperatures [72, 151, 153] lower during the following physical work bout. These favorable aforementioned responses from a pre-exercise bolus were amplified compared
to no fluid being consumed before exercise [72, 153] or when intermittent fluid was consumed during exercise [151, 152]. However, it is imperative to note that when ad libitum drinking was compared to the pre-exercise bolus condition, no differences in rectal temperature before or after exercise were observed [72]. Whether these relationships between pre-shift fluid bolus consumption and physiological outcomes transfer from the laboratory to the field remains to be seen.

Whether ingesting a bolus of fluid before a firefighting shift has any meaningful effect on firefighter's work activity, heart rate, or core temperature response when fighting wildfire will depend on the firefighters’ behavior, and their ad libitum fluid and food consumption during the shift. No study to date has allowed natural in-field behavior, whereby firefighters are able to freely choose the frequency, volume, timing and type of food and fluid they consume during a shift. Past studies have failed to allow these ‘natural’ behavioral choices and limited firefighter fluid choice to only water [12, 85], or only electrolyte fluid [85] and neglected to include the water obtained from food items consumed - which may contribute significantly to daily water intake [154] over a 10-12 hour workday.

**During the Shift**

According to an Australian study performed in the 1980’s, ‘dry’ wildfire fighters do not drink enough water during fire-line construction with handtools [12]. The firefighters drank more and sweated more than researchers who shared their environment, and became more dehydrated, as determined by changes in body mass [12]. While working, Hendrie et al.’s wildfire fighters drank at an average rate of 490 ml·h⁻¹ and replaced only 43% of their sweat losses [12]. The highest drinking rate of 1352 ml·h⁻¹ provided 96%
fluid replacement which demonstrates that adequate fluid replacement was attainable [12]. Average body mass losses during raking with fire were 0.9 L·hr⁻¹ with a maximum loss of 2.6 L·hr⁻¹ [12].

External to wildfire fighting research, forestry workers (who share similar environments to firefighters) neither ate nor drank during work time [155] or drank sufficiently to maintain bodyweight [156, 157]. Similarly, despite water being freely available, structural firemen failed to ingest any water during 40% of laboratory exercise trials, and the absence of forced rehydration regimes resulted in only 9% of water losses being replaced [87]. In addition, foundry workers [158], laboratory subjects [139, 159], and villagers of the coastal tropics [160] (who shared hot environments which firefighters are frequently exposed to), consistently drank to replace only 50% of their sweat losses. On balance it appears that wildfire fighters as well as workers in many other long duration occupations fail to consume adequate fluids to maintain hydration status throughout a shift.

A recent study performed by Cuddy and colleagues [85] was able to distinguish that the type of fluid consumed during work had an effect on the volume consumed by 16 (12 male, and 4 female) American ‘dry’ firefighters during a 15-hour shift. Half the firefighters consumed only water (504 ± 472 ml·hr⁻¹) while the other half consumed 220 ml·hr⁻¹ less (P<0.05) of a water and an electrolyte mix (285 ± 279 ml·hr⁻¹) [85]. Between groups there was no change exhibited in body weight, drinking frequency or urine-specific gravity results despite the large disparity between volumes of fluid consumed [85]. There was a main effect of time for body weight, demonstrating an overall decrease (78.1 ± 13.3 and 77.3 ± 13.3 kg pre and post-shift, respectively, P
<0.05) across the work shift [85]. Urine specific gravity increased (P<0.05) pre to post-shift, but no differences were apparent between the groups who arrived in a minimally dehydrated state (1.019 ±0.007, 1.019 ±0.005) and finished in a significantly dehydrated state (1.023 ± 0.010, 1.024 ±0.009 for water versus water and electrolyte groups, respectively) [85] according to the classification outlined by Casa (Table 2) [57]. Limitations to the data presented by Cuddy include the lack of baseline data, as firefighters were already several days into a 14-day deployment; no effort was made to equalize the taste of beverages between hydration groups, possibly affecting palatability and subsequent consumption; no dietary information was recorded which may have impacted body mass changes; and only two markers of hydration status (body mass and urine specific gravity were conducted). Obtaining additional information such as differences in the volume of urine produced between water and water with electrolyte groups would have been an interesting and valuable addition to this study as others have suggested that sodium supplementation (electrolyte) reduces urine output, expands plasma volume and hastens rehydration [161, 162]. In conclusion, the authors advised that by supplementing water with electrolytes, firefighters could reduce the amount of fluid necessary to consume and transport during extended activities which could minimize carrying excessive weight and possibly reduce the fatigue experienced during the shift (although fatigue was not directly measured). To reiterate, while Cuddy et. al.’s [11] HotShot firefighters consuming the electrolyte additive drank less fluid overall; firefighters in both groups were significantly hypohydrated at the end of the shift. This raises the question of whether increasing the overall fluid intake volume, with access to both electrolyte and water, could result in euhydrated firefighters.
Forced drinking is based on research which proposes that only full replacement of fluid during exercise can optimize performance and minimize health risks [22, 57, 163, 164]. In individuals performing arduous work in temperate and warm-hot environments, forced drinking strategies out-perform limited fluid in laboratory and field research [90, 92, 146]. It should be noted that forced drinking may have its drawbacks. For instance, large fluid volumes were forcibly consumed by soldiers to avoid dehydration and related heat injuries, regardless of the environmental conditions [147]. As a consequence, there were 190 military hospitalizations from water intoxication in a 10-year period (1989-1999) [165, 166] and a call to revise the inappropriate fluid consumption recommendations [167]. The more recently developed US Army fluid recommendations take into account a soldiers’ work intensity, work to rest ratio, the environment and also sets an hourly and daily upper limit on fluid consumption [167-169]. Given the numerous exercise-associated hyponatremia cases [165, 166, 170, 171], some which resulted in death [172-174], consuming vast volumes of fluid is controversial [175]. Ad libitum drinking reduces the risk that individuals will over-drink and induce exercise-associated hyponatremia, risking death, as they will develop uncomfortable symptoms during exercise [163, 164, 170, 176-183]. Additionally, no conclusive evidence is available which demonstrates that athletes do not perform optimally when ad libitum drinking dictates fluid intake [22, 163, 164, 176]. While ad libitum fluid intake during exercise in the heat does result in an incomplete replacement of body water losses [12, 97, 184], experimental data confirms that performance is improved when some fluid is consumed during exercise compared to no fluid [185-189]. Numerous studies strengthen the argument that ad libitum drinking is at least as effective at reducing the risk of heat stroke and improving performance as full fluid replacement [163, 185-189].
Fire agencies in Australia (Table 4) and elsewhere, currently prescribe target hourly drinking rates for their firefighters to follow while suppressing wildfires [13]. The scientific evidence supporting these prescribed drinking targets is, unfortunately, lacking. The aforementioned disagreement in the hydration literature and the lack of studies performed directly on firefighter fluid needs, may have contributed to the considerable variation in fluid volumes prescribed by fire agencies across Australia’s states and territories (Table 4).

Table 4: Australian Fire Agency Fluid Consumption Guidelines, 2008.

<table>
<thead>
<tr>
<th>Fire Agency (State)</th>
<th>Fluid Volume (litres per hour)</th>
<th>Fluid Product (in addition to water)</th>
<th>Total Fluid (litres in 12 hour shift)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country Fire Authority* (VIC)</td>
<td>1.8</td>
<td>Staminade Hydrate</td>
<td>21</td>
</tr>
<tr>
<td>Department of Sustainability and Environment (VIC)</td>
<td>1</td>
<td>None promoted</td>
<td>12</td>
</tr>
<tr>
<td>Country Fire Service* (SA)</td>
<td>1 - 1.5 for moderate conditions, more may be required</td>
<td>Any Sports Drinks</td>
<td>12 – 18 or more</td>
</tr>
<tr>
<td>Department of Environment and Heritage (SA)</td>
<td>1</td>
<td>Any Sports Drinks</td>
<td>12</td>
</tr>
<tr>
<td>Tasmanian Fire Service &amp; Forestry Tasmania* (TAS)</td>
<td>1</td>
<td>Water only</td>
<td>12</td>
</tr>
<tr>
<td>Queensland Parks and Wildlife Service (QLD)</td>
<td>0.5 During heavy activity</td>
<td>Any Sports Drinks</td>
<td>6</td>
</tr>
<tr>
<td>Department of Environment and Conservation (WA)</td>
<td>1 - 3</td>
<td>Any Sports Drinks</td>
<td>12 – 36</td>
</tr>
</tbody>
</table>

* ‘wet’ firefighting agencies.

Target fluid volumes prescribed by Australian fire agencies, range from 500 to 3000 ml·h⁻¹ per firefighter across a twelve-hour fireground shift (Table 4) [14]. This is represented pictorially by the following image (Figure 8), which clearly displays the variation of fluid bottles recommended per shift, per firefighter, depending on their
respective fire agency. This can also inherently create issues of storage space on firefighting appliances/tankers when they are required to carry such a vast quantity of drinking fluid for crews of three to five.

A)

B)

**Figure 8:** The discrepancy between fluid prescriptions currently advised by different fire agencies across Australia. The recommended volumes per firefighter A) 6 liters in a 12 hour shift, B) 36 liters in a 12 hour shift.
These volumes differ from the 900–1400 ml·hr$^{-1}$ now prescribed by the United States (US) Military after the hospitalizations from water intoxication [165, 168, 190] (when military leaders enforced fluid replacement rates of more than 1900 ml·hr$^{-1}$ [168]). The revised fluid intake rates have been associated with a reduced rate of hyponatremia in US soldiers [168]. Though few studies have evaluated whether the fluid volumes ingested within the revised US Military fluid intake guidelines [167] significantly affect work productivity, exercise performance and/or physiology.

**Practically Prescribing Fluid During Work and Compliance**

The consequences, positive or negative, of the agency recommended fluid volumes on firefighter health and performance are not known. The wide range of fluid volumes (6 to 36 liters across a twelve hours shift, Table 4) may also affect logistics planning for multi-agency operations as considerations need to be made for each agency’s firefighters and their respective fluid consumption plans. Firefighting vehicles, carrying five firefighters each, also lack the space on-board to carry 180 bottles of water/sports drink for their crew to sustain the recommended 36 liters per person over the one shift. Additionally, the cost of fluid for hydrating firefighters when consuming 6 or 36 liters of fluid in a 12 hour shift can amount to $24 or $72 per firefighter, per day, respectively (assuming one liter of fluid costs approximately $2). The discrepancy between fluid volumes can amount to great monetary costs when applied to large firefighting populations, emphasizing the need to produce and disseminate scientifically validated findings.

The nature of wildfire firefighting also raises the question of how closely firefighters comply with the prescribed fluid intake targets when they are busy working on the fire
line. Research on fluid intake compliance is minimal and lacking in physically demanding occupations. Data from dialysis patients indicates that adherence to fluid recommendations can be as low as 24% [191]. How poor-compliance translates to wildfire fighter fluid intake is unclear as it is yet to be investigated. Additionally, many difficulties exist when investigating drinking behaviors as a multitude of factors can affect an individual’s chosen fluid intake. Palatability, namely the flavor [125-127, 129] and temperature [57, 90, 192, 193] of the fluid, can affect consumption. The delivery of drinking fluid to an active firefighting crew can also cause a substantial diversion of effort and manpower from the task of fire suppression [12] and workers don’t always want to stop work to consume fluid [80]. Indeed, in Hendrie et al.’s study [12], the firefighters’ inadequate water intake was not attributed to insufficient time for drinking or the availability of water but the fact that firefighters “did not drink more because they simply did not want to.”

**Work Output**

World leaders in firefighter physiology have concluded that “the work (wildfire suppression) predictably leads to numerous cases of dehydration” [194]. While the intensities associated with wildfire fighting are normally less than competitive athletic events [195], working for 10-15 hours [35, 85] per shift could supposedly place firefighters at a similar risk of dehydration to ultra-endurance athletes. It has been suggested that when rehydration strategies are not in place, ultra-endurance athletes have been identified at a ‘high risk of dehydration’, simply due to the length of exercise time (>3 hours) [15]. Additionally, while firefighting is somewhat self-paced and team-based [86], occasionally work is externally paced by the wildfire which may contribute to
higher internal heat loads, thus accentuating sweating and body water losses. Wildfire fighters may also reflect findings from military soldiers who show a high incidence of heat stress when work is not self-paced [196].

Dehydration can adversely affect worker productivity, safety and morale [58]. Dehydration does not, however, have a homogenous physiological effect across the wide range of sporting and work tasks undertaken by humans. Occupational work, in particular, encompasses a variety of components and cannot be categorized as totally anaerobic, aerobic or muscular strength dependent [58].

Wästerlund et al. [80] found that the productivity (measured as m$^3$ pulpwood·day$^{-1}$) of four forestry workers was superior when they consumed prescribed volumes of 1200 ml·hr$^{-1}$, compared to 291 ml·hr$^{-1}$ of water across their shift in cool to mild temperatures (7.8-22.5°C). Effective time and time for cross-cutting were 12% longer in the low fluid consumption condition [80]. Heart rate responses varied greatly between individuals and the authors suggested that different work strategies may have been utilized to deal with the dehydration that supposedly occurred during the low fluid consumption regimen [80]. Unfortunately, no markers of hydration status were reported in this paper, so it is unclear how hydrated the forestry workers were during this study. Other authors have, however, shown that ad libitum drinking typically ranges between 400 ml and 800 ml per hour during most forms of exercise [91] inferring that Wästerlund et al.’s low drinking regimen of 342 ml per hour is less than what forestry workers would be expected to consume naturally. Additionally, only four subjects were studied, the total hours of work were omitted, and the environmental conditions were temperate (7.8-22.5°C) which does not reflect what is commonly faced by Australian wildfire fighters.
Firefighters wearing structural firefighter protective clothing and self-contained breathing apparatus in the heat (35°C) displayed lowered rectal temperatures and extended treadmill walking time, when a 1260 ml·hr⁻¹ enforced consumption rate was compared to 620 ml·hr⁻¹ [197]. Cyclists consuming 1200 ml·hr⁻¹ of a carbohydrate-electrolyte beverage during two hours of laboratory-based cycling in 33°C had a lower heart rate, rectal temperature and a preserved stroke volume compared to when they were instructed to consume 300 ml·hr⁻¹ or no fluid during the same exercise task [198]. These works promote higher volumes of fluid intake however the key distinction is that ad libitum drinking was not compared to the ~1200 ml·hr⁻¹ conditions enforced by Wästerlund et al [80], Selkirk et al. [197] or Montain and Coyle [198].

**Thermoregulation**

When air temperature exceeds 36°C, heat exchange gradients are reversed and the human body gains heat from radiation and convection instead of dissipating it via these mechanisms [184]. Typical Australian wildfire weather conditions expose wildfire fighters to temperatures of 35-45°C and relative humidity lower than 20% [30]. The human body operates with a core temperature of approximately 37°C [199] and a rise of more than 2-3°C can be detrimental to physical performance, potentially lead to heat illness and even progress to death [74, 184, 200]. Sunburn, alcohol consumption, obesity, low fitness, lack of heat acclimation, sweat gland dysfunction, certain medications and recent illness, have all been reasoned to increase the risk of heat illness during physical work [201] and may affect the performance of wildfire fighters during a deployment.
The fire itself also appears to directly affect firefighter drinking and physiology. During rakehoe work around fire, 45% of Australian ‘dry’ firefighters sweat losses were replaced by consuming 602 ± 31 ml·h⁻¹ of water [12]. When raking away from fire, less water (406 ± 32 ml·h⁻¹) was consumed replacing only 43% of sweat losses [12]. The mean sweat rates were 194 ml·h⁻¹ (maximum 422 ml·h⁻¹) away from fire and increased to 1144 ml·h⁻¹ (P<0.001) (maximum 2139 ml·h⁻¹) when working around fire [12]. When raking away from fire, rectal temperatures averaged 38.1 ± 0.16°C and peaked at 38.5 ± 0.26°C; skin temperatures averaging 33.5 ± 0.9°C (thigh) and 35.7 ± 2.3°C (cheek) [40]. Whereas, when firefighters worked beside the fire, rectal temperatures averaged 38.2 ± 0.16°C (peaked at 38.6 ± 0.21°C), and skin temperatures rose to 35.4 ± 0.9°C and 36.5 ± 1.4°C for thigh and cheek, respectively [40]. When performing physical work in hot and humid environments (humid environments are created under personal protective clothing [202], individuals can become significantly strained even on mildly hot days [203]). An evaporation level may be required that exceeds the capacity of the environment to accommodate more water vapor, resulting in critical heat load which limits exercise performance and increases the risk of heat illness [184].

While evaporation sweat loss is the human body’s primary mechanism to maintain core temperature during exercise, (the complete evaporation of 1.0 liter of sweat had been calculated to remove 2427 kilojoules of heat from firefighters [121]); the evaporation of sweat leads to a continual loss of body water [204] and may result in dehydration if not matched by fluid intake. When hypohydrated, evaporative heat loss is reduced because sweat rates are lower for any given core temperature [128, 205]. Indeed, higher core temperatures and a reduction in both whole body and local sweating have been shown
during dehydration (Figure 9) [206]. Hence dehydration results in increased core
temperatures during work in temperate [16, 17] and hot environments [18-20] with a
reported increase of 0.1-0.2°C with each 1% increase in dehydration [21, 22]. This
response is known as adaptive heterothermy and is well described in desert dwelling
animals [175]. Both the rate of rise and level of core temperature reached have been
implicated in the development of heat exhaustion [23-26]. Heat exhaustion, (exhaustion
from heat strain) has occurred in 50% of exercising subjects during field trials at core
temperatures of 39.5°C, which is higher than the core temperature level (38.6°C)
observed during laboratory trials [207].

Figure 9: Graded Dehydration increases the core temperature
threshold for sweating and reduces sweating sensitivity during
exercise. Data from Cheuvront [206] adapted from Montain [208] and
Sawka [74]. BWL = body water loss.

The effect of hydration status on core temperature in wildfire fighters has not been
examined but is worthwhile because evidence supports a key role for fluid ingestion
in attenuating rising core temperatures. Fluid ingestion does this by acting as a means for additional heat storage [56, 210] and/or by sustaining the sweat rates required for evaporative cooling [211]. Fluid ingestion also helps maintain blood volume and hence cardiovascular function [198]. Additionally, when hypohydrated, core temperatures are elevated during exercise which negates any further advantages conferred by high aerobic fitness and/or heat acclimation [122-124]. Furthermore, modest increases in core temperature have been connected to muscle weakness and loss of balance [212] which present serious health and safety risks to wildfire fighters who perform repetitive manual handling tasks [35] over 10-15 hour shifts [35, 85].

Wearing full protective clothing, compared to wearing partial protective clothing (which exposes the face, neck and hands) has been shown to decrease the core temperature at exhaustion by 0.6°C (P<0.05), increase the sweat rate by 6 g·min⁻¹ (P<0.05) and shorten exercise time by ~49 minutes (P<0.05) [213]. However, Australian fire agencies do not encourage firefighters to expose their face, neck and hands during work on the fireground [37]. It has also been suggested that over time the effect of thermal protective clothing is more pronounced [214]. In particular, research into personal protective clothing worn over shifts up to 15 hours [85], which are common to wildfire fighters, is lacking. Again, this proposed effect needs to be assessed directly across live wildfire fighting shifts.

**Heart Rate Response**

During wildfire fighting, where durations are over extended periods (10-15 hours [35, 85] on consecutive days), the work intensity that is maintained could decrease as a result of cardiovascular strain. However, this is yet to be investigated in wildfire fighters, as is
any interaction of fluid intake with cardiovascular strain. The reduction in cardiac output associated with dehydration may also result in an insufficient supply of cool blood to the brain, which, in healthy workers, can manifest as heat exhaustion or collapse [215]. The higher body temperatures also raise catecholamine levels which increases heart rate independently of hydration status [216].

Australian ‘dry’ wildfire fighters recorded average heart rates of 152 beats·min⁻¹ in the 1980’s via the radial pulse method [12]. ‘Wet’ firefighters (n = 42) average heart rates logged continuously throughout a shift were 54.4 ± 5.0% of their age predicted maximum, while peak heart rates reached 92.0 ± 9.2% of their age predicted maximum [35]. These peak heart rates are consistent with those measured during a charged hose advance [217, 218] and fast handtool raking [36]. To give further context, the average and peak heart rate data compiled in Australian ‘wet’ wildfire fighters equates to ‘moderate’ and ‘very hard’ intensities, respectively, as defined by the American College of Sport Medicine [219]. Although the majority of ‘wet’ wildfire work is not vigorous, these brief periods of intense work are performed regularly [220] and high heart rates may put certain firefighters (those who have established or undetected heart disease) at risk of a cardiac event [28, 29], particularly unfit or usually sedentary individuals, or if the vigorous work bout is something the firefighter is unaccustomed to [221].

Most importantly, it has been shown that these cardiovascular responses (higher heart rate and reduced stroke volume) are attenuated with fluid ingestion [198]. Montain et al. reported lower heart rates when athletes drank 1190mL·hr⁻¹ and 712mL·hr⁻¹ compared to 292mL·hr⁻¹ during 110 minutes of constant-load laboratory cycling [198]. Highlighting the potential value that higher fluid intake might exert on firefighter health and
performance. However, during outdoor manual harvesting work, Wästerlund et al. [80] failed to demonstrate a consistent relationship coupling greater fluid intake to lower mean heart rate, although their subject sample was only four. Another major criticism of previous studies performed in humans has been the recruitment of ‘normal volunteers’, who tend to have above average physical fitness and above average cardiac reserves [222]. It is therefore supposed that wildfire fighters, (typically male, aged 45-54 years in volunteer cohorts [137]), could be at an even greater risk from the combinations of dehydration with heat-exercise and their effect elevating heart rates, than the ‘normal volunteer’ under laboratory conditions [222].

**RATINGS OF PERCEIVED EXERTION**

Increased ratings of perceived exertion (RPE) typically accompany an increase in heart rate [58]. Whether this trend of elevated RPE occurs when wildfire fighters are hypohydrated remains to be determined. Studies exploring this are of value since assessing RPE in the field requires no equipment, minimal expertise, and can be performed at any given time. Although RPE is a subjective assessment, it integrates information from many sources [223]: including feelings of strain in the working muscles, tendons, and joints; the volume and frequency of breathing; sensations arising from skin and muscle and tissue lactate levels [223, 224]. Feelings of perceived exertion have also been hypothesized to provide cues by which ‘dry’ firefighters pace themselves at sustainable work rates that balances their work productivity against the physiological cost of fire-line construction [36]. This is in agreement with others [223, 225, 226] who suggest that RPE predict the duration of exercise that remains until exhaustion is
reached. Also, psychological factors such as motivation and social influences should not be overlooked as they can influence drinking and affect RPE [227].

**Excess Fluid Intake and Blood Sodium/Hyponatremia Risk**

The interplay between rapid fluid intake and active/inactive sodium stores within the body culminating in hyponatremia (water intoxication), during exercise and occupational work, remains to be fully understood. We do not currently know whether wildfire fighters are at risk of hyponatremia or whether there have been cases in the past as this level of specificity is not detailed in Australian fire agency reports. These issues are further complicated by anecdotal evidence in which hyponatremia often being misdiagnosed as dehydration (as the individual has been sweating while performing physical work in the heat) and treated with the addition of more fluid.

What we do know is that clinical symptoms become apparent when blood sodium falls below 120 mmol·L⁻¹ [173] and patients with mild hyponatremia (plasma sodium 130-135 mmol·L⁻¹) are usually asymptomatic [228]. Hyponatremia is believed to be caused by considerable fluid overload occurring independent of appreciable sodium losses [170]. There have been numerous exercise-associated hyponatremia cases [165, 166, 170, 171], some which have resulted in death [172-174]. Hence, upper ceilings for fluid intake have been recommended for healthy drinking [168]. Interestingly, a report by Dugas and Noakes [229] emphasized that poor health can indeed manifest from drinking during physical work even at rates beneath the ‘safe’ levels proposed by various sporting and government bodies. As evidenced by cases of hyponatremia developing during exercise when fluid intakes are lower than 1200 mL·hr⁻¹ [183, 230, 231]. Hence, more investigations in this area are worthy, particularly in the field of prolonged occupational
work in the heat. From the available information we can gather that the incidence of hyponatremia in wildfire fighters is currently not known.

**Between Shifts on Multiple Day Deployments**

Campaign wildfires can last several days, weeks, and sometimes even months. It is usual for firefighters to provide their services for ‘tours of duty’ which last three to five consecutive days during large scale campaign wildfires. From the past research we have gained an appreciation of the hypohydrated state in which firefighters complete their shift [10, 12, 85]. But what happens between their shifts? Do they start the following shift hypohydrated if they worked the day prior? We do not know what type of beverages nor how much firefighter’s drink between wildfire fighting shifts. Anecdotally, alcohol appears to play a role on multiple day tours of duty [108] and the influence this has on hydration status and performance is unknown.

The opportunity to restore hydration status and replenish electrolytes lost from the physically demanding work of a previous shift may prove important in mediating any accumulative effect of strain on firefighter performance and health across multiple shifts. Most of the available research has been limited to a single work-day [11, 12, 232], conducted in mild to warm weather [12, 232] (or did not disclosed the temperature conditions [10]), and utilizing a narrow selection of physiological measures [10, 12].

Previous, wildfire fighter investigations have examined fluid consumption (and/or hydration status) during [11, 12, 43] the shift. Inferences that dehydration is present in American HotShot ‘dry’ firefighters during a five-day tour of duty can be drawn from the isotope dilution study performed by Ruby [10]. They showed daily water turnover rates averaged $6.7 \pm 1.4 \text{ L\cdot day}^{-1}$; with a simultaneous loss of 1.0 kg (1.4%) in nude body
mass (P<0.05) and 0.9 kg in total body water (P<0.05) [10]. One of the difficulties of Ruby et al’s [10] isotope dilution method is defining a baseline due to the wide variability in body composition and natural variability in total body water levels [233]. Additionally, extended periods of time are required for this technique as measuring tracer concentrations prior to an equilibrium being reached (3-4 hours) in the fluid spaces threatens its reliability and accuracy [233]. Despite this, the total error of isotope dilution with a tracer is 1% and, hence, it is sufficiently accurate for detecting small changes in total body water [233] in wildfire fighters performing work over a 3-5 day period. Interestingly, no studies have focused on the recovery post-shift and between firefighting shifts despite common practice requiring firefighters to work on consecutive day shifts.

Few investigations into consecutive day work involving physical labor have been undertaken [232, 234, 235]. Most of the available research has been conducted using limited research designs or methodologies. For instance, during construction work in the heat, there was no differences in average heart rate over the duration of a shift (am vs. pm) or over consecutive days [232, 234]. Similarly, no differences in average heart rate (in beats-min⁻¹) were noted in two workers on a steel plant who worked consecutive days [235]. Whether average heart rate was the best measure for quantifying strain during occupational work, which is largely intermittent in nature, and involves a broad range in age of workers [235] and therefore relative intensities; is questionable. Additionally, these consecutive day studies in the heat lacked a measure to quantify work (eg. activity counts [236]). This creates challenges when interpreting results as heart rate is often a response to the physical work being performed. Hydration status
before and after the shift and over consecutive days of construction work was also not
found to be different [234]. However, these authors [234] relied on urine specific
gravity, an inferior marker of hydration status. Urinary based markers of hydration
commonly disagree with the more robust, plasma osmolality [105, 233], and may result
in a misclassification of hydration status [232] as demonstrated (Figure 7). Further
research into the drinking responses after a shift of occupational work and before the
following days’ shift, are therefore in need of investigation. The use of robust measures
and a suite of work and physiological indices to contextualize results and infer
implications are required.

Hence, this thesis will investigate a broad range of physiological and work behavior
markers over two consecutive work days on the fire-ground. Of particular interest is
how hydration status and heart rate response recover (i.e. return to basal levels) during
these timeframes and also how changes in these variables may affect the following day
of wildfire fighting work. These markers may affect firefighter productivity,
physiological strain, fatigue, health and/or safety.

SUMMARY
There is still a great deal to be discovered about the body’s tolerance to prolonged work
during emergency wildfire situations and the practical limitations of fluid consumption
and hydration during such events. The extent of dehydration in Australian wildfire
fighters is presently unknown, although hydration issues are likely [10, 12, 33, 85, 109-
111] and have been demonstrated in other occupations [58, 88] and prolonged sporting
events [15, 127, 188, 211, 237-239]. Theoretically, by improving a firefighters’
tolerance to strain, (by ensuring adequate fluid intake and euhydration) the rate of
fatigue development (Figure 5) would likely reduce. If this effect results in a work performance improvement and whether this improvement manifests as a physiological response (e.g. lower heart rates or less time spent in a high heart rate zone, or reduced core temperatures when working in the heat); or a practical response (more ground cleared by rakehoe teams, greater distances covered on foot); or a psychological response (better sensations of recovery between shifts or reduced mental fatigue); no one knows as it is yet to be explored. These positive changes to firefighter strain may delay fatigue and keep firefighters within safe and productive work ranges (Figure 4, Figure 5). The effect of maintaining a safe and productive workforce to curtail the spread of wildfire and the damage they cause could prove to be invaluable.

Research into this extreme event is therefore needed with various drinking regimes being trialed and a wide range of physiological processes being monitored. The following body of work addresses these key issues. Additionally, this research will be directed at the magnitude of physiological change provided by various drinking protocols during emergency wildfire events and prescribed burns which will be of value to the wildfire fighters themselves and fire agencies worldwide. Further, this research will add to our understanding of the processes influencing hydration during extreme events while performing prolonged, intermittent work while wearing personal protective clothing.
CHAPTER THREE:

PRE-SHIFT FLUID INTAKE: EFFECT ON PHYSIOLOGY, WORK AND DRINKING DURING EMERGENCY WILDFIRE FIGHTING

As published in Applied Ergonomics:


Note: References are collated at the end of the doctoral thesis.
ABSTRACT

Wildfire fighters are known to report to work in a hypohydrated state, which may compromise their work performance and health.

Purpose: To evaluate whether ingesting a bolus of fluid before the shift had any effect on firefighters’ fluid consumption, core temperature, or the time they spent in high heart rate and work activity zones when fighting emergency wildfires.

Methods: Thirty-two firefighters were divided into non-bolus (AD) and pre-shift drinking bolus (PS, 500 ml water) groups.

Results: Firefighters began work hypohydrated as indicated by urine colour, specific gravity and plasma osmolality (P\text{\textsubscript{osm}}) results. Post-shift, firefighters were classified as euhydrated according to P\text{\textsubscript{osm}} and hypohydrated by urinary markers. No significant differences existed between the drinking groups in pre- or post-shift hydration status, total fluid intake, activity, heart rate or core temperature.

Conclusion: Consuming a bolus of fluid, pre-shift provided no benefit over non-consumption as both groups had consumed equivalent ad libitum volumes of fluid, 2.5 hours into the shift. No benefits of bolus consumption were observed in firefighter activity, heart rate response or core temperature response across the shift in the mild weather conditions experienced. Ad libitum drinking was adequate to facilitate rehydration in firefighters upon completion of their emergency firefighting work shift.

Key words: hydration, thermoregulation, cardiovascular strain.
INTRODUCTION

Worldwide, the threat and severity of wildfires are on the increase. Wildfires claim lives, destroy homes, cripple communities, and raise the demand on firefighters. Wildfire fighting is hazardous; the required work is physically demanding, often in conditions of extreme heat and smoke over long durations (10-15 hour shifts) for multiple (3-5) days, whilst wearing impermeable protective clothing. In addition, wildfire fighters contend with remote locations, hygiene challenges, poor sleep, changes in diet, and sometimes food and/or fluid restriction [44].

One element identified with the potential to impair firefighter health, safety and performance is dehydration [12]. In non-firefighting contexts, hypohydrated individuals display elevations in heart rate [60], reductions in physical work capacity [61-66], and increases in core temperature [60], which can eventually lead to exhaustion or collapse [66, 72-74]. Unfortunately there has been limited scientific exploration [10-12] into dehydration and its proposed ill-effects on wildfire fighters. The collective efforts of Hendrie et al. [12], Cuddy et al. [11], Ruby et al. [10] and Raines et al. [27] have, however, established that the wildfire fighting work environment threatens hydration status [10-12]. Accordingly, their research found that firefighters arrived on shift hypohydrated [10, 11, 27] and maintained their level of hyophydration [10, 27] or accentuated it [11, 12] upon conclusion of their work shift.

Given that previous research demonstrates firefighters arrive on shift hypohyhydrated, and there are potential health and performance risks associated with this [66, 72-74]; fire agencies require practical strategies to counter dehydration in their personnel. A logical and convenient option is to provide firefighters with a bolus of fluid before their shift.
The American College of Sports Medicine recommends that dehydrated individuals consume 5-7 mL·kg\(^{-1}\) four hours prior to and, potentially, a further 3-5 mL·kg\(^{-1}\) two hours before exercise [92]. Direct evidence supporting this specific fluid volume prescription before exercise (or work) is, however, scarce. Nonetheless, results from laboratory studies show that consuming a bolus of fluid (ranging 100-3500 ml) before activity extends exercise time until exhaustion [151], and lowers heart rate [72, 151-153] and rectal temperatures [72, 151, 153] during physical work. These responses from a pre-exercise bolus, which ranged from 100-3500 mL, were exaggerated beyond that observed when fluid consumption was intermittent during exercise [151, 152] or when no fluid was consumed before exercise [72, 153]. Although, it is also important to note that when ad libitum drinking was compared to the pre-exercise bolus condition, no differences between rectal temperature before or after exercise were observed [72]. Whether these relationships between bolus consumption and physiology transfer from the laboratory to field study environments where temperature changes and self-paced exists; remains to be seen.

The question therefore remains; does ingesting a bolus of fluid before a firefighting shift have any tangible effect on firefighter's work activity, heart rate, or core temperature response when fighting wildfire? The answer to this question will depend, at least in part, on firefighter's behavior, and in particular, their fluid and food consumption during the shift. To the authors' knowledge, no study has allowed natural in-field behavior, whereby firefighters are able to freely choose the frequency, volume, timing and type of food and fluid they consume during a shift. In contrast, past studies have limited firefighter fluid choices to only water [11, 12], or only electrolyte fluid [11] and failed to
include the water obtained from food consumed; which may make a significant contribution to daily water intake [154] over a 10-12 hour workday. As such, firefighter's freely chosen fluid consumption when fighting wildfire is unknown. Without accurate representation of normal firefighter behavior and fire-ground practices, any application of previous research into dehydration and fluid consumption during wildfire fighting may be irrelevant.

Hence, the aim of the current study was to evaluate whether ingesting a bolus of fluid before the shift had any effect on core temperature, fluid consumption, or the time firefighters spent in high heart rate and work activity zones, when fighting emergency wildfires and consuming fluid ad libitum. We hypothesized that enforced fluid intake before the shift would decrease the in-shift time spent in high heart rate zones but not alter core temperature, or fluid and food consumption. The effect of bolus consumption on activity is unknown as this is yet to be investigated in occupational field work environments. However, our hypotheses are based on findings from tightly controlled laboratory studies in athletic populations, performing constant-pace exercise, not wearing personal protective clothing, whose drinking was controlled, and duration of exercise was considerably less than our wildfire fighters’ shift.

**METHODS**

**Participants.** Thirty-two firefighters (31 male, one female) were recruited from Australian and American firefighting crews, employed to assist the Victorian (‘Black Saturday’ February 2009) wildfire suppression and recovery operations. Standard fire retardant personal protective clothing (jacket, pants, gloves, boots, goggles, and hard-hat), designed to shield the firefighter from environmental hazards and injury was worn
throughout the shift as per fire agency guidelines. Prior to testing, firefighters provided written informed consent indicating they understood the risks and benefits of the study and that their participation was voluntary. The study was approved by the Deakin University Human Ethics committee prior to testing.

**Overview of Experimental Procedures.** Firefighters were age-matched into one of two groups: ad libitum (AD; firefighters self-selected the volume, beverage type (water or sports drink) and timing of intake, n=17) and pre-shift (PS; consumed a 500 ml water bolus prior to leaving the research station then continued drinking ad libitum for the remainder of the shift, n=15). The two groups were not likely to have experienced different environmental and work conditions as each member of one group was paired with a member in the other group and deployed on the same vehicle and worked together throughout the entire shift. Before deploying on shift, firefighters provided biological samples (blood and urine), were fitted with research equipment (heart rate, core and skin temperature and activity monitors) that recorded data throughout the shift, and those in the PS group consumed the pre-shift fluid bolus. Firefighters were instructed to adhere to normal work practices and reminded to eat and drink as much or as little as they desired, and to record all food and drink intakes and urine produced in the booklet provided. Firefighters were then released for their firefighting shift. At the completion of the work shift the aforementioned measures were repeated. At this time; research equipment was removed, data files downloaded and firefighters were released.

**Firefighting Shift.** For the purposes of this study, the ‘firefighting shift’ encompassed the moment firefighters left the research station at the staging area (preparatory zone at a safe distance from the fire) to their dismissal after the day’s work. It included not only
the tasks performed on the fire ground, (intense but intermittent manual labour [28], including manual lifting, carrying, stepping on and off vehicles [195], using handtools and chainsaws to clear low lying vegetation, and using hoses to apply water, retardant or foam suppressants) but also vehicle transit time, attendance at briefings, ad libitum fluid and food consumption, the loading of vehicles and performing equipment checks prior to departure from the staging area; all which contribute to the firefighters workday.

**Ambient Temperature.** Ambient temperature was obtained from local weather stations which recorded temperature at ten-minute intervals [240] and were located approximately 10 km from the worksites.

**Hydration Markers.** Plasma osmolality, urine colour and urine specific gravity (USG) were measured upon arrival to the staging area before and after the shift to identify acute changes in firefighter hydration status. A post-treatment (PS bolus) measure of hydration was not practical given the limited time (thirty minutes) researchers had with firefighters before their shift. As such, verifying the hydration state which firefighters began their shift was not possible after the PS group consumed the fluid bolus. Venous blood samples were obtained in 10 ml lithium-heparin tubes, via the vaccutainer method, from an antecubital vein with participants in a seated position, two minutes prior to sampling. Thirty (n=15 AD, n=15 PS) blood samples were obtained prior to the shift and twenty-nine (n=16 AD, n=13 PS) samples post-shift. Whole blood was pipetted into tubes and centrifuged at 10,000 rev·min\(^{-1}\) for four minutes at room temperature. Plasma was then aliquoted and stored at -20°C for up to two days before transferring into a -80°C freezer. Plasma osmolality (\(P_{\text{osm}}\)) was analyzed by freezing point depression, whereby values \(\geq 290\ \text{m·Osmol·L}^{-1}\) were classified as dehydrated in accordance with previous literature.
Mid-stream urine samples were provided by participants before (n=31; n=16 AD, n=15 PS) and after (n=32; n=17 AD, n=15 PS) their work shift. Researchers also estimated firefighter hydration status based on the current fire agency urine colour ($U_{\text{col}}$) chart [13]. This determination was recorded before performing a urine specific gravity (USG) test in triplicate using a portable refractometer (Atago, Japan). Before USG analysis, a drop of distilled water was placed on the face of the prism. Using distilled water as the standard, the instrument was adjusted to 1.000. Samples were classified according to the ranges for USG utilized by previous authors [241-243]. Analysis of urine occurred within 40 minutes of firefighters providing the sample. During the shift firefighters (n= 29; n=15 AD, n=14 PS) recorded the time, colour and volume of urine produced using a personal 1.0 L measuring jug, a level surface, and the booklet provided.

**Food and Fluid Consumption.** Food and fluid data recording began first thing in the morning (including any food and fluid consumed before reporting to the research station) and continued until the end of the shift. No cold beverages were available as the fluids were stored in lockers on firefighting vehicles and therefore likely to be above ambient temperatures. Firefighters were required to record the time, quantity and detailed ingredients of food and fluid consumed. Dietary intake was assessed using a food record with estimated household measurements. The instructions included a pictorial measuring guide to common utensils used by firefighters on deployments (Styrofoam cup, teaspoon, and tablespoon); the difference in size between a small and large fruits; 12 different portion sizes of vegetables, steaks, potato and casserole on a dinner plate; and alcohol servings based on 17 pictorial examples. Care was taken to
ensure that pictorial representation and food record instructions were relevant and easy to understand for the firefighting population. Four firefighters did not complete the food diary and hence were not included in the fluid contribution from food section of this study (n=28; n=16 AD, n=12 PS). The dietary record data was entered into the Foodworks (v3.02) nutrient analysis software (Xyris Software Pty Ltd., Brisbane, Australia) incorporating nutrient tables for use in Australia (AUSNUT, Canberra, 2000).

**Heart Rate Response.** Heart rate was recorded every five seconds using Polar heart rate monitors (Polar RS800G3, Pursuit Performance, Adelaide, Australia). The heart rate monitor watch was attached to the wrist and the chest band fitted by the researcher. Data was downloaded via an IrDA port into the Polar ProTrainer software (version 5.10.120) at the conclusion of the firefighters’ shift. Heart rate data was expressed as a percentage of each firefighter’s age-predicted maximum (220 - age = theoretical maximum heart rate (HRmax)), to normalize cardiovascular strain to the individual firefighter from the large spread in age across this population. The time spent in hard (70-89% HRmax), moderate (55-69% HRmax), and light (35-54% HRmax) intensity zones [244] was then determined as this was of greater interest opposed to absolute heart rate values as wildfire fighting is intermittent and does not follow the continuous pattern of laboratory exercise trials. Twenty-five (n=12 AD, n=13 PS) firefighters’ heart rate data are presented in the analysis, as seven monitors failed to record data during emergency wildfire fighting.

**Worker Activity.** Firefighters wore an Actical Activity Monitor (MiniMitter, Bend, Oregon) mounted on the centre of the heart rate belt, positioning the device over the firefighters’ xiphoid process. This device placement was different to that of Cuddy et al
who affixed monitors to the firefighters’ jacket pocket, as jackets may be removed during opportune moments of the work shift to facilitate cooling (as per fire agency guidelines). Actical Activity Monitors recorded whole body motion on a three-dimensional plane at one minute intervals. Data was downloaded using Actical software (version 2.1) and expressed as absolute counts and time spent in sedentary (0-100), light (101-1500) and moderate (1501-5000) activity count zones [236]. Twenty-six (n=12 AD, n=14 PS) firefighters’ activity data is presented in the analysis, as six monitors failed to record data during the emergency wildfire fighting shift.

**Thermoregulation.** Firefighters ingested a core temperature capsule (Jonah™ MiniMitter, Bend, Oregon). A VitalSense Monitor (Vitalsense™ MiniMitter, Bend, Oregon) was attached to the firefighters’ belt loop, which received the intra-abdominal core temperature results every 15 seconds with a precision of ± 0.25°C (temperature range 25-32°C and 42-50°C) [245]. The time elapsed before using the recorded core temperature data was 30 minutes after pill consumption. Time spent at or above a core temperature of 38°C was also determined. Eight (n=5 AD, n=3 PS) of the thirty-two firefighters participated in core temperature recording, due to the limited number of VitalSense Monitors available for testing at each emergency wildfire fighting shift.

**Statistical Analyses.** Means and standard deviations (SD) or 95% confidence intervals (CI) are presented for descriptive data, unless otherwise stated. For basic univariate comparisons between groups, t-tests were used. For more complex analyses involving both between-subjects group effects and within-subjects effects - repeated measures analysis of variance taken in two-hour time blocks throughout the shift were used. When significant main effects for time were observed, paired t-tests with Bonferroni correction
were completed to determine the location of pair-wise differences. Analyses were carried out using the Statistical Package for the Social Sciences (SPSS GradPack 18, PASW Statistics, Champaign, Illinois). Significance was assumed at or below the 5% level.

**RESULTS**

No differences existed between AD or PS drinking groups in terms of participants’ age (P=0.49), body mass (P=0.71), body mass index (BMI, P=0.86) or the duration of their shift (P=0.77; Table 5).

**TABLE 5: FIREFIGHTER CHARACTERISTICS. MEAN ± SD (RANGE).**

<table>
<thead>
<tr>
<th></th>
<th>Ad Libitum</th>
<th>Pre-Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Age (years)</td>
<td>41.4 ± 14.9 (21 - 62)</td>
<td>37.5 ± 14.7 (17 - 66)</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>84.4 ± 14.4 (56 - 107.9)</td>
<td>86.2 ± 12.6 (64.5 - 108.0)</td>
</tr>
<tr>
<td>BMI (kg·m⁻²)</td>
<td>26.7 ± 4.1 (20.6 - 35.6)</td>
<td>27.1 ± 4.1 (20.0 - 35.6)</td>
</tr>
<tr>
<td>Shift Duration (hours)</td>
<td>9.9 ± 2.2 (6 - 13)</td>
<td>9.7 ± 2.3 (6 - 13)</td>
</tr>
</tbody>
</table>

**Ambient Temperature.** Differences existed in ambient temperature between workdays (P<0.001) but not between drinking conditions (P=0.85). When dividing the shift into two hour blocks, ambient temperatures were significantly different (P<0.001) at all times except for 6-8 h (P=0.39) and 8-10 h (P=0.42), where daily peaks occurred. Average (peak) ambient temperatures across the shifts for the seven days of firefighting studied were considered mild to warm: Day One 17.12°C (20.10°C); Day Two 15.81°C (18.60°C); Day Three 25.48°C (30.90°C); Day Four 25.78°C (31.60°C); Day Five 26.39°C (33.90°C); Day Six 18.18°C (20.70°C); and Day Seven 18.41°C (21.70°C).
**Hydration Status.** No significant differences existed between the drinking groups for any hydration marker ($U_{col}$, $P=0.44$; USG, $P=0.92$; $P_{osm}$, $P=0.41$). Firefighters began work dehydrated according to $U_{col}$ ($2.8 \pm 0.4$ AD, $2.7 \pm 0.6$ PS) and USG ($1.019 \pm 0.007$ AD, $1.020 \pm 0.006$ PS) results (Figure 10). There was a significant effect of time for the overall decrease in both $U_{col}$ ($P=0.00$) and USG ($P=0.01$) post-shift, although firefighters were still considered dehydrated. Plasma osmolality results revealed that firefighters arrived on shift dehydrated and ended the shift euhydrated ($P<0.0001$, Figure 10). An analysis of discrepancies classifying hydration status using $U_{col}$, the fire industry standard, compared with $P_{osm}$ was also conducted. The percentage of classifications in which $U_{col}$ disagreed with $P_{osm}$ was 20% of firefighters before the shift and 53% of firefighters after the shift.
FIGURE 10: A) Urine colour, B) urine specific gravity, and C) plasma osmolality before and after firefighting. Mean and SD. Effect of time

*P<0.05. A & B) n=16 AD, n=15 PS. C) n=30; n=16 AD, n=14 PS.
CHANGES WITHIN SHIFT

The following results are based on a two-factor analysis of each outcome measure, by drinking condition and time within shift (in two hour blocks).

**Fluid Intake.** A main effect was observed for time within shift (P<0.0001) while no effect for drinking condition (P=0.85) or interaction between drinking condition and time within shift were noted (P=0.11; Figure 11A). The volume of water (1.9 ± 1.4 L AD; PS 2.0 ± 1.4 L PS) was greater than the volume of sports drink consumed (0.8 ± 0.7 L AD; 0.5 ± 0.7 L PS, P<0.001). However, no significant differences in beverage choice existed between drinking groups (P=0.81). An additional volume of 0.8 ± 0.5 L (0.6 - 1.1 L; 95% CI) and 0.8 ± 0.4 L (0.6 - 1.1 L; 95% CI) of water was provided from the food that firefighters consumed during the shift by AD and PS drinkers, respectively. No differences existed between drinking groups (P=0.98). The water obtained from food represented 30% of firefighters’ total in-shift fluid intake. There was no difference between groups in total fluid intake from both drink and food combined (AD: 3.4 ± 1.6 L; PS: 3.7 ± 2.9 L; P=0.730).
Urinary Output. Urine output averaged $1.6 \pm 1.0 \text{ L} (1.0 - 2.1 \text{ L}, 95\% \text{ CI})$ and $1.3 \pm 0.6 \text{ L} (0.9 - 1.6, 95\% \text{ CI})$ throughout the shift by AD and PS drinkers, respectively. No significant differences were apparent between the groups ($P=0.39$).
**Heart Rate Response.** Across the entire shift, there was no significant effect of time within shift (P=0.41), drinking condition (P=0.47) or interaction between time within shift and drinking condition (P=0.56) observed for the time firefighters spent in hard heart rate zones (70-89% HR\textsubscript{max}). Similarly there were no differences between drinking groups for the percentage of time spent within light (35-54% HR\textsubscript{max}; P=0.17) or moderate (55-69% HR\textsubscript{max}; P=0.22) heart rate zones (Figure 12). Across both groups, firefighters spent approximately 55 ± 43%, 51 ± 41%, and 4 ± 9% of the shift in light, moderate and hard heart rate zones, respectively (Figure 12).
Work Activity. There was no effect of time (P=0.30), drinking condition (P=0.95) or interaction (P=0.98) observed in self-selected activity over the work day which averaged 230 ± 195 counts·min⁻¹. Throughout each two-hour period, firefighters regularly spent 3
± 3\% in moderate (most vigorous movement), 43 ± 28\% in light, and 54 ± 28\% in sedentary (least movement) activity zones (Figure 13).

A)

![Figure 13: Percentage of time spent within each activity zone: A) Ad libitum, B) Pre-shift. Activity zones classified according to Heil [236]. N=26 (N=12 AD, N=14 PS).](image)

B)
Thermoregulation. There was a significant effect for time (P<0.001) but no effect for
drinking group (P=0.38) or interaction (P=0.27) in core temperature response.
Firefighter’s core temperature fluctuated across the shift (Figure 14) averaging 37.42 ±
0.17°C and 37.47 ± 0.33°C for AD and PS drinkers, respectively. No differences existed
in peak core temperature (38.05 ± 0.07°C (AD); 38.15 ±0.14°C (PS); P=0.06) or pre-
bolus consumption core temperature (37.12 ± 0.16°C (AD); 36.90 ± 0.08°C (PS); P=0.08) between drinking groups. The difference between peak and pre-bolus
consumption core temperature between groups was significant (P=0.012; Figure 14B).
Core temperatures above 38°C were attained by all subjects, and the time spent at or
above a core temperature of 38°C was not different between groups (2.9 ± 0.1% AD; 3.6
± 1.3% PS).
FIGURE 14: A) Core temperature over the entire shift; B) delta change in core temperature comparing peak and pre-bolus consumption. Mean and SD. (n=5 AD, n=3 PS). Effect of group *P<0.05.
CHANGES WITHIN THE FIRST FOUR HOURS OF THE SHIFT
While the previous analyses revealed no statistically significant differences between drinking condition groups and only one significant time effect (in core temperature) across the shift as a whole, there were some indications of group differences in the patterns of fluid intake during the first four hours of the shift, with the AD drinking group appearing to lag initially but then “catch up” on the PS group’s fluid intake. In order to examine this more closely, including any consequential effects on core temperature, heart rate response and firefighter activity during the initial period, further investigation was performed on data for the first four hours of the shift broken down into half-hour segments.

Fluid Intake. Figure 2 shows the accumulated volume of fluid in each group, for the shift as a whole in two hour blocks, and for the first four hours of the shift in half-hour blocks. It was apparent that PS drinkers had consumed more fluid before they commenced their shift (i.e. they consumed the pre-shift bolus), and at all time points leading to 2.5 hours into the shift (P<0.05, Figure 11). At 2.5 hours into the shift, no differences existed between groups for the total accumulated volume of drinks consumed (P=0.09, Figure 11), suggesting that AD drinkers fluid intake ‘caught up’ to PS firefighters. No differences (P=0.42) existed between AD and PS conditions for the volume of water obtained from food (AD = 447 ± 329 ml; PS = 344 ± 382 ml) in the first four hours of the shift. Across both groups, this volume provided 56% (AD) and 43% (PS) of the total water obtained from food during the entire firefighting shift.

Core Temperature Response. During the first four hours of the shift, a significant effect for time (P<0.0001), with no effect of drinking condition (P=0.46) or interactions (P=0.99) were observed for core temperature. Average core temperature was 37.30 ±
0.19°C for AD and 37.22 ± 0.32°C for PS firefighters during the first four hour period of the shift.

**Heart Rate Response.** During the first four hours of the shift, there was no effect of time (P=0.78), drinking condition (P=0.14) or interaction (P=0.90) observed for the time firefighters spent in hard heart rate zones. Non-bolus drinking firefighters spent 54 ± 11% in light, 44 ± 11% in moderate and 2 ± 1% of their time in the hard heart rate zones. While bolus drinkers spent 44 ± 11% in light, 53 ± 10% in moderate and 3 ± 2% of their time in the hard heart rate zones.

**Work Activity.** There was a significant effect of time for both average (P=0.02) and peak (P<0.001) activity counts which decreased across the first four hours of the shift. However, no effects of drinking condition (P=0.23, P=0.59) or interactions (P=0.69, P=0.39) were observed for average or peak activity counts, respectively. During this period mean activity counts were 281 ± 52 counts·min⁻¹ for AD and 236 ± 111 counts·min⁻¹ for PS drinkers. Although peak activity counts values did not reach significance, they were highest during the initial 30 minutes of the shift, reaching 2180 counts·min⁻¹ and 2162 counts·min⁻¹ before settling to mean values of 1394 ± 441 counts·min⁻¹ and 1139 ± 653 counts·min⁻¹ for AD and PS drinkers, respectively for the remaining 1-4 hour period.

**DISCUSSION**

As previous research determined firefighters arrive on shift dehydrated, and there are potential health and performance risks associated with this [66, 72-74], wildfire fighters in the current study were provided with a bolus of fluid, to counter dehydration, before commencing work. The subsequent effect of ingesting this bolus on fluid consumption,
the time firefighters spent in high heart rate and work activity zones, core temperature, and post-shift hydration status when fighting emergency wildfires was examined. It was hypothesized that enforced fluid intake before the shift would decrease the in-shift time spent in high heart rate zones but not alter core temperature, or fluid and food consumption. The effect on physical activity was unknown. Results demonstrate that bolus consumption only affected fluid intakes in the initial portion of the shift, agreeing with the hypotheses that over the course of the shift, fluid consumption and core temperature would not be different between groups. Activity was also not found to be different between PS and AD drinkers. However, contrary to our hypothesis no differences in the time firefighters spent in high heart rates throughout the shift was observed. As only three published studies [10-12] have investigated fluid intakes in wildfire fighters using impure ad libitum drinking conditions, and in some cases, non-emergency wildfires, and none have implemented a pre-work fluid consumption strategy, this research niche has been largely unexplored.

**Bolus & Fluid Intakes**

In agreement with our hypothesis, consuming a bolus of fluid before work had no effect on overall fluid consumption across the wildfire fighting shift. As part of the research design, firefighters on the enforced bolus condition (PS) had greater fluid intakes than AD drinkers before the shift commenced. This higher accumulated fluid volume was observed in PS drinkers each thirty minutes until 2.5 hours into the shift where no differences emerged between the groups (Figure 3.2B); suggesting that AD drinkers ‘caught up’ on the fluid intakes of bolus drinking firefighters. Studies exploring subsequent ad libitum fluid intakes after bolus consumption during physical work are
lacking. Hence no data observing this ‘catch up’ phenomenon post-bolus, to the authors’ knowledge, has been previously reported. We can, however, speculate that the catch up phenomenon may be influenced by a greater thirst sensation which increased fluid intakes during the initial portion of the shift in AD firefighters not receiving the bolus; until the sensation of thirst was satiated. The work of Maresh and colleagues [145, 150] does support this phenomenon as participants in their studies altered their fluid intake during 90 minutes of exercise in a dehydrated (-3.4% body mass) state, consuming an additional 1.65 liters of fluid compared to commencing exercise in a euhydrated state. They displayed no differences in core temperature, heart rate, plasma osmolality, or thirst ratings at the completion of exercise, when comparing the two trials. 

We know that a slight reduction in total body water can lower blood volume and pressure and increase plasma osmotic pressure (plasma osmolality) [105]. These changes are detected by the hypothalamic-pituitary-adrenal axis which then signals a thirst cascade, increases arginine vasopressin (anti-diuretic hormone) and aldosterone; thereby beginning a process to increase water consumption and water retention [246]. Plasma osmolality results do indeed corroborate that all firefighters were hypohydrated (294 ± 5 mOsm·L⁻¹ AD; 293 ± 4 mOsm·L⁻¹ PS) upon arrival at the research station. However, based on past research [92, 241], it is probable that PS firefighters achieved a euhydrated state after consuming the 500-ml water bolus. This euhydrated state (with plasma osmolality decreased) would most likely be accompanied by an absent or reduced thirst sensation [242] which quelled the drive to drink during in the initial portion of the shift in those firefighters receiving the bolus (PS). One study, by Greenleaf and Castle [72], on bolus consumption and ad libitum drinking may appear similar to the present study, however, the ad libitum drinking condition they employed did not allow subjects to
freely choose the volume, timing or type of fluid. When true ad libitum conditions were allowed in the current study, consuming the bolus had no effect on drinking volumes (264 ml·h⁻¹) across the entire shift. It appears that bolus drinking also had no effect on the quantity of fluid consumed in food items as both groups obtained 30% of their total daily fluid intake from food. Even during the initial portion of the shift, when fluid intakes from drinks differed between groups, the fluid obtained from food items did not differ, suggesting that bolus consumption had no effect on the desire to eat. Possible reasons for the similarities between the groups may be the timing of access to food as well as the type of food items made available to firefighters throughout the emergency firefighting shift. For instance, limited opportunities to eat meals and snacks on the fireground may or may not appear during their shift, and so firefighters may grasp opportunities to eat regardless of hunger. Unfortunately, the contribution that food items make to daily water intake has not been included in past studies, despite advice to do so [247]; hence comparisons with previous wildfire fighting literature cannot be made.

**HEART RATE RESPONSE**

The lack of difference between groups in the time spent in hard heart rate zones across the shift was contrary to our hypothesis. Based on previous well-controlled laboratory studies [72, 151-153], a lower heart rate response was expected (from the increased blood volume) for the PS group (at least during the initial period) when fluid consumption was higher than AD firefighters (Figure 11). The reason for the unexpected heart rate finding is not clear, but raises the question whether the relationship observed in controlled laboratory studies, between fluid consumption and heart rate during specified physical exercise, translates to self-paced firefighting (or other occupational)
work. Heart rate is altered by several factors including stress, posture, dehydration, exercise and temperature [248]. Exploring such variables in the current study, physical activity was consistent across both PS and AD drinkers throughout the shift and during the initial portion of the shift. Therefore the lack of difference observed in heart rate response between fluid conditions cannot be attributed to differences in physical activity, which could offset the purported heart rate lowering effect of a fluid bolus [72, 151-153]. There were differences in ambient temperature across all work days; nevertheless, firefighters were evenly divided among the PS and AD drinking groups on each day. The experimental protocol therefore limited any effect of inter-day differences in ambient temperature; so the stability of heart rate between groups cannot be attributed to ambient temperature. Interestingly, in a sub-sample of subjects, the change in core temperature was greater in PS bolus drinking firefighters (this will be discussed in further detail, later). Briefly, when core temperature is raised it is expected that heart rates would be increased in order to deliver blood flow to the skin and facilitate cooling. However no elevation in heart rate was observed in PS drinkers. So whilst core temperatures were elevated in PS bolus drinkers, another factor may have been concomitantly acting to reduce heart rate; the net effect which resulted in no change in heart rate in the PS group. Hydration status may be this factor. All firefighters in this study arrived on shift similarly dehydrated and half received a bolus. Previous work demonstrates that a 500 ml bolus was sufficient to euhydrate subjects [92, 241]. This potential euhydration (which was not possible to measure after bolus drinking) or greater fluid intake in PS bolus drinkers may be the factor which nullified the potential rise in heart rate resulting from elevations in core temperature (although the sample size of the core temperature data is too small to draw concrete conclusions). Whether the time
firefighters spend in hard heart rate zones remains unchanged on days of extreme fire behavior (i.e. when work may become externally paced by fire, ambient temperature conditions are hotter and the impact of wearing impermeable protective clothing and dissipation of heat provide greater strain on wildfire fighters’ cardiovascular systems), remains to be seen and requires further research.

**PHYSICAL ACTIVITY**
The findings of this study demonstrated that consuming a fluid bolus before work had no effect on the activity of firefighters across an emergency wildfire suppression shift. Nor did any effects emerge in the early portion of the shift when differences between groups in terms of total fluid intake were apparent. These findings suggest that activity is not sensitive to fluid intake, at least using the experimental protocols employed in this study. Failing direct comparisons in the literature it was unclear of the relationship between a pre-exercise fluid intake and physical work on the fireground. Relationships showing that bolus consumption increases time to exhaustion in constant load cycling [151] and that greater overall volumes of fluid during work improve productivity in forestry workers [80] lend credence to the prospect that bolus consumption and/or higher overall fluid intakes might increase firefighter physical activity. However, this proposed relationship was not demonstrated during emergency wildfire fighting shifts. Possible explanations for this include; 1) that a direct relationship between increased fluid, euhydration and greater physical activity (work output or productivity) may be different when comparing field and laboratory conditions, 2) that AD firefighters performed more physical work by returning to the vehicle for drinks while PS firefighters performed equal activity yet used it productively on fire suppression activities, 3) that the bolus of
fluid was not sufficient to euhydrate firefighters, 4) that being dehydrated does not actually impair performance [22], and 5) that physical activity is a proxy measure and does not capture wildfire fighting performance. To expand the latter, successful firefighting is not measured by the firefighters’ ability to perform maximal exhaustive exercise or push themselves to the limit. Wildfire fighting is instead geared towards intermittent self-paced work sustained over a 10-12 hour period [220] and arriving home in good health. Hence being dehydrated may not exert the same impact on physical activity and physiology as it may under exhaustive exercise pressures. Activity measurement also has limitations as a number of common fireground tasks, like spraying water from a hose, involve producing force (increasing heart rate) whilst remaining stationary (potentially no activity), and hence it may not provide a holistic picture of wildfire fighting work demands. The milder temperatures and fire conditions may also be another explanation for the stability of physical activity across groups during the firefighting shift. For instance, some may anticipate more activity would be performed by firefighters when fire behavior intensifies (e.g. during the hotter part of the day or when wind speeds rise) or conversely that firefighters would reduce their work rate when daily ambient temperatures peak (to reduce internal heat build-up); however, neither of these were realized. The nature of emergency wildfire fighting, which allows self-pacing and task sharing among firefighters within their team may also have affected the consistency across activity results. Hence, future investigations into drinking strategies and their effect on wildfire fighter activity are warranted to further our understanding of human physiology during this and other occupational work.
**CORE TEMPERATURE RESPONSE**

Consuming a fluid bolus before wildfire fighting work had no effect on average core temperature response across the shift, in support of our hypothesis. However, the rise in core temperature for PS bolus drinkers was significantly greater than that displayed by AD drinkers (P=0.012). This finding was unexpected and contrary to the purported relationship between fluid bolus consumption which commonly reduces body temperature during physical work in the laboratory [72, 151, 153]. Raising the possibility that this relationship may not be as strong in self-paced field working environments when encapsulated protective clothing is worn, at least in mild ambient weather conditions. The recorded core temperatures were, however, small and not in the heatstroke range, hence, the authors believe did not represent an important physiological change as this was not accompanied by adjustments in heart rate or physical activity. Although it was possible that the greater rise in core temperature blunted a lowering of heart rate which was expected in PS firefighters’ (as described earlier). Since no differences were observed in peak or initial core temperature between groups, and any effect of the consumed fluids’ temperature influencing the core pill was ruled out; it is possible that this result is a by-product of a chance finding (type 1 error) from the small sample. While the average core temperature data supports our hypothesis, they should be interpreted with caution, given the small sample size. Additionally, whether these findings remain consistent during days of extreme ambient temperature conditions remain to be determined.

**HYDRATION STATUS**

Regardless of bolus consumption and arriving on shift dehydrated, ad libitum drinking was sufficient to euhydrate firefighters upon completion of their emergency wildfire
fighting shift. Our urinary and plasma based findings were in agreement with previous research which identified that firefighters arrive on shift dehydrated. While the post-shift urinary-based findings agreed with the urinary-based hydration measures of the past, which demonstrated firefighters maintained the level of dehydration [10, 27] or accentuated it [11, 12] upon conclusion of their work shift; $P_{\text{osm}}$ results disagreed. The discrepancy between $P_{\text{osm}}$ and urinary findings was 53% post-shift and the reader is referred to Popowoski et. al. [100] and Armstrong [233] for further explanation on the differences between these markers of hydration. The ability of firefighters to rehydrate across the work day without enforced drinking regimes may be due in part to the mild weather and free access to food, water and sports drink during their work shift. Unfortunately, it was not possible to provide a clear answer as to when firefighters became euhydrated during this study. As has been suggested by Cuddy [11], it is possible that firefighters fluctuated between a state of euhydration and dehydration during the course of their shift. The lack of within-shift hydration measures are a common limitation of all published wildfire fighting studies [10-12]. In each case, the authors were unable to collect such data for reasons including the integrity of biological samples, access to firefighters, the safety of crews/researchers and the emergency nature of wildfire fighting. Obtaining a post-bolus consumption measure of hydration status was also impossible in the current study given the limited time researchers were able to interact with firefighters before their shift. However, based on past research, it is probable that firefighters on the bolus condition achieved a euhydrated state after consuming the 500 ml water bolus; as similar volumes have consistently produced favorable changes in urinary and blood markers of hydration [92, 241].
QUALIFICATIONS

It is also important to note that these findings apply to wildfire fighters’ working day-shifts in mild to warm ambient temperatures. As dehydration commonly reduces prolonged exercise performance during field investigations in temperate [80] and warm-hot [84] environments, further research in hotter ambient temperatures would be a valuable addition to fire agencies and our understanding of wildfire fighter physiology and other occupational performances in challenging environments. Additionally, the results of this study may have underestimated the extent of dehydration as firefighters in normal circumstances might pay less attention to drinking than the study participants who were required to record fluid intake as the shift progressed.

CONCLUSION

Pre-shift fluid consumption provided no benefit over non-consumption as both groups had consumed equivalent ad libitum volumes of fluid, 2.5 hours into the shift. In relation to core temperature response, heart rate response and firefighter activity across the shift, no benefits of bolus consumption were observed. When both food and fluid availability and choice were not limited, in mild to warm ambient temperatures, ad libitum drinking was adequate to facilitate rehydration in firefighters upon completion of their emergency firefighting work shift.
ACKNOWLEDGEMENT

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CHAPTER FOUR:

THE EFFECT OF PRESCRIBED FLUID CONSUMPTION ON PHYSIOLOGY AND WORK BEHAVIOR OF WILDFIRE FIGHTERS

As published in Applied Ergonomics:


Note: References are collated at the end of the doctoral thesis.
**ABSTRACT**

The purpose of this study was to examine 1) wildfire fighters’ ability to consume the prescribed fluid volume (1200 ml·hr⁻¹), 2) the effect of fluid intake on plasma sodium and hydration, and 3) the effect of fluid intake on firefighters’ heart rate, core temperature and activity during emergency suppression shifts.

**Methods:** Thirty-four firefighters were divided into ad libitum (AD, n=17) and prescribed (PR, n=17) drinking groups.

**Results:** PR drinkers did not meet the prescribed fluid target, yet consumed over double the volume of AD drinkers. No differences between groups in plasma sodium or hydration were noted. PR drinking resulted in lower core temperature between 2-6 hours. This did not coincide with reduced cardiovascular strain, greater work activity or larger distances covered when compared to AD drinkers.

**Conclusion:** Extra fluid consumption (above AD) did not improve firefighter activity or physiological function (though PR firefighters core temperature was lower earlier in their shift). Firefighter can self-regulate their fluid consumption behavior and work rate to leave the fireground euhydrated.
INTRODUCTION
Wildfire fighters perform physically demanding work intermittently over long hours in hot environments, wearing heat-retaining personal protective clothing [44]. Factors which, in isolation, are likely to challenge body water balance and when combined, increase the likelihood of dehydration. In non-firefighting contexts, fluid restricted and hypohydrated individuals have displayed increased cardiovascular strain [60], reduced physical work capacity [61-66], and elevated core temperatures [60], which can eventually lead to exhaustion or collapse [66, 72-74]. To reduce the likelihood of dehydration and perceived health and safety risks, fire agencies in Australia and elsewhere, prescribe target drinking rates for their firefighters to follow whilst suppressing wildfire [13]. The scientific evidence supporting prescribed drinking targets is lacking. Recent research [232] suggests that prescribing fluid intake could be unnecessary, at least in mild-warm weather, as ad libitum drinking was shown to be sufficient to euhydrate wildfire fighters working in such conditions.

Considerable variability exists in the target fluid volumes prescribed by Australian fire agencies, ranging from 500 to 3000 ml·h\(^{-1}\) per firefighter across a twelve-hour fireground shift [14]. The prescribed values are larger than the 300 ml·h\(^{-1}\) of fluid that wildfire fighters consumed, ad libitum in mild weather conditions, during their twelve-hour emergency shifts [232]. The consequences, positive or negative, of the agency recommended fluid volumes on firefighter health and performance are not known. Indeed, consuming too much fluid during physical work can have profound health risks [92]. Over-drinking has been linked to hyponatremia [92, 165, 166, 170, 171, 173, 176-178, 181, 183, 249] and death [172-174] in otherwise healthy individuals. The United States (US) Military now prescribe fluid intakes of 900–1400 ml·hr\(^{-1}\) after 190 soldiers
were hospitalized from water intoxication (i.e. low blood sodium; hyponatremia) [165, 168, 190] after military leaders enforced fluid replacement rates of more than 1900 mL·hr⁻¹ [168]. The revised fluid prescription rates in US soldiers have since been associated with a reduced rate of hyponatremia [168].

Few studies have evaluated whether the fluid volumes ingested within the revised US Military fluid intake guidelines [167] significantly affect work productivity, exercise performance and/or physiology. Wästerlund et al. [80] found that when four forestry workers operating in ambient temperatures of 7.8 - 22.5°C consumed 1200 ml·hr⁻¹, their productivity was superior to when they consumed 291 ml·hr⁻¹ of water across their shift. Selkirk et al. [197] showed that treadmill walking time was extended and rectal temperature lowered, while wearing structural firefighter protective clothing and self-contained breathing apparatus in the heat (35°C), when a 1260 ml·hr⁻¹ enforced consumption rate was compared to 620 ml·hr⁻¹. In another study [198], cyclists consuming 1200 ml·hr⁻¹ of a carbohydrate-electrolyte beverage during two hours of laboratory-based cycling in 33°C had a lower heart rate, rectal temperature and a preserved stroke volume in comparison to when instructed to consume 300 ml·hr⁻¹ or no fluid during the same exercise task. Ad libitum drinking was not compared to the ~1200 ml·hr⁻¹ conditions enforced by Wästerlund et al. [80], Selkirk et al. [197] or Montain and Coyle [198]. Whether their findings of improved work performance and physiological function when consuming the larger quantity of fluid are sustained when compared to an ad libitum condition remains to be demonstrated.

Given the nature of actual wildland firefighting is unlike tightly controlled laboratory studies, it is highly impractical to enforce compliance to a prescribed fluid ingestion
volume. The nature of wildland firefighting raises the question of how closely firefighters comply with the prescribed fluid intake targets when they are in the field. Literature exploring compliance to fluid intake recommendations is minimal and lacking in physically demanding occupations. Research in dialysis patients indicates that adherence to fluid intake recommendations can be as low as 24% [191]. How the issue of non-compliance translates to wildfire fighter fluid intake is unclear.

The initial aim of the current study was to examine the firefighters’ ability to consume the prescribed target fluid volumes during the shift as well as the effect their consumption had on plasma sodium and hydration status. A second aim of this study was to compare the effect of a 1200 ml·hr⁻¹ fluid intake target with ad libitum drinking on firefighters' heart rate, core temperature and physical activity during an emergency wildfire suppression shift. The primary hypothesis of the study was that prescribed fluid intakes would be greater than ad libitum drinking volumes consumed, but that compliance to the target volume would be low. Furthermore, it was hypothesized that post-shift, firefighters in the prescribed fluid intake group would have similar hydration and sodium levels to firefighters in the ad libitum group. Finally, it was hypothesized that firefighters following the prescribed fluid intake instructions would reduce their time spent in high heart rate zones, be more physically active and exhibit lower core temperatures than ad libitum drinkers.

**METHODS**

**Participants.** Thirty-four firefighters (32 male, 2 female) were recruited from crews employed to assist the Victorian 2009 wildfire suppression and recovery operations. Standard fire retardant personal protective clothing (jacket, pants, gloves, boots, goggles,
and hard-hat), designed to shield the firefighter from environmental hazards and injury were worn as per fire agency guidelines. Prior to testing, firefighters provided written informed consent indicating they understood the risks and benefits of the study and that their participation was voluntary. The study was approved by the Deakin University Human Ethics committee. The study is part of a series of experiments conducted during 2009, and some of the ad libitum group data reported here has been submitted for publication previously [232].

**Overview of Experimental Procedures.** Firefighters were age-matched into one of two groups: ad libitum (AD) firefighters self-selected the volume of water or sports drink and the timing of intake, n=17; and prescribed target (PR) firefighters were instructed to consume 600 ml of water and 600 ml of sports drink containing carbohydrate-electrolyte each hour of their shift, n=17. Firefighters in the PR condition were instructed to try their very best to drink the 1200 ml·hr⁻¹. The rate was encouraged but not enforced. The two drinking groups were not likely to have experienced different conditions (ie. work, environmental conditions etc.) as each member of one group was paired with a member in the other group and deployed on the same vehicle and worked together throughout the entire shift. Firefighters were instructed to adhere to normal work practices and reminded to eat as much or as little as they desired, and to record all food/drink intake and urine volume produced in the booklet provided.

**Firefighting Shift.** The work of wildfire fighters in the present study involved physical, mental and emotional stress during live-fire suppression, blacking out, and patrolling forested and urban areas. The wildfires burnt 450000 hectares and killed 173 people in one of the most devastating fire events in Australian history [250]. The ‘firefighting
shift’ began the moment firefighters left the research station at the preparatory zone located a safe distance from the fire, to their dismissal after the day’s work. The shift included the tasks performed on the fire ground; intense but intermittent manual labor [28] including manual lifting, carrying, stepping on and off vehicles [195], using handtools and chainsaws to clear low lying vegetation [33, 36], and using hoses to apply water, retardant or foam suppressants [37]. The shift also included vehicle transit time, attendance at briefings, the loading of vehicles and performing equipment checks prior to departure.

**Ambient Temperature.** Ambient temperature was obtained from local weather stations which recorded temperature at ten-minute intervals [240] and were located approximately 10km from the worksites.

**Food and Fluid Consumption.** Food and fluid data recording began first thing in the morning and firefighters were required to record the time, quantity and detailed ingredients of items consumed. No cold water was available as the beverages were stored in lockers on firefighting vehicles and therefore likely to be above ambient temperatures. Dietary intake was assessed using a food record with estimated household measurements. The instructions included a measuring guide to common utensils used by firefighters. Care was taken to ensure that pictorial representation and food record instructions were relevant and easy to understand. Four participants did not complete the food diary and hence were not included (n=16 AD, n=14 PR). The data was entered into nutrient analysis software (Foodworks v3.02, Xyris Software Pty Ltd., Australia) incorporating nutrient tables for use in Australia (AUSNUT, Canberra, 2000). Firefighters were asked to rank their level of stomach discomfort (no discomfort to very
severe discomfort, five-point scale) before and after the shift to determine why PR firefighters may or may not adhere to the target fluid prescription.

**Hydration Markers.** Plasma osmolality ($P_{\text{osm}}$), urine colour ($U_{\text{col}}$) and urine specific gravity (USG) were measured before and after the shift to identify acute changes in hydration status. Venous blood samples were obtained in 10mL lithium-heparin tubes via the vacutainer method from an antecubital vein with participants being seated for two minutes prior to sampling. Twenty-eight firefighters (n=16 AD, n=12 PR) had blood samples taken before and after the shift. Whole blood was pipetted into tubes and centrifuged at 10,000 rev·min$^{-1}$ for four minutes at room temperature. Separated plasma was then aliquoted and stored at -20°C for up to two days before being transferred into a -80°C freezer. Plasma osmolality was analyzed by freezing point depression, whereby values $\geq 290$ m·Osmol·L$^{-1}$ were classified as dehydrated in accordance with previous literature [20]. Plasma sodium, associated with hyponatraemia, was analyzed using the Ion Selective Electrode method and values ranging 130-155 mmol.L$^{-1}$ were classified within the normal range [251]. Mid-stream urine samples were provided by firefighters before (n=16 AD, n=17 PR) and after (n=17 AD, n=16 PR) their work shift. Analysis of urine occurred within 40 minutes of providing the sample. Researchers estimated firefighter hydration status based on the fire agency $U_{\text{col}}$ chart [13]. Urine specific gravity (USG) was determined in triplicate using a portable refractometer calibrated using distilled water (Atago, Japan). Samples were classified according to the published ranges for USG [57, 105]. During the shift, firefighters (n=15 AD, n=17 PR) recorded the time, colour and volume of urine produced using a 1.0L measuring jug.
**Heart Rate Response.** Heart rate was recorded every five seconds using Polar heart rate monitors (Polar RS800G3, Pursuit Performance, Australia). Data was downloaded via an IrDA port into the Polar ProTrainer software (version 5.10.120). Heart rate data was expressed as a percentage of each firefighters age-predicted maximum (220-age = theoretical maximum heart rate (HRmax)). The time spent in hard (70-89% HRmax), moderate (55-69% HRmax), and light (35-54% HRmax) intensity zones [244] was then determined. Time spent in intensity zones was of greater interest than absolute heart rate values as wildfire fighting is intermittent [28] and mean data may not give a clear profile of firefighters’ work patterns and cardiovascular responses. Twenty-four (n=12 AD, n=12 PR) of the 34 firefighter’s heart rate data are presented as ten monitors failed to record data.

**Wildfire Firefighter Activity and Distance Walked.** Firefighters wore an Actical Activity Monitor (MiniMitter, Bend, Oregon) mounted on the heart rate belt positioned over the subjects’ xiphoid process. The device placement was different to that of Cuddy et al. [44] who affixed monitors to the firefighters’ jacket pocket because, at least in Australian conditions, jackets may be removed during opportune moments of the work shift to facilitate cooling as per fire agency guidelines. Actical Activity Monitors were programmed to record whole body motion on a three-dimensional plane at one-minute intervals. Data was downloaded using Actical software (version 2.1) and expressed as absolute counts and time spent in sedentary (0-100), light (101-1500) and moderate (1501-5000) activity zones [236]. Twenty-four (n=12 AD, n=12 PR) of the 34 firefighter’s activity data is presented in the analysis as ten monitors failed to record data during the emergency wildfire fighting shift. Differentially logged GPS co-ordinates
downloaded from the devices (GPSports SP110, with a 1Hz sampling rate) were converted into distance and velocity information using Team AMS software (GPSports, Australia). Distance data was expressed as the cumulative distance covered on foot; speeds over 8 km·hr⁻¹ were excluded and counted as vehicular travel. Thirty-two (n=16 AD, n=16 PR) of the GPS data are presented as two monitors failed to record data.

**Thermoregulation.** Before deploying on shift, firefighters ingested a core temperature capsule (Jonah™ MiniMitter, Bend, Oregon). A VitalSense Monitor (Vitalsense™ MiniMitter, Bend, Oregon) attached to the firefighters’ belt loop received the intra-abdominal core temperature result every 15-seconds with a precision of ± 0.05-0.10°C (temperature range of 32-42°C) [245]. The time elapsed before using the recorded core temperature data was 30 minutes after pill consumption. A degree of uncertainty is present in the first hour of core temperature measurement [252]. After one hour it is unlikely that any fluid ingestion directly affects the pill. Time spent at or above a core temperature of 38°C was also determined, as the World Health Organization reported detrimental health effects when working at and above this temperature [253]. Eleven (n=5 AD, n=6 PR) of the 34 firefighters participated in core temperature recordings due to the limited number of monitors available.

**Statistical Analyses.** Means and standard deviations (SD) or 95% confidence intervals (CI) are presented for descriptive data, unless otherwise stated. Statistical analysis involved pair-wise comparisons within (factor, time) and between subject (factor, group) analysis of variance (ANOVA). When the ANOVA was significant, post-hoc analysis involved pair-wise comparisons with Bonferroni correction. An ordinal logistic regression (polytomous universal model) analysis was also performed to test the effects
of treatment and fluid intake on stomach discomfort. Analyses were carried out using the Statistical Package for the Social Sciences (SPSS, GradPack 18, PASW Statistics) and GraphPad Prism (Prism 5, GraphPad Software Inc). Significance was assumed at or below the 5% level.

RESULTS

No differences existed between AD or PR drinking groups in terms of participants’ age (P=0.240), body mass (P=0.779), body mass index (BMI, P=0.935) or the duration of their shift (P=0.441; Table 6: Firefighter Characteristics. Mean ± SD (range). n = number of participants, BMI = body mass index, kg = kilograms, kg·m² = kilograms per meter squared. Table 6).

| Table 6: Firefighter Characteristics. Mean ± SD (range). n = number of participants, BMI = body mass index, kg = kilograms, kg·m² = kilograms per meter squared. |
|---|---|---|
| **Ad Libitum** | **Prescribed** |
| n | 17 | 17 |
| Age (years) | 41 ± 15 (21 - 70) | 36 ± 14 (18 - 60) |
| Body Mass (kg) | 84.4 ± 14.4 (56 - 107.9) | 85.9 ± 16.7 (59.6 - 127.0) |
| BMI (kg·m²) | 26.7 ± 4.1 (20.6 - 35.6) | 27.3 ± 4.7 (20.2 - 38.3) |
| Shift Duration (hours) | 9.9 ± 2.2 (6 - 13) | 10.5 ± 2.2 (6 - 13.5) |

Ambient Temperature. Differences existed in ambient temperature between workdays (P<0.001) but not between drinking conditions (P>0.05). When dividing the shift into two-hour blocks, ambient temperatures were significantly different (P<0.001) at all times except for 6-8h and 8-10h (P>0.05), where daily peaks occurred. Average (peak)
ambient temperatures across the shifts for the seven days of firefighting were considered mild to warm: Day One 17.12°C (20.10°C); Day Two 15.81°C (18.60°C); Day Three 25.48°C (30.90°C); Day Four 25.78°C (31.60°C); Day Five 26.39°C (33.90°C); Day Six 18.18°C (20.70°C); Day Seven 18.41°C (21.70°C).

**Fluid Intake.** Main effects for time (P<0.001) and drinking condition (P<0.001) were observed while no interaction between drinking condition and time were noted (P=0.091; Figure 15). Across both groups, firefighters chose to consume greater volumes of water than sports drink (P=0.002; Figure 15), despite PR drinkers being instructed to consume equal quantities of both beverages. Regardless of consuming more fluid per hour than AD drinkers (P<0.0001), the PR drinkers did not meet their prescribed intake target of 1200 mL·hr⁻¹ (532 ± 232 ml·h⁻¹ PR; 218 ± 198 ml·h⁻¹ AD). An additional volume of 0.80 ± 0.48L (0.54 - 1.10 L; 95% CI) and 0.55 ± 0.26 L (0.40 – 0.70 L; 95% CI) of water was provided across their shift from the food that AD and PR firefighters consumed. No differences were shown between groups (P=0.097). Prescribed drinking firefighters had higher total water intakes (7.1 ± 3.1 L PR), from the combination of drinks and food than AD firefighters (3.4 ± 1.6 L AD, P<0.001).
FIGURE 15: A) Fluid consumption over the entire shift, B) beverage choice during wildfire fighting, C) average fluid consumption per hour of the wildfire fighting shift. Mean and SD. Effect of time *** P<0.0001, effect of beverage type ** P<0.01, effect of drinking condition ^^^ P<0.001. N=30; n= 16 AD, n= 14 PR. Dotted line in A) denotes prescribed fluid target (2.4 L per two-hour period).
No stomach discomfort was perceived by AD and PR drinkers pre-shift. Ad libitum drinkers reported no change in stomach discomfort rating post-shift while PR drinkers recorded mild discomfort. Individual drinkers who consumed over 10 L during the shift reported moderate levels of discomfort at shifts’ end suggesting a positive relationship between ingested fluid volume and stomach discomfort. An ordinal logistic regression analysis which models the log odds of the occurrence of successive degrees of stomach discomfort such as a function of drinking group and level of fluid intake, was applied to the data. The data revealed an effect of fluid intake volume (P=0.01) and no effect of drinking group (P=0.89).

**Urinary Output.** Significant differences (P<0.001) were apparent between the groups for urine output, which averaged 1.6 ± 1.0 L (1.0 – 2.1 L, 95% CI) and 3.6 ± 2.7 L (3.2 – 6.2 L, 95% CI) throughout the shift for AD and PR drinkers, respectively.

**Hydration Status.** Group by time interactions were apparent in urinary (U\textsubscript{col} P<0.01; USG P<0.001) based markers. Firefighters in both drinking groups began work dehydrated, according to USG (1.019 ± 0.007 AD, 1.016 ± 0.005 PR). Figure 16A shows post-shift, PR drinkers (1.004 ± 0.002) exhibited significantly (P<0.001) lower USG values than AD drinkers (1.016 ±0.008). The lower USG values result in a classification change from dehydrated to euhydrated for PR firefighters while firefighters in the AD drinking group were still considered dehydrated. U\textsubscript{col} results identified firefighters in both groups as dehydrated on arrival for their shift (2.8 ± 0.4 AD v 2.6 ± 0.5 PR). Despite reductions (P<0.01) in U\textsubscript{col} intensity post-shift, both AD (2.3 ± 0.8) and PR (1.4 ± 0.5) drinkers were classified as dehydrated at the end of their
shift (Figure 16-B). No interactions were noted for plasma measures ($P_{osm}$ $P=0.893$; plasma sodium $P=0.119$). Plasma osmolality results revealed no differences between groups ($P=0.371$) where firefighters in both groups arrived on shift similarly dehydrated and post-shift reduced $P_{osm}$ to achieve similarly euhydrated states ($P<0.0001$; Figure 16-C). The percentage of misclassifications in which $U_{col}$, the fire industry standard, disagreed with $P_{osm}$ was 14% of firefighters before the shift and 44% of firefighters after the shift. Plasma sodium decreased over time ($P=0.006$) from 141.4 ± 1.8 mmol·L$^{-1}$ before the shift to 140.3 ± 1.5 mmol·L$^{-1}$ after the shift. All firefighters were classified within the normal sodium range, pre- and post-shift, with no effect of drinking condition ($P=0.715$) or interaction apparent ($P=0.119$).
FIGURE 16: HYDRATION MARKERS BEFORE AND AFTER WILDFIRE FIGHTING: A) USG, B) U_{COL} AND C) P_{osm}. MEAN AND SD. # P<0.05 AND ## P<0.001 DIFFERENT TO PRE-SHIFT USG FOR PR GROUP; ### P<0.0001 COMPARED TO BEFORE SHIFT MEASURES IN THE SAME GROUP. A & B) BEFORE AND AFTER (N=16 AD, N=17 PR); C) BEFORE AND AFTER, N=28 (N=16 AD, N=12 PR).
**Heart Rate Response.** Across the entire shift, there was no main effect of time (P=0.352), drinking condition (P=0.335), or interaction between these factors (P=0.828) observed for the time firefighters spent in hard heart rate zones (70-89% HR$_{\text{max}}$). Ad libitum and PR drinkers spent 2.6 ± 5.4 min and 4.4 ± 9.9 min of each two-hour period in the hard heart rate zone, respectively (Figure 17).

![Figure 17: Percentage of time spent within each ACSM [244] heart rate zone: A) Ad libitum, B) Prescribed drinkers. N=24; N= 12 AD, N=12 PR.](image)
Work Activity and Distance Walked. No effect was reported of drinking condition (P=0.220), time (P=0.773), or interaction (P=0.295) between these factors, in self-selected activity over the work day which averaged 272 ± 28 counts·min⁻¹ and 186 ± 29 counts·min⁻¹ for AD and PR drinkers, respectively. Throughout each two-hour period, AD drinkers spent 3.9 ± 7.7 min in moderate (most vigorous movement), 43.2 ± 24.2 min in light, and 60.9 ± 26.2 min in sedentary (least movement) activity zones (Figure 18). Firefighters in the PR group on average spent 2.4 ± 4.0 min in moderate, 37.9 ± 20.9 min in light, and 75.2 ± 23.7 min in sedentary activity zones during each two-hour period (Figure 18). No differences were apparent between drinking groups for the distances firefighters covered on foot (P=0.562) which equated to 9.26 ± 4.68 km and 10.90 ± 8.17 km for AD and PR drinkers, respectively.
FIGURE 18: PERCENTAGE OF TIME SPENT WITHIN EACH ACTIVITY ZONE: A) AD LIBITUM, B) PRESCRIBED. ACTIVITY ZONES CLASSIFIED ACCORDING TO HEIL [236].

N=24; N= 12 AD, N=12 PR.
**Thermoregulation.** There was an interaction between drinking condition and time (P=0.043) for core temperature response. Ad libitum drinkers displayed elevations in core temperature, above that of PR drinkers, at 2-4 hours (1.1 ± 0.5°C, P<0.01) and 4-6 hours (1.0 ± 0.3°C, P<0.05) into the shift. Firefighter’s core temperature averaged 37.42 ± 0.17°C for AD drinkers and 36.68 ± 0.40°C for PR drinkers (Figure 19). The trend was for a higher peak core temperature (38.05 ± 0.07°C (AD); 37.37 ± 0.37°C (PR); P=0.068) in the AD drinking group compared to PR firefighters. Core temperatures above 38°C were attained by all AD drinkers and 17% of PR drinkers. No differences (P=0.550) existed between groups in the actual time spent at or above a core temperature of 38°C which approximated 2.9% and 1.6% of the shift for AD and PR drinkers, respectively.

![Figure 19: Average core temperature response over time. Mean and SD. Effect of drinking condition ** P<0.01, *P<0.05. n= 5 AD, n= 6 PR.](image-url)
**DISCUSSION**

One of the aims of this study was to ascertain the firefighters’ adherence to the prescribed fluid target. The results indicated that PR drinkers were unable to meet the required 1200 mL·hr⁻¹ volume. The effect of fluid intake on hydration and blood sodium were not different, with both groups achieving euhydration and maintaining normal sodium levels, post-shift. No differences were observed between drinking groups in the time firefighters spent in high heart rates throughout the shift, their physical activity, or the distances they covered on foot, contrary to our hypothesis. Core temperatures were lower in PR firefighters compared to AD firefighters during the first six hours of the emergency shift, consistent with our hypothesis.

**FLUID**

In agreement with our hypothesis, prescribed target fluid intakes resulted in higher overall fluid consumption across the wildfire fighting shift when compared with ad libitum drinking (Figure 15). Prescribed drinkers did not meet the fluid volume target of 1200 mL·hr⁻¹ supporting the hypothesis that compliance would be low. Previous research in dialysis patients indicated that adherence to fluid intake prescriptions can be as low as 24% [191]. Despite serious health complications arising from non-compliance, dialysis patients still found it difficult to comply [254]. Findings from broader health behavior literature also indicate that compliance to health messages is low [255-257]. Possible mechanisms for this could be behavioral [255-257], physiological or a combination of both. The physiological basis for the low compliance rate may relate to a feedback loop whereby gastrointestinal discomfort reduces further fluid intake [163, 258]. Indeed, previous athletes attempting to drink a liter an hour (for as little as two hours) developed disabling gastrointestinal symptoms in which “it
became apparent that further attempts to ingest fluids would have been intolerable” [258]. Noakes [163] has attributed these symptoms to the large residual of unabsorbed fluid present in the stomachs of these athletes. This is supported by our data which demonstrated that the few firefighters’ who adhered best to the PR target by consuming most fluid, experienced the highest levels of stomach discomfort. Any relationship between fluid volume and stomach discomfort was undermined by a lack of ‘moderate stomach discomfort’ being reported by any firefighter in the AD group. The limited range of the stomach discomfort data does not provide sufficient information for a valid assessment of the effects of fluid intake and drinking condition on stomach discomfort level.

Prescribed drinking firefighters in the current study were non-compliant towards the type of beverage prescribed. The PR group was required to consume equal quantities of water and sports drink (containing electrolyte and carbohydrate). Both PR and AD firefighting groups chose to consume greater volumes of water than sports drink (Figure 15B). Consumption of water over sports drink is in contrast to previous work which showed that industrial workers who perform prolonged periods of work operating at low metabolic rates found electrolyte-carbohydrate sports drinks more palatable than water even though the volumes consumed were not significantly different [259]. Cuddy [11] recommended that American wildfire firefighters consume an electrolyte-water beverage in preference to water as this resulted in an equivalent hydration state being achieved with 200g less fluid being carried and consumed each hour. Given the low compliance toward the 50:50 beverage type recommendations for PR drinkers in the current study, it is unlikely that prescribing only one beverage type would be accepted and practiced by
firefighters as it appears their own preference override their desire to follow recommendations. No firefighter freely chose to consume sports drink exclusively.

Prescribed fluid intake had no effect on the quantity of water provided by the food items firefighters consumed. Higher fluid intakes may not necessarily affect preferences for food items (i.e. foods naturally lower in water content) nor the total quantity of food consumed. The latter is in contrast to previous work which associated greater food intake with higher fluid consumption [149]. As suggested previously [232], some possible reasons for the similarities between the groups in the current study may be the timing of access to food as well as the type of food items made available to firefighters. As opportunities to eat could be limited during the emergency firefighting shift, firefighters may consume food when convenient to do so, even if they were not hungry. PR drinkers who consumed approximately 3.7L more fluid than AD drinkers produced 2.0L more urine across the shift, suggesting that these subjects were drinking at least 2L more than they require. The quantity of urine produced (1.6 ± 1.0L) by AD drinkers during emergency wildfire fighting, was greater than the 0.078L of urine previously reported [12] during simulated burn operations. Discrepancies between the two reported figures are likely to be due to the different durations studied, 9.9h versus 5.5h, and that 91% of firefighters produced urine in this cohort compared to 36% in Hendrie’s study [12].

**HYDRATION STATUS**

Urinary and blood markers of hydration confirm that firefighters from both drinking conditions arrived on-shift, to fight emergency wildfires, in a dehydrated state. The dehydrated state of firefighters was in agreement with previous findings from American
wildfire [10, 11] and Australian controlled burn [27] and emergency wildfire [232] firefighting studies. Despite firefighters arriving in shift dehydrated, PR and AD drinkers became euhydrated upon completion of their shift, supporting our hypothesis. The finding is in contradiction to the notion that ad libitum drinking leads to dehydration after prolonged physical work [11, 12]. Probable reasons which may have enabled firefighters to achieve euhydration post-shift include but are not limited to: i) the intermittent work profile which allowed for breaks to drink, ii) the mild-warm weather conditions which may have reduced the fluid lost in sweat compared to work in hotter weather, iii) fire agencies providing free access to food and drink at staging areas, and iv) crews loading firefighting vehicles with ample food and drink supplies for the duration of their shift. Unfortunately, the current study could not provide a clear answer as to when firefighters became euhydrated during this study. However, in agreement with Cuddy et al. [11], it is possible that firefighters fluctuated between a state of euhydration and dehydration during the course of their shift.

Despite the large differences in overall fluid intake (Figure 15), hydration status as determined by $P_{\text{osm}}$ indicated that both drinking groups were euhydrated post-shift. Finishing a wildfire suppression shift euhydrated is in contradiction to previous work in Australian firefighters during prescribed burn operations [12] and American firefighters during emergency wildfire fighting [10, 11]. Notwithstanding differences in environmental conditions, and length of shift, a probable reason for the contradiction could be the methods utilized to discern hydration status. Differences between $P_{\text{osm}}$ and other hydration markers are common [100, 233]. In the current study, relying solely on USG would result in a misleading conclusion that AD drinkers were hypohydrated
despite there being little to no evidence that USG is sensitive to changes in hydration status unlike $P_{\text{osm}}$ [93, 99, 100]. Further, $U_{\text{col}}$ (the fire industry standard) misclassified 44% of firefighters post-shift as hypohydrated when they were in fact euhydrated according to $P_{\text{osm}}$ results. One explanation for the latter finding is that urinary markers often mimic the volume of fluid consumed, rather than the amount retained by the body [101].

**PLASMA SODIUM**

Plasma sodium, in agreement with our hypothesis, remained stable and within the ‘healthy’ range for both AD and PR firefighters. The risk of hyponatremia was low as the actual fluid intakes over time were below the recommended ceilings for healthy drinking [168]. As PR firefighters didn’t consume the target 1200 mL·hr$^{-1}$ volume, it is unclear if that specific drinking volume would have produced results in the critically low sodium range in certain individuals. Cases of hyponatraemia developing during exercise when fluid intakes are lower than 1200 mL·hr$^{-1}$ do exist [183, 230, 231]. The reports emphasize that poor health can manifest from drinking during physical work even at rates beneath the ‘safe’ levels proposed by the various sporting and government bodies [229]. Ad libitum drinking according to the dictates of thirst [163, 260] despite being coupled to mild dehydration [144, 145], though not in this study, may be more salient advice to firefighters and other workers. The ad libitum approach is purported to substantially lower the likelihood that a person will voluntarily over-drink and reach hyponatremia [163].
HEART RATE RESPONSE
The lack of difference between groups for the time firefighters spent in the hard heart rate zone was contrary to our hypothesis. Based on previous findings [198], a lower heart rate response (via expanded blood volume) was expected for the PR group when fluid consumption was higher than that of the AD drinkers. Montain et al. [198] reported lower heart rates after 110 minutes of constant-load laboratory cycling when athletes drank 1190 mL·hr⁻¹ and 712 mL·hr⁻¹ compared to 292 mL·hr⁻¹. Montain et al.’s [198] highest volume relates closely to the PR firefighters’ target (1200 mL·hr⁻¹). PR firefighters did not meet that target and consumed 180 mL·hr⁻¹ less than Montain et al.’s 712 mL·hr⁻¹ condition. The AD firefighters consumed 74 mL·hr⁻¹ less than Montain et al.’s [198] cyclists on the lower drinking condition. Given the relatively similar volumes, the reason for the unexpected heart rate finding in the current study is not clear. Two methodological differences may account for the inter-study differences. Firstly, cyclists’ heart rates, as reported by Montain et al [198], may not be different if the comparison was between 712 mL·hr⁻¹ and ad libitum drinking. Secondly the relationship between heart rate and fluid consumption, demonstrated in constant-pace cycling, may not persist during intermittent weight-bearing work. In support of the second possibility and the current study findings, Wästerlund et al. [80] was unable to show consistent relationships coupling greater fluid intake to lower mean heart rate during outdoor manual harvesting work. Wästerlund et al. [80] only investigated a total of four subjects, hence the strength of their findings are questionable. The lack of difference observed in firefighters’ heart rate response between drinking conditions cannot be attributed to differences in physical activity as this was consistent across both PR and AD drinkers throughout the shift. Firefighters were evenly divided and paired among the PR and AD
drinking groups on each day limiting any effect of inter-group differences in ambient temperature across work days. The stability of heart rates across groups cannot be attributed to changes in ambient temperature. A sub-sample of subjects showed the elevation in core temperature was greater in AD firefighters. When core temperature is raised, it is expected that heart rates would be increased. No elevation in heart rate was observed in AD drinkers. So whilst core temperatures were elevated another, as yet unidentified, factor may have been concomitantly acting to reduce heart rate. The net effect resulted in no change in heart rate in the AD group. Whether the time firefighters spend in hard heart rate zones remains unchanged on days of extreme fire behavior when work may become externally paced by fire, ambient temperature conditions are hotter, and the wearing impermeable protective clothing may place further strain on wildfire fighters’ cardiovascular systems, remains to be seen and requires further research.

**PHYSICAL ACTIVITY AND DISTANCE COVERED**
The current study demonstrated that ingesting a greater fluid volume than ad libitum drinking, did not result in extra physical activity or greater distances covered on foot during emergency wildfire suppression. The results do not support earlier findings showing that higher rates of fluid consumption improved productivity in forestry workers [80]. The current study findings were in agreement with a previous investigation which manipulated beverage type and demonstrated that drinking more (500mL·hr⁻¹ water compared to 285 mL·hr⁻¹ water-electrolyte) was not linked to higher activity rates in wildfire fighters [11]. In the current study, the value of increased fluid on physical activity may not have been realized as firefighters may not choose to transiently increase productivity across their shift preferring to pace themselves.
throughout, in contrast to harvesting environments where more work equals more pay [80]. Secondly, the current findings suggest that additional fluid intake (above ad-libitum volumes) may not convey any further benefit to physical activity or distance covered. In fact, a number of studies suggest this may indeed be the case. No differences in performance markers including treadmill running ‘as far as possible in 30 minutes’ [188], time-trial cycling [189], or cycling till exhaustion [186] were reported when ad libitum fluid consumption was compared to higher enforced rates of fluid intake. Additionally, a recent meta-analysis by Goulet showed that ad libitum drinking provided equal performance to prescribed drinking [261].

**CORE TEMPERATURE**
Firefighters in the PR target group displayed slower rises in core temperature, in support of our hypothesis. Physiologically the greater fluid volumes consumed by PR drinkers in the current study may have acted as a heat sink, thereby buffering the rise in core temperature. These findings support the work of Selkirk [262]. Core temperature differences observed in the current study occurred two to six hours into the shift, a period where some authors question the validity of core temperature pill measurements. Wilkinson et al. [263] asserted that cold (5-8°C) fluid may cool specific portions of the gastrointestinal (GI) tract producing artificially low core temperature readings from the ingestible pill. Whether these conclusions are valid for warmer fluids, as fluid in the current study was stored in non-insulated lockers on firefighting vehicles during the day and certainly not 5-8°C, is not clear. Whether cooling specific portions of the GI tract truly affects global core temperature is unclear. Notwithstanding these unanswered questions, if core temperature was truly lowered, the PR firefighters did not choose to
perform more physical work. The wildfire fighting condition represents a fundamental
difference to sporting contexts where physiological benefits transfer to higher work rates
in pursuit of optimal performance. In the emergency response context, perhaps workers
pace themselves for the whole shift leaving some reserves in case of sudden urgency,
and don’t transiently increase their work rate even when physiologically able to do so.
Remembering that these results were obtained during emergency wildfire fighting in
mild to warm temperatures, indeed differences may be noted in extremes of heat. Also,
the risk of heatstroke was low due to the low intensity of physical effort sustained over
the prolonged period of firefighting.

CONCLUSION
Prescribed fluid consumption, compared to ad libitum drinking, resulted in significantly
lower core temperature at two to six hours and a blunted rise in core temperature across
the work-day. However, these differences did not coincide with lower cardiovascular
strain, greater work activity nor larger distances covered on foot when compared to ad
libitum drinking. Additionally, when both food and fluid availability and choice are not
limited, ad libitum drinking was adequate to facilitate euhydration in firefighters upon
completion of their emergency firefighting work shift. The current study findings
demonstrate that wildfire fighters, regardless of age or work location, can self-regulate
their fluid consumption behavior and work rate to leave the fireground euhydrated at
least in mild to warm weather conditions.
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CHAPTER FIVE:

FLUID INTAKE, HYDRATION, & WORK PHYSIOLOGY OF WILDFIRE FIGHTERS WORKING IN THE HEAT OVER CONSECUTIVE DAYS

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Note: References are collated at the end of the doctoral thesis.
ABSTRACT

Purpose: 1) To evaluate firefighters’ pre- and post-shift hydration status across two shifts of wildfire suppression work in hot weather conditions. 2) To document firefighters’ fluid and food intake during and between two shifts of wildfire suppression work. 3) To assess any changes in heart rate, firefighter activity, perceived exertion and core temperature across the two consecutive shifts of wildfire suppression work.

Method: Across two consecutive days, twelve firefighters’ hydration status and perceived exertion (RPE) were measured immediately pre- and post- their work shift. Hydration status was also measured two hours post-shift. Work activity, heart rate, and core temperature were logged continuously during each shift. Ten firefighters also manually recorded their food and fluid intake before, during, and after both fireground shifts. Results: Firefighters were hypohydrated at all time-points on day one (292 ± 1 mOsm·L⁻¹) and euhydrated across day two (289 ± 0.5 mOsm·L⁻¹). Fluid consumption following firefighters’ shift on day one (1792 ± 1134 mL) trended (p = 0.08) higher than day two (1108 ± 1142 mL). Daily total fluid intake was not different (p = 0.27), averaging 6443 ± 1941 mL across both days. Core temperature and the time spent in the ‘hard’ heart rate zone were significantly elevated on day one (when firefighters were hypohydrated). Firefighters’ work activity profile was not different between both days of work. Conclusion: There was no difference in firefighters’ pre- to post-shift hydration within each shift, suggesting ad-libitum drinking was at least sufficient to maintain pre-shift hydration status, even in hot conditions. Firefighters’ relative dehydration on day one (despite a slightly lower ambient temperature) may have led to elevations in core temperature, more time in the ‘hard’ heart rate zone, and a higher post-shift RPE, but was not associated with inter-shift differences in physical activity.
INTRODUCTION
Wildfire regularly ravages rural and regional areas in North and South America, Southern Europe and Australia [264]. To suppress these fires, salaried and volunteer firefighters can be required to work long (~ 12) hours (h), often across multiple days (or nights [265]). The available literature on firefighters’ work behavior and physiological responses over multiple days is limited to one source [266]. Ruby et al. (2003) found that firefighters’ total body water decreased significantly across the five days of a multi-day fire deployment. The measures reported by these researchers could not show the changes in fluid balance across or between shifts, and since no other measures were reported, the relationships between water loss, fluid consumption, work behaviour and physiology could not be determined.

Documenting firefighters’ fluid intake (including that derived from food), work behaviour and physiology across a multi-day wildfire deployment have important health and resource implications for fire agencies. At present, many fire agencies prescribe fluid intake in an attempt to alleviate firefighter strain in response to a range of occupational stressors [108, 267]. The evidence-base for such prescriptions is, however, small, drawing more on sweat rates and fluid prescription guidelines from sport and occupations other than wildfire suppression work [268]. The risk of this approach is that some firefighters may not be receiving sufficient fluid, and may therefore suffer the adverse effects associated with dehydration (i.e., critical elevations in core temperature and heart rate, impaired decision making, etc; [205]). Other personnel, who may strictly follow fluid intake prescriptions, over and above their own sensations of thirst, could be at risk of over-drinking; including collapse and, in extreme cases, death [174, 190]. The available evidence shows that when firefighters had ad-libitum access to water and
carbohydrate-electrolyte beverages whilst were working to suppress Australian wildfires, they completed their shift euhydrated, as measured by plasma osmolality [269]. The data presented, however, was collected across temperatures that were, on average, considered mild to warm (15.8 to 26.4°C; [269]), rather than the high heat that can often accompany wildfires [270]. Given the relationships between dehydration and high ambient temperatures in other contexts [271], it is premature to conclude that ad-libitum drinking is sufficient to maintain firefighters’ hydration during wildfire suppression in the heat. A more detailed analysis of fluid intake, particularly following firefighters’ work shifts, could also provide greater insight into common observations that firefighters are hypohydrated before they commence their fireground work. Across experimentally-lit fires in Australia [272], and emergency fires in North America [266, 273] and Australia [269], firefighters’ pre-shift urinary and/or plasma measurements indicate that firefighters start their shift hypohydrated. It is not clear from the published literature whether these pre-shift measures follow a night ‘at home’ or following a night ‘in camp’ between consecutive shifts. To this end, the first aim of this study was to evaluate firefighters’ hydration levels pre-shift, immediately after working on the fireground, then two hours post-shift, across two days of wildfire suppression work in hot weather conditions.

Whether or not fire agencies move to ad-libitum fluid intake recommendations or continue to prescribe fluid intake ranges, they are still likely to provide their firefighters with access to fluid before, during, and after their fireground shifts. At present, there are no data on firefighters’ ad-libitum fluid (and food) intake following a wildfire suppression shift and/or between consecutive shifts at a multi-day wildfire. At present,
the recommendations for firefighters regarding their fluid intake after their shift can be very broad [267], rather than based on dedicated analysis of existing behaviors or controlled experiments demonstrating the efficacy of a particular fluid type (e.g., water, alcohol), timing or volume. The interplay between fluid intake, hydration, and common work physiology indices (e.g., heart rate, core temperature, physical activity counts) has been shown during wildfire suppression in mild to warm (15.8 to 26.4°C) weather conditions [269]. Ad-libitum fluid intake was associated with euhydration at the end of a fireground shift. Additional fluid intake did not alter in-shift physical activity or heart rate, but did lower core temperature early in the shift. In contrast, a recent case study [270] showed that at extremely high (45°C) ambient temperatures, core temperature continued to rise during physical work, leading to the firefighter collapsing, even in the presence of high fluid intake (840 mL·h⁻¹). Understanding the interplay between fluid intake, hydration, and work physiology may have critical safety implications for firefighters [270] and the communities they serve. At present, a broad spectrum of work physiology measures (e.g., heart rate, core temperature, hydration, work activity, and subjective measures of exertion) during wildfire suppression work have only been collected in mild to warm temperatures [272, 274] and limited to one fireground shift only. As an increasingly large number of wildfires require firefighters to deploy for multiple, consecutive shifts [265], the third aim of the current study is to describe firefighters' work physiology and rating of perceived exertion across two days of wildfire suppression in the heat.
METHODOLOGY

Twelve male wildfire firefighters participated in two consecutive days of live-fire prescribed operations in the Mallee forests of Ngarkat National Park, South Australia. Six firefighters were in each cohort, timed five days apart. All firefighters stated that they performed the same tasks for similar durations during this prescribed burn as they have previously at emergency wildfires: building rake-hoe containment lines, chasing spot-fires, applying water, and back-burning with drip torches. These tasks are consistent with those identified during a recent job inventory for Australian rural firefighters suppressing bushfires [275]. Additionally, prescribed burn operations are common for these firefighters, whereas wildfires make up a smaller percentage of their season [276]. Further, whilst these prescribed burns were not emergency wildfires, the forest was burnt under hot, dry conditions at the end of the fire season. Standard fire retardant personal protective clothing (jacket, pants, gloves, boots, goggles, and helmet), designed to shield the firefighter from environmental hazards and injury was worn throughout the shift as per fire agency guidelines. Prior to testing, firefighters provided written informed consent indicating they understood the risks and benefits of the study, and that their participation was voluntary. The study was approved by the Deakin University Human Ethics committee prior to the start of data collection.

Overview of Experimental Procedures

Before deploying on shift, firefighters provided blood samples and were fitted with research equipment (heart rate, core temperature sensors, and physical activity monitors) that recorded data throughout the shift. Firefighters were instructed to adhere to normal work practices (including to eat and drink as much or as little as they desired), and to record all food and drink intakes in a booklet provided. Firefighters were then released
for their firefighting shift. At the completion of the work shift (12 h), blood samples were provided at the burn-site. Two hours following their deployment (14 h), firefighters again provided blood samples for analysis. Between the 12- and 14-h data collection points firefighters drove from the burn-site to nearby accommodation, showered, ate and drank freely.

**Fluid and Food Consumption**

Fluid and food data recording began first thing in the morning (including any food and fluid consumed before reporting to the research station) and continued until the end of the second day. No cold beverages were available at the burn site as the fluids were stored in lockers on firefighting vehicles, and therefore were likely to approximate ambient temperatures (refer to Results). Firefighters who normally consume tea/coffee maintained their usual daily intake of caffeine via consumption of these beverages. Firefighters were required to record the time, quantity and detailed ingredients of all fluid and food consumed. Dietary intake was assessed using a food record with estimated household measurements. The instructions included a pictorial measuring guide to common utensils used by firefighters on deployments (e.g., styrofoam cup, teaspoon, and tablespoon); the difference in size between a small and large fruit; 12 different portion sizes of vegetables, steaks, potato and casserole on a dinner plate; and alcohol servings based on 17 pictorial examples. Care was taken to ensure that pictorial representation and food record instructions were easy to understand, and relevant for the firefighting population. Two participants did not complete the food diary across both days of fire suppression in sufficient detail to be included in subsequent analyses. The dietary record data (n = 10) was entered into the Foodworks (v3.02) nutrient analysis
software (Xyris Software Pty Ltd., Brisbane, Australia) incorporating nutrient tables for use in Australia (AUSNUT, Canberra, 2000).

**Hydration Markers**

Plasma osmolality was measured to identify acute changes in firefighter hydration status. Blood samples were collected from each firefighter immediately pre- and post-shift and at a further 2 h post-shift. Venous blood samples were obtained in 10-mL lithium heparin tubes, via the vaccutainer method, from an antecubital vein after participants sat still for 2 min prior to sampling. Whole blood was pipetted into tubes and centrifuged at 10,000 rev·min⁻¹ for 4 min at room temperature. Plasma was then aliquoted and stored at -20°C for up to two days before transfer into a -80°C freezer. Plasma osmolality was analyzed by freezing point depression, and values ≥ 290 mOsmol·L⁻¹ were classified as hypohydrated in accordance with previous literature [20].

**Heart Rate Response**

Heart rate was recorded every five seconds using Polar heart rate monitors (Polar RS800G3, Pursuit Performance, Adelaide, Australia). The heart rate monitor watch was attached to the wrist and the chest band fitted by the researcher. Data (n = 12) was downloaded via an IrDA port into the Polar ProTrainer software (version 5.10.120) at the conclusion of the firefighters’ shift. Heart rate data was expressed as a percentage of each firefighter’s age-predicted maximum (HRmax [244]), to normalize cardiovascular strain to the individual firefighter from the large spread in age across this population. The time spent in the hard (70-89% HRmax) intensity zone [244] was then chosen as a focal point to capture the most demanding aspects of wildfire suppression work [277, 278].
Worker Activity

Firefighters wore an Actical Activity Monitor (MiniMitter, Bend, Oregon) mounted on the centre of the heart rate belt, positioning the device over the firefighters’ xiphoid process [269]. Actical Activity Monitors recorded whole body motion on a three-dimensional plane at 1-min intervals. Data was downloaded using Actical software (version 2.1, MiniMitter, Bend, Oregon) and expressed as absolute counts and time spent in sedentary (0-100), light (101-1500) and moderate (1501-5000) activity zones [279].

Temperature Measurement

Ambient temperature was measured at 10-min intervals from portable weather stations (MAWS, CSIRO, Australia) on the perimeter of the burn-site. Firefighters ingested a core temperature capsule (Jonah® MiniMitter, Bend, Oregon) 1.5 – 2 h before their shift began. This period falls within the 0 – 6 h timeframe where some authors [280] assert that temperature readings are more susceptible to variation. However, there is disagreement in the literature regarding the optimal duration before taking core temperature readings from ingestible capsules [280, 281]. With firefighters’ shifts starting as early as 6 am, the researchers did not wish to burden the participants with ingesting their capsules before 4 am, nor risk firefighters passing the capsule if they had consumed it the night before either shift. Further, as all ingested beverages were stored on vehicles without cooling, they were likely to be near ambient temperature and, as such, the authors reasoned that the purported effect of cold beverages [280] on masking true ‘core’ readings was not likely to be a major confounder to the reported results. A VitalSense Monitor (Vitalsense® MiniMitter, Bend, Oregon) was attached to the
firefighters’ belt loop, which received the intra-abdominal core temperature results every 15 s with a precision of ±0.25°C (MiniMitter, Bend, Oregon).

**Rating of Perceived Exertion**

Prior to their first shift, firefighters were familiarised with a six- to twenty-point scale to measure their rating of perceived exertion (RPE; [282]. Thereafter, the firefighters reported their RPE immediately before and after each fireground shift across the two days. The post-shift RPE assessment asked firefighters to rate their exertion across their shift.

**Statistical Analyses**

All descriptive statistics are presented as means ± standard deviations. All dependent variables were analysed for normal distribution using Kolmogorov-Smirnov tests. The data was collected in two different cohorts, and the characteristics (e.g., body mass, body mass index, age) were compared using independent samples t-tests (following confirmation of normality) before any other analysis. Once a normal distribution was confirmed, shift length, total fluid intake and post-shift fluid intake were analysed using paired samples t-tests across both days. Hydration status, worker activity, heart rate, core temperature, and RPE measurements were analysed using repeated measures analyses of variance with day (one or two), or day and time (either 2-h intervals in-shift, or pre-, post-, 2 h post) as the within-participant factors, where appropriate. If the interaction of day and time was identified as significant, then simple main effects analyses was used to identify where the differences lay. Alcohol intake over successive days was not normally distributed and hence analysed using a Wilcoxin Signed-Rank test. All
analyses were carried out using the Statistical Package for the Social Sciences (SPSS 18, IBM, New York) and p < 0.05 was accepted as statistically significant.

**RESULTS**

**Firefighter Characteristics** Across the two cohorts, there were differences in firefighter age (Trip 1, 36 ± 12 yr; Trip 2, 21 ± 2 yr; p = 0.01) but not body mass (p = 0.44) or body mass index (BMI, p = 0.47). Hence, data from the two cohorts were combined for further analyses.

**Shift conditions** Firefighters’ shift lengths on day one (12.0 ± 2.6 h) were 15.0 ± 15.7 min longer (p < 0.01) than on day two (11.8 ± 2.4 h). Ambient temperatures across the shifts were considered hot. Day one mean temperature was 30.9°C ± 3.6 (peak, 37°C) whilst day two mean temperature was 32.8°C ± 5.7 (peak, 39°C). Across the work shift, the temperature was 1.9 ± 4.1°C hotter (p = 0.02) on day one than day two.

**Fluid Intake** The total fluid intake (from both ingested food and fluid) was not different between day one and day two (p = 0.27), averaging 6443 ± 1941 mL across both days. There was a trend (p = 0.08) that the post-shift fluid intake on day one (1792 ± 1134 mL) was higher than day two (1108 ± 1142 mL). Approximately 20% of firefighters’ fluid intake post-shift was alcohol (1376 ± 801 mL, 35.8 ± 35.8 g, averaged across two days), with no difference (p = 0.53) in consumption following their work on day one or day two.

**Plasma Osmolality** There was no interaction for day × time (p = 0.73) or effect for time (p = 0.99). Plasma osmolality results revealed an effect for day (p = 0.01), with firefighters being hypohydrated at all time-points on day one (292 ± 1 mOsm·L⁻¹) and
within the euhydrated range \[20\] at all time-points on day two (289 ± 0.5 mOsm·L\(^{-1}\); Figure 20).

![Graph showing plasma osmolality](image)

**Figure 20:** Firefighters’ plasma osmolality, measured immediately pre-, post-, and two hours post-shift on two days of wildfire suppression work in hot weather. mOsm·L\(^{-1}\); milliosmole per litre, 2 H; two hours, *; main effect for day (p = 0.01).

**Heart Rate** There was a day × time interaction (p < 0.01) observed for the time firefighters spent in the ‘hard’ heart rate zone (70-89% HRmax). On day one, firefighters spent 1.6 ± 0.4, 4.9 ± 0.6, and 8.4 ± 2.6 min longer in the ‘hard’ heart rate zone between hours 4 – 6 (p = 0.02), 6 – 8 (p = 0.05), and 8 – 10 (p = 0.04) than during the same periods across day two (Figure 21).
**Activity** There was no interaction (p = 0.98), effect of time (in each 2-h period; p = 0.30) or day (p = 0.92) observed in self-selected physical activity.

**Thermoregulation** There was no interaction for day × time (p = 0.66). There was a main effect for day, such that core temperature was 0.59 ± 0.03°C higher (p < 0.01) on day one than day two. A main effect for time (p < 0.01) was also identified, with firefighters’ core temperature increasing across their shifts on both days (Figure 22).
Rating of Perceived Exertion There was a significant day × time interaction for RPE (p < 0.01). Between days one and two, there were no difference in firefighters’ RPE in the morning (p = 0.25). However, firefighters’ end-shift RPE on day one was 4 ± 1 units higher (p < 0.01) than at the same time point on day two (Figure 23).
DISCUSSION
The aims of this study were to measure hydration status, fluid intake and work physiology across two consecutive day shifts of wildfire suppression in hot weather conditions. The major findings were that firefighters remained hypohydrated at all time-points on day one, and euhydrated across day two. Their fluid intake averaged $420 \pm 132 \text{ mL} \cdot \text{h}^{-1}$ per shift and did not differ across the two shifts of wildfire suppression work. Across the first shift, firefighters' core temperatures were higher; they spent more time in the 'hard' heart rate zone and recorded a higher end-shift rating of perceived exertion than for day two. There were no differences in firefighters’ activity counts between the two shifts indicating that the elevated core temperature, heart rate and RPE observed during the first shift may be associated with hypohydration.
Firefighters arrived to work on day one in a hypohydrated state (Figure 20). This finding is consistent with plasma osmolality [269], doubly-labelled water [266], and body mass [272] hydration measures observed prior to wildfire suppression work in mild-warm weather. In contrast to day one, firefighters reported for work euhydrated on day two (Figure 20), and remained so across their shift. The relative stability of firefighters' hydration status across both shifts is in contrast to previous research into ad-libitum drinking during wildfire suppression work [269]. Raines et al., (2012) showed that ad-libitum drinking across a shift led to firefighters’ hydration status changing from hypohydrated pre-shift to euhydrated at the end of the shift. There are few inter-study differences in methods, participants and context to explain the apparent conflict. However, the ambient temperature in the current study was ~ 10°C hotter than the earlier work [269]. It is possible; therefore, that ad-libitum drinking may not be sufficient to euhydrate firefighters across a shift in hotter conditions (≥30°C) when they start work hypohydrated (Figure 20). The relative dehydration across day one (292 ± 1 mOsm) approximates 1 - 3% body mass loss [100]. In contrast, when firefighters started day two euhydrated, they maintained this level at the immediate post-shift measure (Figure 20). Taken together, these findings suggest that in hot (≥30°C) temperatures, ad-libitum drinking may be sufficient to maintain, rather than improve (if starting hypohydrated) pre-work hydration status across a 12-h shift.

Firefighters' in-shift fluid intake was not different between shifts, averaging 420 ± 132 mL·h⁻¹. No previous studies have documented firefighters' fluid intake across shifts, however, the reported intake is ~ 200 mL·h⁻¹ higher than reported for wildfire fighters during a single shift in mild to warm weather [269]. Higher fluid intakes in hotter
working conditions are not surprising [283]. Hotter ambient conditions are likely to induce greater fluid intakes through increased heat retention and sweat rate, which in turn can lead to blood hypertonicity and hypovolemia, ultimately causing an increased drive to drink [283]. The absolute impact of ambient temperature on fluid intake may, however, be confounded by the relative differences in temperature, degree of dehydration and / or work context [283]. Despite a 1.9 ± 4.1°C hotter mean temperature on day two, firefighters’ ‘in-shift’ fluid intake was no different to day one. Whether such a small difference in (already) hot temperatures is sufficient to influence fluid intake is not known. However, no difference could be detected across 12 firefighters in the current study. However, once firefighters stopped working, their post-shift fluid consumption on day one trended higher (684 ± 194 mL·h⁻¹; p = 0.08) than post day two. Adolf [66], supported in a later review by Greenleaf [283], proposed that physical activity decreased fluid intake, whilst leisure time facilitated drinking. It is possible, post-shift, when firefighters were not focused on their suppression duties, their relative hyperosmolality at the end of shift one stimulated a higher consumption than when they were euhydrated on day two (Figure 20). It should be remembered, however, that firefighters' end-shift dehydration on day one was marginally lower than the 295-mOsm level purported to stimulate thirst [283]. Nevertheless, assuming a larger post-shift fluid intake on day one could help explain the euhydrated status immediately pre-shift on day two (Figure 20). The potential influence of hyperosmolality post-shift on fluid intake and next day euhydration must have taken place between 8 pm on night one and 6 am on day two, as firefighters were all still hypohydrated 2 h post-shift on day one (Figure 20).
The present findings, together with the available literature, raise the possibility that firefighters’ pre-shift hydration status and fluid intake may be impacted by their location on the night before their shift. This theory arises from contrasting pre-shift dehydration on day one, when firefighters’ deployed from home, and pre-shift euhydration on day two, after a night ‘in camp’. It is possible, that when in camp, away from family and domestic duties, the firefighters are simply able to focus on food and fluid intake to replenish after a day’s work, in preparation for the next day. This premise aligns with findings in truck and train drivers who reported they could afford more time to sleep between shifts when ‘on the road or rails’ than when at home where they preferentially engaged with their family [284-287]. It is important to note, however, that without an understanding of the firefighters’ work, hydration status, food and fluid intake, and family environment on the night before their first shift, the presented theory remains to be verified. It is also possible that peers or supervisors also positively influenced food and fluid consumption post-shift. Future research, should explore how a firefighter’s environment, such as being at home or in camp, influences their engagement in safety behaviours (e.g., fluid intake for hydration pre- and post-shift). The ensuing findings could produce valuable outcomes for agencies striving to promote and preserve the health and safety of their workers across multi-day deployments.

Despite differences in hydration status across the two shifts (Figure 20), there was no difference in firefighters’ activity profile across shifts. The stability of the firefighters’ activity pattern, despite the 3.0 ± 0.9 mOsm difference (main effect) in hydration is not surprising. Firstly, the level of hypohydration, estimated to be equivalent to 1 – 3% body mass [100], is unlikely to be associated with sub-optimal endurance performance [261].
Secondly, previous research by the current group has shown that firefighters’ physical activity across a wildfire suppression shift is not influenced by increasing fluid intake (and presumably hydration, though it could not be measured ‘in shift’) before or during a shift [269, 274]. Before concluding that firefighters’ physical activity is not influenced by fluid balance within the range reported in the present study, it should be acknowledged that the ambient temperature on day two was $1.9 \pm 4.1^\circ C$ hotter than day one. Previous researchers have shown humans pace their physical activity in hotter conditions to preserve a level of comfort (see [288] for review). However, it is not clear whether changes in work pace would occur with such small differences in temperature. So it is possible that the slight influence (if any) of dehydration to reduce work-rate on day one was counter-balanced against a slight decrease (if any) in worker activity in the marginally hotter conditions on day two. Firm conclusions on the relative impact of ambient temperature and hydration on self-paced physically demanding work (e.g., firefighting) are, however, premature. More rigorous experiments with tight control over independent factors and precise measurement of worker output (not always possible in the field) are required to further understand this area.

Across day one, firefighters’ core temperatures were $0.59 \pm 0.03^\circ C$ hotter ($p < 0.01$) than across day two (Figure 22). Their relative hyperthermia occurred despite a $1.9 \pm 4.1^\circ C$ lower mean ambient temperature and no difference in physical activity. It is highly likely that the hyperthermia was mediated by firefighters’ relative dehydration on day one (Figure 20). In a seminal review, Sawka [205] presented that core temperature during exercise increased by 0.1 to 0.4$^\circ C$ for every 1% loss in body mass. This relationship is mediated through a reduction in heat dissipation through either a decrease
or delayed onset of sweating for a given core temperature [289]. In turn, the reduced sweating rate is thought to be mediated through increases in plasma osmolality [289]. Though sweat rate was not measured in the current study, it is likely that the firefighters’ relative hyperosmolality on day one reduced their’ sweat rate, increasing heat storage and elevating core temperature despite marginally (though significant) cooler ambient temperatures.

The influence of firefighters’ relative dehydration on day one may also be implicated in their heart rate (Figure 21) and RPE (Figure 23). On day one, firefighters spent ~ 15 min longer in the 'hard' (70 - 89%HRmax) heart rate zone from 4 – 10 h (Figure 21). Further, firefighters’ RPE at the conclusion of their day one shift was 4 ± 1 units higher (p = 0.01) than at the same point on day two (Figure 23). Dehydration can lead to a decrease in blood volume, which in turn reduces stroke volume and results in a concomitant increase in heart rate to preserve cardiac output [289]. A hypohydration-mediated increase in heart rate later in the day one shift could also materialize in the end-shift RPE results (Figure 23). As reviewed by Cheuvront et al. [290], cardiopulmonary factors, and in particular, heart rate makes a prominent contribution to RPE. As such, firefighters in the current study may have recalled or still felt the additional exertion (as shown by the elevated heart rate) late in their day one shift when completing their end-shift RPE questionnaire.

CONCLUSION
The current study found that firefighters’ were hypohydrated at all time-points on day one, and euhydrated across day two of consecutive wildfire suppression shifts in hot weather conditions. The relative dehydration on day one appears to have increased core
temperature and time in the hard heart rate zone, despite no inter-day differences in physical activity and slightly lower (though still hot) ambient temperatures. Firefighters’ ad-libitum fluid intake appeared sufficient to maintain their pre-shift hydration status, despite the hot weather conditions. Firefighters’ reporting to their second shift euhydrated is a novel finding and should compel researchers to investigate what influences that workers’ food and fluid consumption post-shift can have on their work, a health and safety, on their next shift.

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CHAPTER SIX: SUMMARY & FUTURE DIRECTIONS

The theme of this doctoral thesis focused on the practical problem of fluid consumption during wildfire fighting and the effect this had on physiological strain. Results emanating from this thesis inform, challenge and may alter existing practices by fire agencies. This chapter begins by presenting the aims and major findings of this dissertation. The ensuing discussion will weave the findings of the three studies together and outline the emerging stance on how fluid intake influenced the key variables (time in the heart rate hard zone, core temperature, activity etc.) describing physiological strain in wildfire fighters. This chapter concludes by outlining the limitations of this work and the specific issues for future researchers in this area to consider.

AIMS

The objectives of this thesis were:

1. To evaluate whether ingesting a bolus of fluid before the shift had any effect on firefighter fluid consumption, core temperature, or the time spent in high heart rate and work activity zones when fighting emergency wildfires.

2. To examine i) the wildfire fighter’s ability to consume a prescribed fluid volume (1200 ml hr⁻¹), ii) the effect of fluid intake on plasma sodium and hydration, and
iii) firefighters heart rate, core temperature response and activity during emergency suppression shifts.

3. To evaluate i) firefighter pre- and post-shift hydration status across two shifts of wildfire suppression work in hot weather conditions, ii) to document firefighter fluid and food intake during and between two shifts, iii) to assess any changes in heart rate, activity, perceived exertion and core temperature across the two consecutive shifts.

**MAJOR FINDINGS**

The major findings of this dissertation were:

1. Consuming a 500 ml bolus of fluid, in mild to warm ambient temperatures, before commencing the emergency wildfire fighting shift had no effect on core temperature response, heart rate response or firefighter activity across the shift.

2. Pre-shift bolus drinkers had consumed equivalent volumes of fluid, to ad libitum drinkers 2.5 hours into the shift.

3. A prescribed fluid intake of 1200 ml·hr⁻¹ during the shift, in mild to warm ambient temperatures, was not well adhered to by the firefighters.

4. Though the prescribed group (532 ± 232 ml·h⁻¹) consumed approximately twice as much fluid as the ad libitum group (218 ± 198 ml·h⁻¹), there were no
differences in cardiovascular strain, work activity or distance covered between the groups.

5. Prescribed drinking resulted in lower core temperatures at two to six hours and a blunted rise in core temperature across the work-day.

6. Ad libitum drinking was adequate to facilitate euhydration in firefighters upon completion of their emergency firefighting work shift, in mild to warm weather.

7. The ad libitum fluid intake of firefighters was sufficient to sustain a euhydrated status from the start to the end of the shift, despite hot weather conditions.

8. Ad libitum fluid intake did not facilitate euhydration at the completion of a shift in hot weather when firefighters began hypohydrated.

9. The total ad libitum fluid intake (from both ingested food and fluid) was not different between consecutive days of work in hot weather, averaging $6.4 \pm 1.9$L.

10. The dehydration on day one appeared to be associated with increases in core temperature and time spent in the hard heart rate zone, despite no inter-day differences in physical activity and slightly lower (though still hot) ambient temperatures.
GENERAL RECOMMENDATIONS FOR WILDFIRE FIGHTER FLUID INTAKE AND HYDRATION RESEARCH

DRINKING
The findings from the studies conducted in mild to warm weather conditions (Chapter 3 and 4), concur that when both food and fluid availability and choice are not limited, ad libitum drinking is adequate to facilitate euhydration in firefighters upon completion of their emergency firefighting work shift. The study in hot weather (Chapter 5) demonstrated that a pre-shift euhydrated state was indeed possible to be maintained by the completion of the workday when firefighters consumed fluid ad libitum. Furthermore, a pre-work bolus of fluid (500 ml) displayed no additional benefits to firefighters above ad libitum drinking. Prescribing a set amount of fluid (1200 ml) per hour did not translate into greater work performed on the fire ground nor reduced time in the hard heart rate category. The increased fluid intake appeared, however, to blunt the rise in core temperature in the first six hours of the shift, and increase urine production by 2L whilst causing intestinal discomfort.

The findings of these studies support the work of Noakes, who states that “perhaps the best advice is that drinking according to the personal dictates of thirst seems to be safe and effective [176].” This is a paradigm shift from the views of the past where fluid intake guidelines for athletes (and workers) were to replace the water lost via sweat, to consume the maximal amount of fluid that could be tolerated, or to drink 600-1200 ml per hour [90]. The assumptions that these aforementioned guidelines made, as stated by Noakes [176], were: “Firstly, that all the weight lost during exercise must be replaced if health is to be protected and performance is to be optimized, since, as the guidelines state, the greatest threat to health and wellbeing during prolonged exercise, especially
when performed in the heat, is dehydration [291]. Secondly, that the sensations of thirst underestimate the real fluid requirements during exercise. Thus athletes must be told how much to drink during exercise. Thirdly, that the fluid requirements of all athletes are always similar so that a universal guideline is possible. Fourthly, high rates of fluid intake can do no harm.” It is clear from this dissertation that ad libitum drinking (according to the dictates of thirst, or “drink whatever you want, whenever you want”) could be the appropriate drinking condition for firefighters. High rates of fluid consumption can do harm (as evidenced by numerous deaths from overdrinking/hyponatremia cited in the literature [172-174]) and in practice, a prescribed fluid consumption guideline is not fully adhered to by firefighters during emergency wildfire suppression shifts.

Wildfire fighting industry practice in Australia should be encouraged to change based on the outcomes of the studies in this thesis. Current recommendations by fire agencies regarding specific quantities of fluid (500-3000 ml/hr⁻¹, Table 4) should be adjusted to reflect ad libitum drinking as the key condition in mild to warm and hot weather work days; and firefighters’ arriving for work euhydrated on hot days is encouraged. In the interim, or during the policy change period, an upper ceiling of total fluid intake per day is also recommended as the current advice from some Australian Fire Agencies may put firefighters at risk of water intoxication/hyponatremia (substituting water with electrolyte fluid will not overcome the risks associated with consuming the vast fluid volumes [292]). The exact upper ceiling level as applied to firefighters on multiple day deployments is not clear. Until there is agreement of an ad libitum drinking policy (which should reduce the risk of overdrinking as firefighters would cease when they felt
uncomfortable), it is suggested that the current ‘ceiling’ from the US Military of 909-1364 ml h\(^{-1}\) and 10.9 L per day [177] be adopted. The current body of firefighters who consumed high volumes of fluid similar to the US Military upper daily intake ceiling, reported stomach discomfort. A pre-shift drinking bolus was not a fix-all for achieving euhydration in firefighters and it did not transfer any physiological benefits beyond what ad libitum drinking provided. Beginning the shift in a euhydrated state is favorable in delaying the rise in core temperature in hot weather, but likely to come from the ad libitum consumption of fluid by firefighters ‘in camp’ the previous night not a pre-shift bolus of fluid. The fire industry should be congratulated for their adequate provision of food and fluids to working crews and be encouraged to continue to offer a range of fluid types (water and sports drink) and food so that firefighters are able to regulate their ad libitum intake of fluid so that there are no adverse effects on their plasma sodium levels. Interestingly, some firefighters consumed 100% of either water or sports drink operationally, hence we cannot be more prescriptive as the range in beverage selection was large.

**HYDRATION STATE**
Ad libitum drinking was able to preserve the euhydrated state or improve a hypohydrated state during firefighting in mild to warm weather. The results from this thesis (Chapter 5) demonstrated that firefighters were capable of commencing work euhydrated and maintaining this status by shift completion; even when working in the heat. This was after spending the previous night ‘in camp’ and consuming fluid ad libitum throughout the duration of the study, despite hot weather conditions. This ‘in camp’ situation is an interesting area to explore further as recovery (and fluid intake)
from the day’s work is the focus of firefighters - to enjoy others company, eat, drink, talk, and sleep. Whereas the environment of the home may often be affiliated with differing social expectations and demands from family; e.g. domestic duties and/or other distractions that may affect recovery between shifts in a different manner. This has been postulated in sleep research (in truck and train drivers who sleep more between shifts when ‘on the road or rails’ than when at home and engaged with their families [284-287]); but not in other areas.

Being able to commence work euhydrated and maintain this state was contrary to the collective findings from previous wildfire fighter physiology researchers who supported the presence of dehydration in this population. Namely that firefighters arrive hypohydrated [7, 8] and maintain [10, 27] or exaggerate [11, 12] their level of dehydration throughout their work shift. There could be two possibilities for these inter-study differences; i) that firefighters in the previous studies were actually hypohydrated; or ii) that the firefighters in the previous studies were actually euhydrated; but the measures used were largely body mass and urinary based (the latter which have been well known to result in a delayed response) [93, 99, 100], hence may not reflect the firefighters’ actual hydration status at that point in time unlike the blood marker, plasma osmolality [100]. The differences may also be due to a number of other possibilities not limited to: differing work approaches by firefighters from country to country; that ad libitum fluids provided were limited to one beverage type [11] - not a choice of water or sports drink (containing electrolytes and carbohydrates); that wildfire is unpredictable and work rates can vary (although activity monitors logged no inter-day differences in the current body of work), and lastly that the local fire-weather and climate can change
temperature, wind speed and humidity dramatically - potentially affecting the sweat rates of firefighters.

**HEART RATE**
The three studies in this thesis showed that firefighters spend time in the hard heart rate zone consistently throughout their shift (2.6 ± 5.4 min and 4.4 ± 9.9 min of each two-hour period in the hard heart rate zone for ad libitum and prescribed drinkers respectively, Chapter 4, (Figure 17); averaging 4 ± 9% of the total shift time spent in hard heart rate zones, Chapter 3, (Figure 12)) regardless of the deployment objective or their age. For health and safety reasons it is likely to be advantageous to minimize a firefighters’ time they spend in the hard heart rate zone. This reduced exposure effect was noted when firefighters held a euhydrated state and consumed fluid ad libitum in hot weather (Chapter 5). Which stresses the importance of each individual firefighter’s overnight preparation relating to fluid consumption to enable euhydration before the day shift begins in hot weather. In mild to warm weather, none of the drinking conditions affected the time spent in the heart rate hard zone. The specific measure of time in the heart rate hard zone is better than relying on a single peak heart rate marker as that may be influenced by so many variables in an already challenging field environment. It is recommended that future firefighting studies maintain the use of this time-based measure of cardiovascular intensity.

**CORE TEMPERATURE RESPONSE**
Core temperatures were lowered for the first half of the day shift, and demonstrated a delayed rate of rise when a prescribed drinking volume of 1200 ml·h⁻¹ was attempted on warm to mild days. The actual fluid intake rate of prescribed drinkers (532 ± 232 ml·h⁻¹
was more than double the natural ad libitum drinking intake of 218 ± 198 ml·h⁻¹. When working in the heat, (and activity and fluid intake remaining consistent across days) hypohydrated firefighters displayed elevated core temperature responses compared to the day when they commenced work euhydrated (as determined by plasma osmolality). These collective findings support the roles of the larger volume of total body water in sustaining the sweat rates required for evaporative cooling [211] and/or its potential role as a ‘heat sink.’ The latter relates to the body water acting as heat storage [56, 210], thereby absorbing the heat generated internally by the firefighter and that externally created from his/her environment. Due to this finding it is worth educating firefighters of this heat absorbing effect, however the author maintains that ad libitum drinking should be the guideline promoted by Fire Agencies, even in hot weather.

**ACTIVITY**
The findings from these three thesis studies display the regularity of work performed by firefighters across days and work locations and tasking. There were no differences in work by drinking condition. This was likely to be from the fact that physiological benefits do not always translate into greater activity in work environments. Firefighters may not choose to transiently increase productivity across their shift, preferring to pace themselves throughout, in contrast to harvesting environments where more work equals more pay [80]. The current finding aligns with a previous investigation which demonstrated that drinking more was not linked to higher activity rates in wildfire fighters [11]. The study design whereby firefighters were paired with the opposing drinking condition on each truck and sharing the immediate environment demonstrates that regardless of tasking or location on the fireground, wildfire fighters will be
performing consistent work in the sedentary and light category across all shifts. Activity does have its limitations with respect to measuring workload during isometric tasks such as static hose holding; however it is an important marker to allow for comparisons of workloads between firefighters, strike team deployments and other research and hence should be included in future studies. Activity can also help contextualize heart rate responses in workers, though a few studies have failed to use this valuable tool [42, 234].

**Summary Contribution**
The original and innovative studies within this thesis have practical significance for firefighters, fire agencies and may be extrapolated, with caution, to similar emergency services/occupations who share long duration work periods in the heat wearing protective clothing. The findings from this group of studies informs firefighters of what influence drinking fluid, does and does not have on physiological strain. Specifically, the appropriateness of fluid consumed as a pre-shift bolus (500 ml) and prescribed fluid protocols during work (1200 ml/hr⁻¹), versus ad libitum drinking in mild to warm and hot weather. It also advises fire agencies (for planning, logistics and management purposes) on the quantities of fluid now practically expected for firefighters to consume during and between shifts in mild-warm and hot weather conditions.

**Limitations of the Doctoral Investigation and Further Recommendations for Future Studies**

Field research, as challenging as it is with access to crews and the unpredictability of call outs to incidents; should continue to be the setting for future work of this nature as
the effects of weather, fire behavior, job sharing, and pacing for the demands of the workday cannot be simulated in a laboratory. The advice of the current author to future researchers is to make the best use of the opportunities you have available with the firefighting crews you have the privilege to work with. One particular advantage is utilising two firefighters on the same appliance/truck so that they may act as each other’s ‘control’; thereby they share the same workload, tasking, and are exposed to the same immediate environment.

A major caveat of this body of work was that the data was limited to day shift work. Night shifts were not explored as this would have added another element of variability. It is recommended that night shift responses are explored as behavioral ad libitum drinking may alter (as could sweat rates) without the additional radiant heat from the sun. The physiological strains experienced may have differing effects on night shifts; also the recovery between night shifts may be rather different. Whether ‘in camp’ or at home, the ability of firefighters to rest and sleep during the day in a variety of accommodations, e.g. tents in the heat, hotel rooms with air conditioning, at home with family duties and distractions etc., may pose a greater challenge than that faced by firefighters who have opportunity to sleep during night hours. Hence fatigue may be further aggravated in the population of night shift firefighters especially over multiple campaign deployments. Fatigue has been identified as a significant problem in pilots; largely because of the unpredictable work hours, long duty periods, circadian disruptions, and insufficient sleep [235] (factors they may share with night shift firefighters). Compared to people who are well-rested, those who are sleep deprived think and move more slowly, make more mistakes, and have memory difficulties [235].
Whether this is manifested and how it is manifested in night shift firefighters remains to be explored.

The other gaps remaining in the firefighter fluid intake/physiology literature in which future studies could aim to address also include exploring the way fluid is delivered to firefighters. Further, whether there is any meaningful benefit to pre-cooling fluid when working in the heat. How this might affect intake, palatability, hydration and physiological strain. Also, a longitudinal study following the changes in fire agency fluid prescriptions over a number of years is advised. Whether the new fluid intake recommendations have been absorbed by agencies, how they are communicated to firefighters, and how they are being practically implemented on the fireground. Also investigations simultaneously tracking cases and the diagnosis of dehydration at campaign fires and the subsequent reporting of this condition could be of interest. Additionally, performing a ‘set amount of work’ (e.g. a forestry step test) pre- and post-shift to monitor changes in cardiovascular strain (heart rate response) and fatigue; when firefighters are euhydrated versus hypohydrated over multiple days of campaign fire work would be of value.

Given the apparent challenges of wildfire fighting work, reduced mental performance can have a profound effect on every firefighter, their team and wildfire fighting objectives. The interested reader is referred to papers by Gopinathan [68] and others [58, 67-71, 82, 293-298]. In high risk settings, such as the wildfire environment, any increase in psychological strain or impairment in mental functioning may place firefighters at an increased risk of accidents [30, 299]. The relationships between
hydration, heat and/or physical work on mental performance therefore requires further exploration.

Feelings of thermal discomfort may also been implicated in reducing firefighter performance. While few studies directly assess subjective ratings of thermal comfort, it is expected that increases in core temperatures, as noted with dehydration [15, 128, 145, 300], would be likely to cause thermal discomfort during wildfire fighting work. One study described the inability of structural firefighters to detect changes in heat stress (denoted by the absence of significant differences in levels of perceived exertion and thermal comfort while wearing different personal protective clothing) and their failure to ensure adequate levels of hydration (despite free availability of water), as being potentially lethal [87]. Hence, personal perceptions of exertion and thermal comfort could be valuable for individual firefighter health and safety. Further study is required to determine if ratings of perceived exertion and thermal comfort are valuable in-field assessment tools, sensitive to changes in hydration status.
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Laboratory: Department of Defence: Defence Science and Technology


