Do extreme temperatures affect cognition? A short review of the impact of acute heat stress on cognitive performance of firefighters

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1 Abstract

Research shows that exposure to high environmental temperatures can affect task performance. Theoretical explanations outline that heat is a source of stress that competes for limited-capacity resources, therefore if a task is resource-intensive, and/or if heat stress is extreme, performance will suffer. One occupation in which individuals are required to complete demanding tasks and make difficult decisions, often in temperatures exceeding 200°C, is firefighting. Yet very little is currently known about the impact of heat stress on the cognitive functioning of firefighters. This short review summarizes the limited research in this area, focusing on studies that have measured cognition of firefighters following a realistic training exercise. The findings are mixed with evidence that heat stress improves, impairs, and has no impact on cognitive functioning. Whilst there are differences in the firefighting activities utilized across different studies, and the temperatures that participants have been exposed to, it is argued that the varied findings can be attributed to the tasks used to assess cognitive processing, and the type of cognitive function being measured. In accordance with the wider field of research in heat stress and cognition, it is concluded that complex functioning, such as sustained attention, vigilance, and working memory is negatively impacted by acute exposure to extreme heat. Greater understanding of factors affecting cognition would inform safety practices and more research is needed to understand how and when acute heat stress may influence cognition in firefighting scenarios.

2 Introduction

In search and rescue operations the role of a firefighter is cognitively demanding, requiring vigilance, memory for spatial locations, and rapid decision-making. Cognitive ability in such scenarios is impacted by experience and expertise, but may also be influenced by stressors, including physical demand, the complexity of the rescue task, and the emotional load of the situation. One source of stress relatively unique to firefighting is heat stress. Studies have shown that task performance in the workplace can suffer when environmental temperatures exceed 23°C (Ramsey et al., 1983), and the working environment of a firefighter often exceeds 200°C (Willi et al., 2016). Additionally, Schmit et al. (2017) concluded that cognitive function will suffer when core body temperature increases beyond 39°C and core body temperature when firefighting often exceeds 38.5°C (Horn et al., 2017). This suggests that firefighters may be at-risk of heat stress, ultimately impacting their ability to protect lives. It is therefore important to understand how heat can affect cognition in this population.

Studies measuring the effects of heat stress on cognitive processing have shown mixed findings. In line with Ramsey et al. (1983), Seppänen et al. (2006) found that task performance of office workers is best at 22°C but starts to deteriorate as temperatures rise above 23-24°C. However, when testing performance of trainee surgeons, Berg et al. (2015) found no impairment when working in 26°C heat. Ashworth et al. (2021) also found no effect of temperature on cognition when participants walked on a treadmill in 33°C heat. In contrast to this, Liu et al. (2013) found impairments to executive control after participants spent 45-minutes in a chamber heated to 50°C (compared to 28°C) and Saini et al. (2017) found that sustained attention and executive functioning of soldiers working in desert conditions was worse in June (42-43°C) compared to March (24-27°C).

The findings above indicate that more extreme temperatures have a greater impact on cognition. However, the relationship is more complex. Hancock and Vasmatzidis (2003) suggest that the effect of heat on cognition will vary depending on factors such as expertise, acclimatization to the heat, and duration of heat exposure, however they argue that the key factor is task complexity. In accordance with the Maximal Adaptability Model (Hancock & Warm, 1989) they propose that stressors compete for limited capacity cognitive resources. Individuals can adapt to this, for example by devoting more attention to a task, but as complex tasks utilize more resources, the ability to compensate reduces, meaning that stressors (i.e., heat) will impact complex tasks more than simple tasks. This is potentially illustrated by Berg et al. (2015) who found that whilst heat did not affect cognition, participants reported increased cognitive load and distraction suggesting they were having to expend more effort to maintain performance.

Hancock and Vasmatzidis (2003) propose that demanding tasks, such as vigilance and monitoring, will be most vulnerable to heat stress, and this is a concern given the importance of such tasks in firefighting, the complexity of situations a firefighter may be exposed to, and the difficult decisions they are required to make. Yet it is unclear how heat affects firefighter cognition because most past research does not represent the working conditions faced by firefighters. To better understand the risks of acute heat stress on firefighter cognition, this review outlines a selection of studies (summarized in table 1) that have tested the effects of heat on firefighter cognition using real-life scenarios and firefighters as participants.

3.1 Extreme heat improves cognition

Early attempts to assess the impact of heat on firefighter cognition found evidence of improvements following live-fire training activities. In a study by Greenlee et al. (2014) firefighters completed a continuous performance test (CPT) to measure sustained attention before and after participating in an indoor live-fire training scenario for 18-minutes. Despite environmental temperatures reaching 82°C and core body temperature increasing from a mean of 37.1°C pre-training to a mean of 37.8°C post-training (reported in Horn et al., 2011), reaction times were faster post-training, indicating improved ability to sustain attention and remain vigilant after exposure to extreme temperatures.

The maximal adaptability model suggests that stress initially enhances performance (arousal), but as stress levels increase and compensation is not possible, performance starts to decline. In the study conducted by Greenlee and colleagues, it may be that the level of stress caused by the high environmental temperatures was insufficient to compete for resources (i.e., due to temperatures not being extreme enough, core body temperature not exceeding the critical levels identified by Schmit et al., 2017, and a short duration of heat exposure). However, Walker et al. (2015) also found improved performance following an indoor training exercise when firefighters were exposed to temperatures up to 115°C (core body temperatures reached 41°C) for 40-minutes (two 20-minute activities). Participants completed search and rescue scenarios in the extreme temperatures and the researchers measured speed of processing, vigilance, and working memory before and after the firefighting activity. Whilst they found no difference in performance pre- and post-activity for speed of processing and working memory, consistent with Greenlee et al. (2014) they found evidence of improved vigilance.

These findings seem in direct contrast to studies in the wider field of heat stress and cognition (e.g., Liu et al., 2013; Qian et al., 2015), potentially suggesting that firefighters are less impacted by heat stress than the general population. This could indicate some form of familiarization, or acclimatization, with firefighters better able to manage heat stress because they are more accustomed to it. In support of this, Radakovic et al. (2007) found that cognitive performance of soldiers was impaired after completing a heat stress test in 40°C compared to 20°C heat, unless they had been acclimatized to the heat for ten days.

3.2 Extreme heat impairs cognition

Evidence against firefighters being acclimatized to heat comes from studies that show heat has a negative impact on firefighter cognition. Hemmatjo et al. (2017) tested cognition before and after an indoor firefighting scenario using a smoke diving room and environmental temperatures were relatively low compared to other investigations. They tested participants following activities completed in low heat (29-31°C), moderate heat (32-34°C), and extreme heat (35-37°C) and measured information processing and working memory using a paced auditory serial addition task (PASAT). In this task participants hear numbers spoken one after the other and are asked to add each number to the previous one. For example, hearing the numbers 8, 2, 5 participants should respond "10" after the second digit and "7" after the third digit. Hemmatjo et al. found decreased accuracy across all three conditions post-activity, although the difference between pre- and post-activity scores was most pronounced in the severe heat condition.

In a later study, Hemmatjo et al. (2020) found similar effects after an outdoor live-fire training exercise. Firefighters were asked to pass through a fire in a large outdoor space, extinguish the fire using a water hose, and then turn off the hose. Before and after this they completed an auditory and visual PASAT, and an auditory and visual CPT. Although they did not collect any measures of temperature, given the nature of the activity it would be assumed that participants were not exposed to the sorts of temperatures experienced by firefighters completing an indoor training exercise (i.e., Walker et al., 2015), yet they found impaired performance across all tasks following the training exercise.

This contrasts with the earlier work of Greenlee et al. (2014) who also used a visual CPT but found improved task performance. However, the tasks used within each study were quite different. Greenlee et al. asked participants to complete 50 trials in which they monitored and responded to numbers, pressing Z for 'frequent' numbers (1-8, accounting for 80% of trials) and pressing M for 'rare' numbers (0 and 9). In contrast, Hemmatjo et al. asked participants to complete 150 trials in which they were presented with one of ten shapes and were asked to press a key if a star shape was shown (20% of trials) but make no response if another shape was presented. Both studies claim to be measuring sustained attention (vigilance), but it may be argued that Greenlee et al. actually used a choice discrimination task and were measuring how quickly participants were able to make their choice and respond, not how effectively they were sustaining their attention. The same argument could be made about tasks used by Walker et al. (2015). For instance, they measured vigilance by asking participants to respond to the colour of playing cards presented on a screen, and measured working memory by asking whether each card matched the one presented previously. These tests seem more similar to simple perceptual judgement tasks than tasks, such as the PASAT (Tombaugh, 2006), that measure the capacity of information processing.

Zare et al. (2018) also measured cognition using a PASAT before and after firefighters engaged in a live-fire training exercise outdoors. The training exercise was the same as that used by Hemmatjo et al. (2020) and they compared this to two other training scenarios; typical training activities in a smoke diving room (carrying and pulling a hose, carrying and climbing a ladder, passing through unfamiliar narrow spaces, and passing through an escape tunnel) and rescue from height (a victim is suspended from the ceiling of a training room and a firefighter must use special ropes attached to the ceiling to lift themselves up to the victim and use a rescue belt to bring the victim down). Again, they found cognitive impairments following the live-fire training exercise. Interestingly, cognitive performance was worse post-exercise across all three conditions and maximum core body temperature was also similar across the three conditions (38.07°C, 38.19°C, and 39°C for live-fire, typical training, and rescue from height respectively). The researchers found the greatest impairment in the rescue from height condition, supporting the argument that heat stress impairs cognition, but also indicating that other sources of stress (e.g., physical fatigue, anxiety associated with rescuing a victim) will interact with heat stress to have a greater impact on cognitive functioning. These findings could be explained by the Global Workspace theory (Baars, 1997), which argues that stimuli compete for limited-capacity resources, and the more competition there is (i.e., from multiple sources of stress), the more strain on cognitive resources, and the more likely it is that performance will be affected.

3.3 Extreme heat has no impact on cognition

The studies above that show impairments to cognition are those that have exposed firefighters to relatively moderate working temperatures. It would seem counterintuitive that more extreme temperatures would lead to no effect, or to improvements (as in Walker et al., 2015 and Greenlee et al., 2014), yet two studies that have involved indoor live-fire training exercises with temperatures exceeding 400°C have found no evidence that heat stress affects cognition. Abrard et al. (2021) measured cognition before and after firefighters experienced a live-fire exercise in a shipping container. They used a cognitive test from the Mini Mental State examination (Folstein et al., 1975) that required participants to count backwards from 100 by 6, 7, or 8 and found no difference in performance before and after the exercise.

Canetti et al. (2022) also measured cognition before and after a live container fire exercise (with temperatures exceeding 400°C) and found no differences. They assessed cognition with three tests; a digit cancellation task in which participants had 90 seconds to cross out specific targets on a sheet of paper, a logical reasoning task in which they had 30 seconds to answer true or false to 20 statements about letter pairings (see Baddeley, 1968), and a recall task in which they were presented with a series of numbers, objects, and pictures for 30 seconds and then had to recall as many as possible.

It should be noted that these two studies had very small sample sizes, and whilst they report temperatures of over 400°C, environmental temperatures in a live-fire scenario can vary significantly.

Abrard et al. report temperatures of 25°C-150°C at the back of the training structure, to over 450°C at helmet height, so perhaps participants were not exposed to such extreme temperatures. This would explain the relatively low maximum body temperatures recorded from participants (see table 1) in comparison to the study completed by Walker et al. (2015). However, a key difference between these studies and those reporting negative effects of heat is the tasks used to assess cognition. Aside from Canetti et al. giving a set amount of time for participants to respond, the tasks they used (and those used by Abrard et al.) did not involve speeded responses, and crucially they did not measure processes that are most likely to be affected by heat stress such as sustained attention and working memory (Hancock & Vasmatzidis, 2003). Tasks that are easy will not draw so heavily on limited cognitive resources, therefore any competition in the form of heat stress is likely to have minimal impact on performance. This would explain why exposure to temperatures of 400°C+ did not impair cognition, but it raises questions over the effect of such temperatures on more complex cognitive functioning, and the suitability of tasks used to assess firefighter cognition.

4 Discussion

Evidence suggests that acute heat stress affects cognitive processing, with impairments found when environmental temperatures exceed 23°C (Ramsey et al., 1983) and core body temperatures exceed 39°C (Schmit et al., 2017). Past research also reveals that task complexity plays a significant role in the effects of heat, with complex functioning (e.g., Saini et al., 2017) impaired to a greater extent than simple functioning (e.g., Ashworth et al., 2021). Hancock and Vasmatzidis (2003) attribute this to the competition for limited-capacity cognitive resources; heat stress puts a strain on resources, and whilst simple tasks are less resource-intensive and therefore not impacted by this, competition in more complex situations will reduce the resources available, impairing cognitive functioning.

Given the evidence from non-firefighter populations and the theoretical explanations for the effects of heat stress, it would be predicted that firefighters are at risk of cognitive impairments. Not only are they routinely exposed to working temperatures over 200°C (Willi et al., 2016), but search and rescue operations require complex cognitive functioning such as vigilance and working memory (Greenlee et al., 2014). Yet the limited studies that measure the effects of heat on firefighter cognition show mixed findings. This review summarized seven research studies that measured cognitive functioning before and after firefighters completed a training exercise in high temperatures. Two studies showed improvements (Greenlee et al., 2014; Walker et al., 2015), three showed impairments (Hemmatjo et al., 2017; Hemmatjo et al., 2020; Zare et al., 2018), and two showed no effect of heat (Abrard et al., 2021; Canetti et al., 2022).

Across these different studies there was no clear pattern in terms of the temperatures experienced (studies reporting the lowest temperatures found negative impacts), the duration of exposure (the longest exposure led to improved cognition), or the type of training exercise (varying effects were found in both indoor and outdoor activities). In accordance with research from non-firefighter populations, the one consistent feature was that acute heat stress had a negative effect on more complex cognitive functioning. Using the classification of Taylor et al. (2016), the work showing no effect of heat stress, or improvements, arguably tested “simple” functions (choice reaction, memory recall, and simple arithmetic) and those showing negative effects of heat stress tested “complex” functions (vigilance, sustained attention, working memory). This is consistent with research by Gaoua et al., (2018) who found that heat stress is a source of cognitive load that affects activity in the frontal cortex, and whilst this does not impact on completion of simple tasks, competition for resources means that performance suffers in complex tasks.

The conclusion that acute heat stress impairs complex cognition is concerning because search and rescue operations require complex functioning and by measuring more simplistic processing the research does not show the true extent of heat stress on firefighters. Future work should make use of cognitive tasks that better reflect the cognitive demands of firefighting. In addition, the limited research in this field provides no information about factors that may moderate the effects of heat stress on firefighters, such as expertise and acclimatization (Hancock & Vasmatzidis, 2003), because no data is collected or presented in relation to this. Therefore, whilst research in this area has the potential to inform operational guidelines and working practices in relation to how long firefighters can work in extreme temperatures and how long they should spend cooling, more work is needed to gain a full understanding of the risks of acute heat stress on firefighter cognition.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

5 Author Contributions

CT designed and wrote the first draft of the manuscript with the help of LF. All authors contributed to the revising and editing of the manuscript. All authors read and approved the submitted version.

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Table 1: A summary of the past research investigating the effects of heat on firefighter cognition.

Authors (and date)	Activity (and duration)	Sample size	Maximum environmental temperature	Maximum body temperature	Cognitive function and task	Outcome
Greenlee et al. (2014)	Live fire training exercise indoors (18 mins)	20	82°C	38.2°C (Core body temperature)	Visual continuous performance test (CPT) to measure sustained attention	Improved performance
Walker et al. (2015)	Search and rescue scenarios inside a purpose-built heat chamber (2 x 20 mins)	77	110°C	41°C (Core body temperature)	Tests to measure speed of processing, vigilance, working memory	Improved vigilance
Hemmatjo et al. (2017)	Firefighting tasks in a smoke-diving room (~30 mins)	17	37°C	38.32°C (Tympanic temperature)	Paced auditory serial addition task (PASAT) to measure information processing and working memory	Impaired performance
Zare et al. (2018)	Live fire suppression outdoors (~20 mins)	18	No data	38.07°C (Temporal artery temperature)	PASAT to measure information processing and working memory	Impaired performance
Hemmatjo et al. (2020)	Live fire suppression outdoors (~30 mins)	18	No data	No data	Visual and auditory PASAT and CPT to measure information processing, working memory, and sustained attention	Impaired performance
Abrard et al. (2021)	Live fire training exercise indoors (~30 mins)	12	+400°C	37.3°C (Skin temperature)	Number subtraction task to measure attention and mental calculation	No effect
Canetti et al. (2022)	Live fire training exercise indoors (15 mins)	7	+400°C	38.9°C (Tympanic temperature)	Tasks to measure speed and accuracy, logical reasoning, and memory recall	No effect

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