Taylor & Francis
Taylor & Francis Group

Ergonomics

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/terg20

In the heat of the moment: the effects of extreme temperatures on the cognitive functioning of firefighters

Catherine Thompson, Lucy Ferrie, Stephen J. Pearson, Brian Highlands & Martyn J. Matthews

ERGONOMICS
https://doi.org/10.1080/00140139.2024.2326584

OPEN ACCESS Check for updates

In the heat of the moment: the effects of extreme temperatures on the cognitive functioning of firefighters

Catherine Thompson[a], Lucy Ferrie[b], Stephen J. Pearson[b], Brian Highlands[b] and Martyn J. Matthews[b]

[a]Department of Psychology, Liverpool Hope University, Liverpool, UK; [b]School of Health and Society, University of Salford, Salford, UK

ABSTRACT
Exposure to high temperatures can have detrimental effects on cognitive processing and this is concerning for firefighters who routinely work in extreme temperatures. Whilst past research has studied the effects of heat on firefighter cognition, findings are mixed, and no work has measured the time course of cognitive recovery. This study compared working memory, vigilance, and cognitive flexibility of 37 firefighters before and after they engaged in a live-fire training exercise with temperatures exceeding 115 °C. To assess recovery, cognition was measured on exiting the fire, then 20- and 40-minutes post-fire. Results showed impaired vigilance and cognitive flexibility (increased errors, slower responses) immediately after the fire, but recovery at 20-minutes. These findings indicate that a live indoor fire negatively impacts cognitive processing, but this effect is relatively short-lived and return to baseline functioning is seen 20-minutes after exiting the fire. The findings could be used to inform re-entry and cooling decisions.

PRACTITIONER SUMMARY:
Acute heat stress may affect cognitive processing, posing a health and safety risk to firefighters. This study demonstrates impaired cognition following a firefighter training exercise in temperatures exceeding 115 °C. Cognition recovered as core body temperature returned to normal, providing evidence for a 20-minute cooling period following exposure to extreme heat.

ARTICLE HISTORY
Received 5 July 2023
Accepted 22 February 2024

KEYWORDS
Heat stress; firefighters; cognitive flexibility; vigilance

Introduction

Firefighters work in challenging and high-risk environments, and they must be capable of making critical decisions. This requires an awareness of the situation and how it could change over time, the ability to formulate a plan using the information available, and the skills to execute the plan. Cognitive functioning is therefore crucial, yet the working conditions faced by firefighters may impact on aspects of cognitive processing. One example of this is the necessity to work in extreme temperatures. Workplace regulations generally advise ambient temperatures of between 16 °C and 24 °C, however firefighters often work in temperatures that reach over 200 °C (Willi, Horn, and Madrzykowski 2016). This is potentially hazardous given that workplace accidents have been found to increase due to heat stress (Tawatsupa et al. 2013) and unsafe working behaviours are more likely to occur when environmental temperatures rise above 23 °C (Ramsey et al. 1983). Moreover, the normal range of core body temperature is 36 °C to 37.5 °C, but during firefighting activities it can exceed 38.5 °C (Horn et al. 2017). A review by Schmit et al. (2017) concluded that cognitive function will suffer when core body temperature increases beyond 39 °C, and this suggests that firefighters may be at-risk, ultimately impacting their ability to protect lives.

The relationship between heat and cognition is complex however, and findings are mixed. In a study measuring the effects of heat stress on surgeons, Berg et al. (2015) found no impairment to performance at ambient temperatures of 26 °C compared to 19 °C, although participants reported significantly greater cognitive workload and distraction in 26 °C heat. Malcolm et al. (2018) compared performance across a range of cognitive tasks before and after participants spent one hour in a chamber heated to 21.2 °C or 39.6 °C and demonstrated that impairments due to heat stress depended upon the task demands. They found that heat had no effect on a working memory task and a sustained attention task, led to slower

CONTACT Catherine Thompson thompsc1@hope.ac.uk Department of Psychology, Liverpool Hope University, Liverpool, L16 9JD, UK.

response times but increased accuracy in a simple visual search task, and resulted in impaired executive functioning. These findings are somewhat surprising as Hancock and Vasmatzidis (2003) stated that heat has the greatest impact on vigilance tasks, and this is supported by Qian et al. (2015) who found that reaction times and self-reported fatigue in a sustained attention test increased after participants spent one hour in 50 °C heat compared to when they spent one hour in 25 °C heat.

The findings of Malcolm et al. (2018) are however consistent with the conclusion made by Hancock and Vasmatzidis (2003) that the impact of heat on cognition will vary according to the cognitive demands of a task. In particular they argued that less attention-demanding tasks will be affected by heat to a lesser extent. This follows the Maximal Adaptability Model of Hancock and Warm (1989) that proposes any form of stress (i.e. heat stress) competes for and drains limited capacity attentional resources. As stress increases, providing resources are available, an individual may be able to adapt to the situation, for example by placing greater focus on a task. However, if stress levels increase further, the reduction in cognitive resources prevents this compensation. This could explain why higher ambient temperatures (i.e. Qian et al. 2015) impair vigilance but lower temperatures (i.e. Malcolm et al. 2018) do not, because with lower levels of heat stress there is less competition for attentional resources. It can also explain why Malcolm et al. (2018) found differing effects of heat across different tasks (because different tasks utilise different amounts of resources), and potential evidence for compensation under heat stress (slower reaction times yet improved accuracy).

The different effects of heat stress across different tasks and varied temperatures have also been demonstrated in firefighter populations. In a study by Walker et al. (2015), firefighters participated in two 20-minute search and rescue scenarios whilst wearing personal protective clothing in a chamber heated to 105 °C. Before and after the scenarios participants were asked to complete three cognitive tasks in which they responded to whether a playing card was turned over (measuring speed of processing), if the card was red (measuring vigilance), or if the card matched the previous one (working memory). Mean core body temperature after the second scenario was 38.9 °C, however there was no difference in speed of processing or working memory before and after the scenario, and there was a significant improvement in vigilance following exposure to the heat. In contrast to this, Hemmatjo et al. (2017) and Hemmatjo et al. (2020) found that engaging in simulated firefighting activities in hot temperatures (up to 37 °C, therefore substantially lower than the ambient temperature used by Walker and colleagues) leads to impairments in working memory and sustained attention. Body temperature after completion of the firefighting scenario was 38.9 °C (core) in the study of Walker et al. (2015) and 38.22 °C (tympanic) in the study of Hemmatjo et al. (2017). It would be expected that if heat stress competes for cognitive resources, individuals who are exposed to hotter environments, and who reach higher temperatures would suffer greater cognitive impairment, but the findings above do not support that argument. Adding to the mixed results, Morley et al. (2012) used a similar working memory test to Hemmatjo and colleagues (a paced serial addition test) and found improved performance in firefighters at core body temperatures of 39.5 °C.

One key difference across each of these studies was the activities firefighters were asked to complete in the heat. These range from realistic fire and rescue scenarios in which firefighters are faced with the same equipment and situations that they may experience in their working practice (e.g. Walker et al. 2015), through to controlled laboratory conditions that may replicate the physical activity involved in firefighting, but not the challenge of the situation (for example Morley et al. (2012) asked participants to walk on a treadmill in a heated chamber). It may be argued that it is difficult to accurately assess the impact of extreme heat on cognitive functioning of firefighters without attempting to duplicate the real-life situations they may face.

Another disparity in the studies cited above is the range of tasks used to measure cognition. Similar to Hancock and Warm (1989), Taylor et al. (2015) argue that heat stress has a greater impact on complex tasks. This is supported by results showing no impairment to cognition in firefighters exposed to temperatures of over 400 °C when they are asked to complete simple tasks such as crossing out targets on a sheet of paper (Canetti et al. 2022) and subtracting numbers (Abrard et al. 2021). Earlier work by Greenlee et al. (2014) measured accuracy and response times in a continuous performance task after participants completed an 18-minute live-fire training exercise in a room heated to 82 °C and found no effect of heat on cognition beyond faster response times. They attributed this to the cognitive test used and argued for the need to explore the effects of heat stress using tests that measure more complex cognitive processing.

Supporting the argument that heat stress impairs complex cognitive processing, past research shows that heat has a negative impact on aspects of executive functioning. For example, Liu et al. (2013) compared performance on an attentional network test (ANT) after participants had spent 45 minutes in an environmental chamber heated to 20 °C or 50 °C. The ANT measures the three attentional networks of alerting, orienting, and executive control (Fan et al. 2002), and whilst alerting and orienting was not impacted by the heat, participants who spent time in the 50 °C chamber showed significantly poorer executive control. Using fMRI Liu and colleagues also found that the pattern of neural activity for the three attentional networks differed between the two groups. They attributed this to a form of compensation whereby different brain areas were recruited in the high temperature condition to compensate for the demands of the heat stress. In line with Hancock and Warm (1989) they proposed that more simple tasks (i.e. involving alerting and orienting) are unaffected by heat because there are sufficient cognitive resources available to compensate for the stress. In contrast, more demanding tasks place more strain on cognitive processing and so the reduction in resources due to heat stress prevents compensation.

Exploring the effects of heat on executive functioning in real-world settings, Saini et al. (2017) measured cognition of soldiers working in desert conditions in India in February (ambient temperatures of 25–27 °C) and June (ambient temperatures of 42–43 °C) using the Trail Making Test (TMT) and the Wisconsin Card Sorting Test (WCST). Participants were significantly slower in both parts of the TMT in high temperatures and also showed a larger difference between part A and B indicating more difficulty in task switching. Similarly, participants made more errors (specifically perseverative errors) on the WCST in high temperatures, showing reduced cognitive flexibility due to heat stress.

Despite the evidence for the effects of heat stress on executive functioning, to date there have been limited attempts to measure this in a firefighter population. This is concerning given that executive functioning has a direct impact on decision making ability (e.g. Skagerlund et al. 2022) and decision making is crucial in firefighting scenarios. Indeed, Abrard et al. (2021) stated that the "safety and effectiveness of firefighters depend on their ability to quickly make the right decisions and effectively execute them" (p186), and an understanding of firefighter decision making is important for maintaining safety and informing operational guidance (Cohen-Hatton and Honey 2015). To make decisions, firefighters must be able to identify and process relevant information, they must be able to respond quickly, and they must be flexible to changing circumstances. Impairments to these processes will affect the ability to make decisions, and this could have significant consequences for the ability to protect life and property. More focus should therefore be given to the effects of extreme temperatures on cognitive processes that support decision making.

A further gap in this field of research is the timeframe of any cognitive recovery following exposure to heat. In the UK, firefighters working in a breathing apparatus team may only re-enter a fire if the incident commander is confident that they are still physiologically and psychologically capable of completing the task they are given (National Fire Chiefs Council 2018). During operational scenarios, basic field measures of core body temperature (tympanic) are routinely conducted by some services post-fire to help inform re-entry decisions. Such measures can be affected by the accuracy of recording devices and cut-off points are inconsistent, but there is also no formal assessment of a firefighter's cognitive abilities prior to re-entry (or indeed prior to any future task, even if that is not related to heat, for example driving home from work). Cognitive impairments due to stress can occur before the physiological system has reached a tolerance limit (Hancock and Vasmatzidis 2003), therefore, rather than relying on physiological measures, it is crucial to investigate whether engaging in a live-fire scenario affects cognitive processing and to measure how long any impairment may last. There have been attempts to measure cognitive recovery, for example Morley et al. (2012) found an effect of heat on cognition in firefighters immediately after exposure to heat and up to 30-minutes later, however they reported improved cognition due to heat, which does not reflect the majority of findings. Greenlee et al. (2014) also reported improvements to cognition following exposure to heat but found that this improvement disappeared 120-minutes post-live fire training exercise. This would suggest a recovery over time, but without testing cognition at varying intervals it is impossible to ascertain when recovery occurs, and again, the researchers were making use of a fairly simplistic cognitive test.

The aim of the present study was to measure the effects of a real-world live-fire training scenario on firefighter cognition and determine the length of time required for cognitive performance to return to normal. The objectives were to (1) compare cognitive processing before and after exposure to extreme temperatures in a live-fire situation, (2) investigate the effects of heat on different cognitive processes, and (3) measure the time course of recovery following acute heat exposure. To achieve these objectives, firefighters completed a battery of cognitive tests prior to a live-fire training exercise and then took the same battery of cognitive tests on exiting the fire and then again 20- and 40-minutes after exiting the fire. The cognitive tests were an n-back task, a sustained attention to response task, and the WCST. These were selected to assess different functions of working memory capacity, vigilance, and cognitive flexibility respectively (categorised as “complex” cognitive processes by Taylor et al. (2015)). These functions have each been investigated previously in relation to heat stress, yet this was the first study to measure performance over time and to measure cognitive flexibility in firefighters exposed to extreme temperatures. It was predicted that performance across each of the cognitive tasks would be significantly worse on exiting the fire compared to before the live-fire training exercise. It was further predicted that cognitive performance would improve as core body temperature returned to normal.

Method

Participants

An initial a-priori power calculation based on an analysis of variance approach with a power of 0.85, an effect size of 0.25, and an alpha value of 0.05, indicated a sample size of 24 as a minimum. The study aimed to recruit a minimum of 30 participants and the final sample consisted of 39 volunteers (37 males and 2 females) with an age range of 19 to 57 years (mean age was 35.05 years, *SD* = 9.23). The participants were all firefighters and took part at Lancashire Fire and Rescue Service Training Centre in Chorley, Lancashire, or at the Fire Service Technical College in Morton-in-Marsh, Gloucestershire as part of their regular training. Participants were recruited via opportunity sampling from those firefighters who were available on each training day. All firefighters attending for training were given a participant information sheet, via internal communications, a minimum of 24-hours prior to their training, and those who were interested in participating were asked to indicate this on the morning of the training. Due to the use of an ingestible temperature sensor, exclusion criteria included individuals with or presenting a risk of intestinal disorders that can lead to obstruction of the digestive tract, including diverticulitis, individuals with known motility disorders of the gastrointestinal tract or who have undergone surgical procedures in the gastrointestinal tract, and individuals with known swallowing disorders.

Participants varied with regard to their firefighting experience, from trainees to experienced instructors. All firefighters who participated in the study were from a White British background. The sample was largely representative of the demographics of the Fire and Rescue Service in England; in 2021 it was reported that 92.5% of firefighters were men, and 95.3% were White (Home Office 2021).

Experimental design

A within-participants design was utilised comprising of one independent variable (Time) with four conditions; participants completed a battery of cognitive tests at Baseline, upon exiting the fire (Time 0), 20-minutes post-fire (Time 20), and 40-minutes post-fire (Time 40). The dependent variables consisted of core body temperature and performance scores on each of the cognitive tasks. The study was granted ethical approval by the Health and Society Research Ethics Committee at the University of Salford (HSRC1819-094). Data was collected between June and November 2022.

Procedure

Firefighters were given full information about the study and volunteers (a maximum of four participants were tested on any one day) were asked to provide written informed consent. They were then asked to swallow a telemetric temperature pill with a glass of water. After taking the pill, participants completed short versions of the cognitive tasks in order to familiarise them with the procedure of each one. This involved completing 20 trials for each of the three tasks (described below). During this familiarisation phase, participants were given full instructions and had the chance to ask the researchers any questions about the tasks. Following this each participant completed the three cognitive tests in full. This was the Baseline time point and was completed in a classroom with participants seated at desks.

The firefighters then returned to their routine training and duties until taking part in a live-fire training exercise, between four to five hours after ingesting the pill. The training exercises took place within a building set alight in a controlled manner. The buildings were made of materials designed to withstand extreme temperatures including concrete blocks and steel (see Figure 1 for an example). All participants wore personal protective equipment for the duration of the training, including gloves, boots, and helmets, as well

Figure 1. The image on the left shows a multi-component training exercise at the Lancashire Fire and Rescue Service Training Centre. This training building consists of steel shipping containers and during the training exercise the firefighters move through the structure which has been set alight in a controlled manner. Firefighters not undertaking the training monitor the situation at all times. The right-hand image shows personal protective equipment and breathing apparatus worn during the live-fire training.

as breathing apparatus sets (see Figure 1). The maximum ambient temperature inside the buildings ranged from 115 °C to 400 °C and firefighters worked in pairs to complete tasks including stoking the fire, searching for and rescuing simulated casualties (mannequins), manipulating heavy equipment, extinguishing fires, and scaling staircases. The duration of the training ranged from 8 to 24 minutes ($M = 16.95$ minutes, $SD = 4.39$) and this was governed by the tasks being completed and/or operational and safety decisions made by those delivering the training.

Upon exiting the fire, participants moved away from the training area to a safe refuge and were given time to remove their personal protective equipment (this took a maximum of 2-minutes and followed standard practice; firefighters would normally remove their equipment on exiting a fire, even if they are subsequently required to re-enter the fire, at which point they would put their protective equipment on again). They were then asked to complete the battery of cognitive tests a second time (Time 0). The tasks were either completed in a classroom, or participants were seated on chairs or benches or in shelter structures situated on the training site near to the training exercise. After completing the tests, participants were given a short break of approximately 10 minutes, they were then asked to complete the full battery a third time (Time 20), followed by a 10-minute break, and finally a fourth time (Time 40). An outline of this procedure is shown in Figure 2.

Physiological measures

Core body temperature was recorded (in degrees Celsius) using e-Celsius ingestible telemetric capsules (BodyCap, Caen, France). The capsules measure and store temperature (resolution 0.1 °C, one recording every 15 seconds) and transmit a continuous low frequency radio wave that is received and stored on a datalogger (e-Viewer® Performance monitor). The pills move through the digestive system over a 24-hour period and exit the body as flushable waste. Telemetric pills are considered a valid method for recording core body temperature during practical activity and applied scenarios, and they show a high level of accuracy when compared to other temperature measures (e.g. Bogerd et al. 2018; Huang, Magnin, and Brouqui 2020). However, sources of error can occur if a pill has not cleared the stomach at the time of measurement, because temperature is then affected by food and drink. This means that a pill should ideally be ingested with sufficient time for it to transit the stomach and move into the digestive tract prior to data collection. Throughout the study there was no restriction on the intake of fluids and

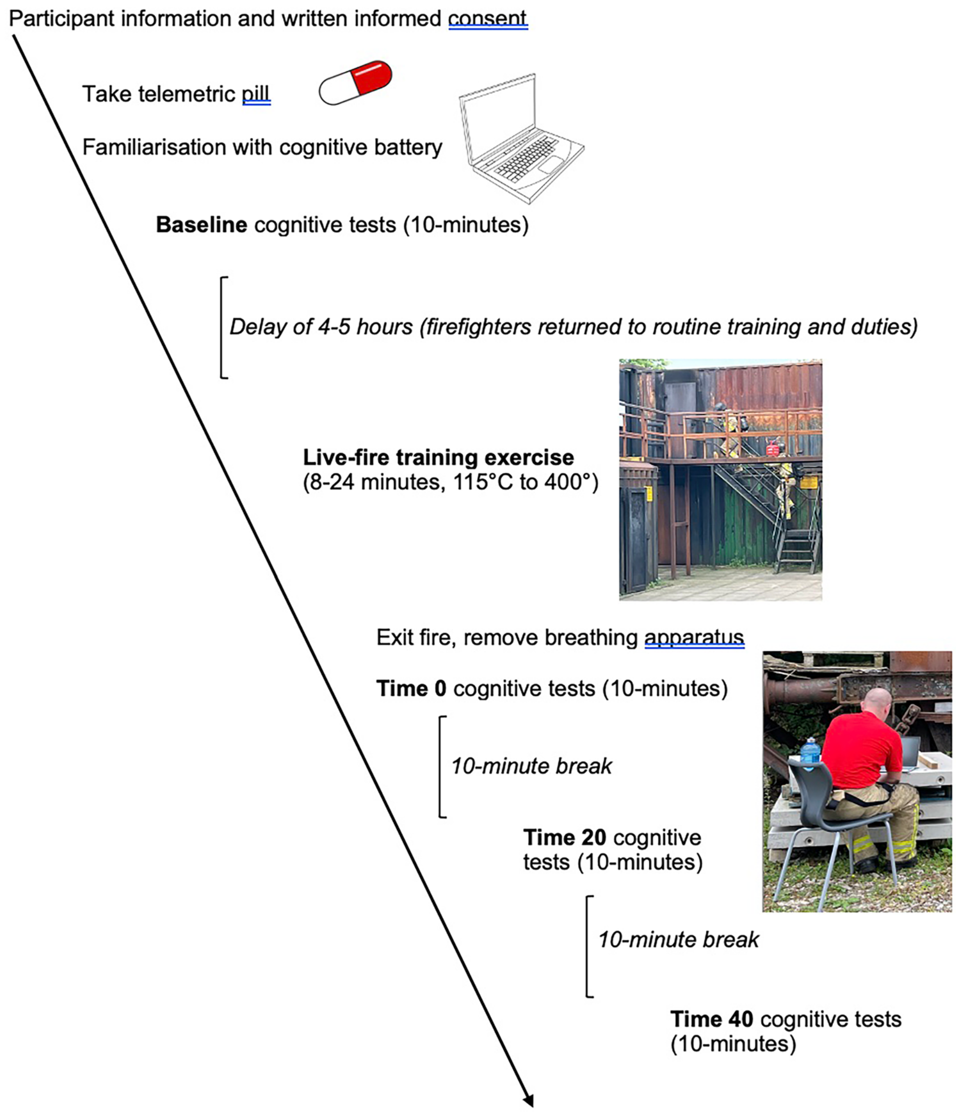

Figure 2. A timeline of activities completed by the participants showing the full experimental procedure.

participants were encouraged to stay hydrated and follow their normal practice with regarding to drinking and eating. On the basis of this, a cautious approach was taken to the recording of core body temperature, ensuring at least four hours from ingestion to monitoring (following Beaufils et al. 2018). It should however be noted that there are individual differences in gastrointestinal transit time, and some studies have used telemetric pills to measure temperature after a much shorter period following ingestion (e.g. Domitrovich, Cuddy, and Ruby 2010). Limitations of the pills include the size of the capsule (similar to a large vitamin) as some people may be reluctant or unable to swallow it, and the fact that after taking a pill an individual is unable to have an MRI scan until the pill has exited the body. All participants were informed of this, and all wore a wristband for 24 hours to show they were not able to have an MRI scan.

Cognitive function measures

The study used three cognitive tasks all built and presented using the software package E-Prime (Psychology Software Tools, Pittsburgh, PA). The tasks were completed on either a Hewlett Packard EliteBook laptop with a 13-inch display or an ASUS X515EA-BQ945T laptop with a 15-inch display. Each participant completed the cognitive tests in the same order for each time point, but this order was randomised across participants.

N-back task

In each trial of the n-back task a fixation cross was presented for 500 ms followed by a letter presented for 500 ms. Stimuli were presented in black Arial font, size 18, in the centre of a white screen and letters could be shown uppercase or lowercase. Participants were asked to respond to each letter to indicate whether it was the same as the letter presented two positions back by pressing the keys 'y' (yes) or 'n' (no) on the keyboard. A total of 60 trials were completed at each time point and the task took approximately three minutes. The trials were presented in a pseudorandom order to ensure presentation of 12 targets (when a letter did match the one presented two positions back; 20%) and 48 non-targets (80%). Two measures were calculated for this task: accuracy (%) and reaction time (ms).

Sustained attention to response task

In each trial in the SART a number (presented in white Arial font in one of five sizes (48, 72, 94, 100, 120) on a black screen) was shown for 250 ms, followed by a mask (a white circle measuring 24 mm in diameter with a cross (X) in the centre) for 900 ms. Participants were instructed to press the 'b' button on the keyboard each time a number 1, 2, 4, 5, 6, 7, 8, or 9 (non-targets) was presented, and make no response each time a number 3 (target) was shown. At each time point participants completed one block of 112 trials, consisting of 12 targets and 100 non-targets. All trials were presented in a random order. The SART took approximately two minutes to complete. The dependent measures consisted of percentage omission errors (the percentage of times (out of a possible 100 trials) that participants failed to respond to a non-target digit), percentage commission errors (the percentage of times (out of a possible 12 trials) that participants incorrectly responded to the digit '3' rather than withholding a response), and reaction time (ms).

Wisconsin Card Sorting Task

The WCST involved presentation of five cards: a stimulus card shown at the bottom of the screen and four response cards shown to the top left of the screen. Each card contained one, two, three, or four identical shapes that were either circles, triangles, stars, or crosses, and the shapes were shown in yellow, green, blue, or red. Each card measured 34 mm x 29 mm. A black fixation cross in Arial font size 18 preceded each trial. Participants were asked to sort each stimulus card according to its colour, shape, or number on to one of the four response cards by pressing the corresponding keys 1, 2, 3, or 4 on the keyboard. Each key was labelled with a sticker showing the same pattern as one of the response cards. Following a response, participants were given feedback on whether their selection was 'correct' or 'incorrect'. Participants were instructed that on receiving 'correct' feedback, they should continue to sort each new stimulus card using the same rule, but if they received 'incorrect' feedback they had to try a different rule. After between 10 and 12 trials, the rule changed meaning participants had to find the new rule. At each time point participants completed 64 trials. There were five rule changes in each block of 64 trials, with each rule (colour, shape, number) used twice in a block. The WCST took approximately five minutes to complete. The dependent measures were number of perseverative errors (incorrectly sorting a card using the previously relevant rule), number of non-perseverative errors (incorrectly sorting a card with a rule that was not used in the preceding run of trials), and RTs to correct trials.

Statistical analysis

Data collected included core body temperature, and performance on each of the three cognitive tasks at each of the four time points (Baseline, Time 0, Time 20, and Time 40). Outliers were removed at +/-3 standard deviations from the mean (e.g. Osborne and Overbay 2004), with a participant's data removed entirely from the dataset if mean accuracy and/or response times were more than 3 standard deviations from the mean, and trials removed when trial reaction times were more than 3 standard deviations from the mean, with data averaged for the remaining trials. Normality checks were conducted on residual values. Commission errors in the SART were normally distributed and were analysed using a one way within-participants ANOVA, followed by planned comparisons that compared Time 0, Time 20, and Time 40 to Baseline. Where none of the comparisons were significant post-hoc t-tests were used to explore the significant main effect. All other measures deviated from the normal distribution and analysis consisted of non-parametric Friedman tests followed by Wilcoxon Signed Rank tests to compare Times 0, 20, and 40 to Baseline. An alpha level of .05 was used for all statistical tests. Effect sizes were calculated for significant results, using eta squared (η^2) for ANOVA results and Cohen's d (*Cohen's d*) for t-tests. Kendall's W is presented for the Friedman tests (*W*), and r is used for Wilcoxon Signed Ranks tests (*r*). Effect sizes were interpreted following Fritz, Morris, and Richler (2012). Data are available at the project's Open Science Framework page (https://osf.io/e49c6/?view_only=43a95d2248694a56b15474476b22a5ba).

Results

Although 39 firefighters participated in the study, two participants did not complete the full test battery at all time points, taking the sample size to 37 (35 males, 2 females,

Table 1. Mean (M) and standard deviation (SD), and median (Mdn) and interquartile range (IQR) of core body temperature and performance in the n-back, SART, and WCST across the four time points. *Indicates temperatures On Entry to fire training exercise rather than at time of Baseline cognitive tests.

			Time point			
Measure	n		Baseline	Time 0	Time 20	Time 40
Core body temperature (°C)	26	*M (SD)*	37.75 (0.55)*	38.82 (0.89)	37.85 (1.23)	37.47 (0.86)
		Mdn (IQR)	37.81 (0.68)*	38.87 (1.17)	38.15 (1.07)	37.54 (0.62)
n-back accuracy (%)	26	*M (SD)*	80.49 (19.08)	77.05 (20.04)	77.61 (19.55)	71.82 (20.76)
		Mdn (IQR)	83.14 (24.61)	78.53 (42.16)	83.05 (31.63)	73.86 (34.67)
n-back RT (ms)	26	*M (SD)*	412.48 (47.37)	391.87 (53.96)	398.53 (40.92)	398.12 (59.51)
		Mdn (IQR)	424.92 (39.15)	398.54 (51.06)	397.86 (43.48)	411.10 (43.94)
SART omission errors (%)	32	*M (SD)*	2.97 (2.6)	5.56 (8.74)	3.03 (3.54)	2.97 (2.66)
		Mdn (IQR)	2.5 (4)	2.5 (4)	2 (3.25)	2 (3)
SART commission errors (%)	32	*M (SD)*	40.36 (20.86)	46.61 (23.93)	37.24 (23.38)	35.16 (16.9)
		Mdn (IQR)	41.67 (27.08)	50.00 (29.17)	33.33 (33.33)	33.33 (16.67)
SART RT (ms)	32	*M (SD)*	124.66 (32.24)	145.62 (44.41)	137.55 (42.71)	132.28 (37.82)
		Mdn (IQR)	118.91 (37.5)	137.06 (40.78)	133.46 (46.73)	128.30 (57.24)
WCST perseverative errors (%)	31	*M (SD)*	7.16 (2.4)	10.03 (4.13)	7.77 (2.55)	7.39 (1.89)
		Mdn (IQR)	7 (2)	9 (4.5)	7 (4)	7 (3)
WCST non-perseverative errors (%)	31	*M (SD)*	5.65 (3.65)	6.81 (3.60)	5.58 (2.33)	4.71 (2.21)
		Mdn (IQR)	5 (2.5)	5 (3.5)	5 (3.5)	4 (3)
WCST RT (ms)	31	*M (SD)*	1382.48 (267.74)	1368.38 (322.21)	1287.21 (305.8)	1202.63 (239.33)
		Mdn (IQR)	1333.42 (383.74)	1261.14 (387.1)	1187.65 (394.26)	1220.25 (342.14)

age range of 19 to 57 years, mean age = 36.62 years, *SD*=9.10). Results from this sample are presented below for core body temperature and each of the three cognitive tests. Descriptive statistics are presented in Table 1.

Core body temperature

Temperature data was recorded for 26 of the 37 participants who completed the full cognitive battery across all time points; there was some loss of data due to errors with the data loggers and not all participants felt comfortable taking the pill or were unable to take the pill due to health reasons (e.g. epilepsy). When analysing core body temperature over time, temperature at the time when participants first entered the live-fire training exercise was taken as the baseline measure (referred to here as "On Entry"), rather than the temperature when they completed the first battery of cognitive tests. Core body temperature ranged from a minimum of 36.15 °C (On Entry; the highest temperature at this timepoint was 38.62 °C) to a maximum of 40.85 °C (Time 0; the lowest temperature at this timepoint was 37.37 °C). There was a significant effect of Time, χ^2 (3, n=26) = 40.198, $p < .001$, W = .515 (see Figure 3). Comparisons revealed that core body temperature was significantly higher at Time 0 compared to On Entry, Z (26) = 4.432, $p < .001$, r = .87, but there was no difference between temperature at Time 20 and On Entry, Z (26) = 1.547, p = .683, and between Time 40 and On Entry, Z (26) = −1.461, p = .144.

N-back task (working memory)

When analysing the data from the n-back task it appeared that participants were not completing the procedure in the expected manner, and instead of making a button press on every trial to respond to whether a letter was shown two positions back or not, they were only responding and making a button press on 26.47% of the trials. This did increase slightly across the course of the experiment (22.04%, 26.61%, 27.09%, and 30.15% at Baseline, Time 0, Time 20, and Time 40 respectively). Accuracy and RT was therefore only analysed for this subset of trials, and the results should be viewed in light of this. Added to this, due to very low accuracy across the task and a large number of participants whose accuracy was more than 3 SDs below the mean, analysis was only conducted on data from 26 participants in total. A further 1.38% of trials were removed due to RTs falling more than 3 SDs from the mean. The analysis showed a non-significant effect of Time on accuracy, χ^2 (3, n=26) = 1.065, p = .785, and a non-significant effect of Time on RT, χ^2 (3, n=26) = 4.385, p = .223.

Sustained attention to response task (sustained attention)

For the SART (see Figure 4), one participant had missing data at Time 0, and four participants were classed as outliers due to data falling more than 3 SDs from the mean. This left a sample of 32 participants. A further 1.6% of trials were removed on the basis of RTs falling +/-3 standard deviations from the mean. For omission errors, there were increased errors at Time 0, however the effect of Time was non-significant, χ^2 (3, n=32) = 1.651, p = .648. For commission errors there was a significant effect of Time, F (3, 93) = 4.021, MSE=198.626, p = .010, η^2 = .115. All contrasts were non-significant, but within-participants t-tests with the alpha level adjusted for multiple comparisons (α = .008) showed that errors were significantly higher at Time 0 compared to Time 20, t (31) = 3.103, p = .004, *Cohen's d* = .548, and at Time 0 compared to Time 40, t (31) = 3.015, p = .005, *Cohen's d* = .533. There was no significant difference between errors at Time 20 and 40, t (31) = .0691, p = .495. This is indicative of increased commission errors at Time 0, and the non-significant difference between Baseline and Time 0 could be due to a practice effect whereby participants made more errors at Baseline as they familiarised themselves with the task.

Analysis of RT to correct trials in the SART showed a significant main effect of Time, χ^2 (3, n=32) = 9.262, p = .026, W = .096. Comparisons showed significantly slower RT at Time 0 compared to Baseline, Z (32) = 2.861, p = .004, r = .51. Reaction times were also significantly slower at Time 20 compared to Baseline, Z (32) = 2.580, p = .010, r = .46. There was no significant difference in RT between Time 40 and Baseline, Z (32) = .729, p = .466.

Wisconsin Card Sorting Task (cognitive flexibility)

A total of four participants had missing data at different timepoints for the WCST, and data from five participants was more than 3 SDs from the mean. Removal of these participants left a sample of 31 participants. Prior to analysing the data, a total of 1.54% of trials were removed due to response times that were more than 3 SDs from the mean. Analysis of perseverative errors (see Figure 5) showed a main effect of Time, χ^2 (3, n=31) = 15.076, p = .002, W = .162. There were significantly more perseverative errors at Time 0 compared to Baseline, Z (31) = 3.330, p < .001, r = .598. There was no difference in perseverative errors

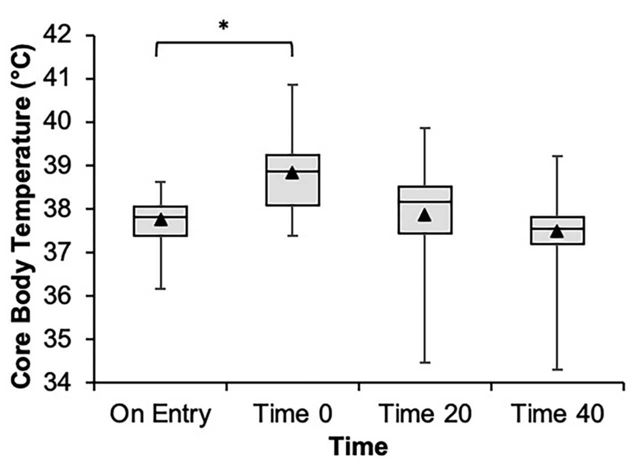

Figure 3. A box plot to show core body temperature (from 26 participants) across the four timepoints. Boxes extend from the 25th to the 75th percentile of the distribution of values within each condition, the horizontal black line across each box is the median value, and the vertical extending black lines represent the minimum and maximum values in each condition. The black triangles denote the mean. Temperature increased significantly post live-fire training exercise and returned to On Entry levels after 20-minutes (*indicates a significant difference).

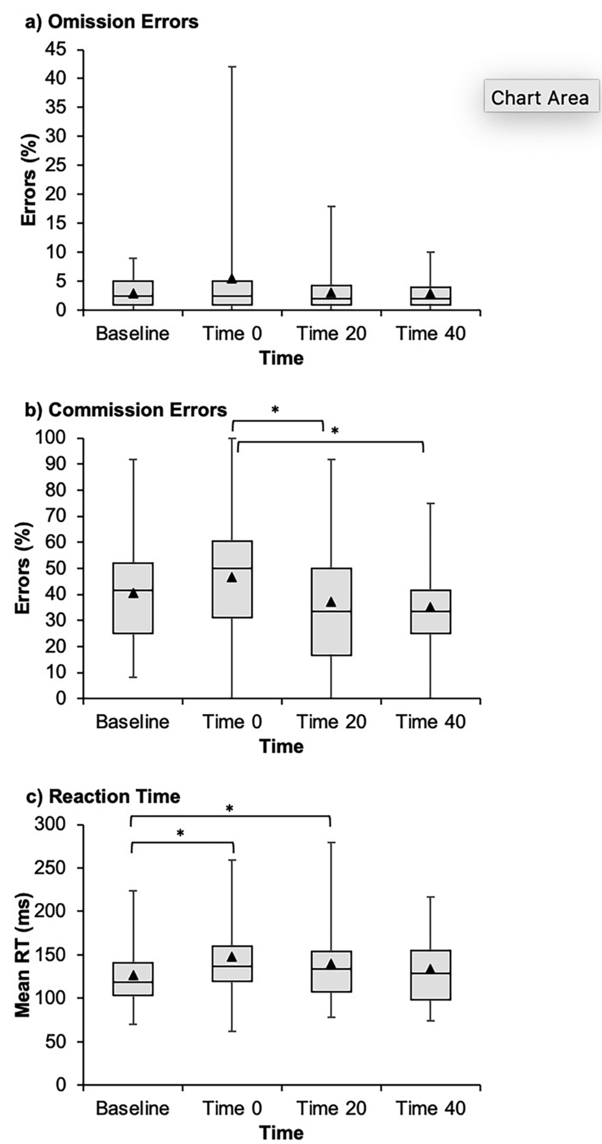

Figure 4. Box plots to show performance in the SART across the four timepoints. Boxes represent interquartile range with the median shown as a horizontal black line across each box. The vertical extending black lines show the minimum and maximum values in each condition and mean values are denoted by a black triangle (*indicates a significant difference). Results show no effect of heat on omission errors (a) but impaired performance at Time 0 for the number of commission errors (b), and response times (c).

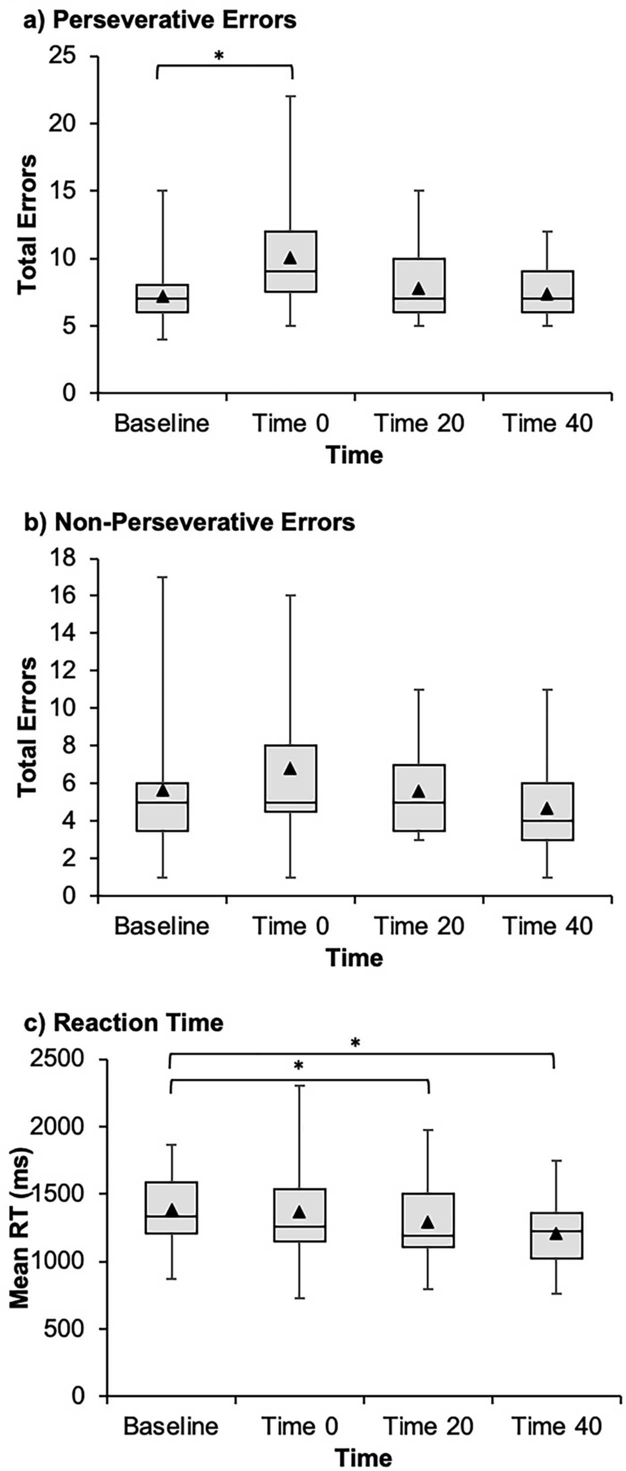

Figure 5. Box plots to show perseverative errors (a), non-perseverative errors (b), and reaction times to correct trials (c) in the WCST. Boxes represent the interquartile range, and the median is shown using a horizontal black line across each box. Minimum and maximum values are indicated by the vertical extending black lines, and black triangles represent mean values. The data suggest more perseverative errors at Time 0 and slower response times (*indicates a significant difference). The impairment may be partially masked by a practice effect leading to poorer performance at Baseline.

between Time 20 and Baseline, Z (31) = 1.135, p = .256, or Time 40 and Baseline, Z (31) = .896, p = .370.

There was a non-significant main effect of Time for non-perseverative errors, χ^2 (3, n=31) = 4.543, p = .208. However, analysis of RT to correct trials showed a significant effect of Time, χ^2 (3, n=31) = 24.948, p < .001, W = .268. Response times were significantly faster at Time 20 compared to Baseline, Z (31) = −2.097, p = .036, r = .38, and Time 40 compared to Baseline, Z (31) = 3.527, p < .001, r = .63. Differences between Time 0 and Baseline were non-significant, Z (31) = −1.039, p = .299.

Discussion

The aim of the present work was to investigate the effects of working in extreme temperatures on the cognitive functioning of firefighters and to measure the duration of any impairment. To improve on previous work in this area and ensure a high level of ecological validity, cognition of firefighters was tested before and after a live-fire training exercise in which participants completed standard firefighting duties, wearing protective clothing and breathing apparatus in temperatures ranging from 115 °C to 400 °C. To measure recovery, cognition was also tested 20- and 40-minutes post-fire. Core body temperature was recorded throughout to determine whether cognitive processing returned to normal in accordance with physiological recovery. The tests used to measure cognition were chosen to assess complex cognitive functions of working memory, vigilance, and cognitive flexibility.

Immediately after the live-fire training exercise participants showed significant impairments in vigilance, making more errors in the sustained attention to response task (SART) and taking significantly longer to make a correct response. Whilst accuracy improved 20-minutes after exposure to high temperatures, reaction times were still significantly slower, potentially suggesting that performance was still impacted by heat stress, but participants were compensating for this by increasing their focus on the task. These findings align with conclusions made by Hancock and Vasmatzidis (2003) that heat stress impairs vigilance. They also support the Maximal Adaptability Model (Hancock and Warm 1989) that proposes heat stress impacts cognition by draining attentional resources, but the effect of heat will vary depending on the resources available to compensate for the impaired performance; immediately after the fire heat stress would be at the highest level, therefore draining more resources and preventing any compensation, however after 20 minutes temperatures are reduced so stress is reduced, putting less pressure on resources and allowing participants to put more effort into the task to improve accuracy.

The findings from the SART are consistent with previous studies measuring the effects of vigilance in both firefighter (e.g. Hemmatjo et al. 2017; Hemmatjo et al. 2020) and non-firefighter (e.g. Qian et al. 2015) populations. However, the results contrast with findings showing no impact of heat on vigilance when participants are exposed to environmental temperatures of 105 °C (Walker et al. 2015). This can be attributed to the different tasks used to assess sustained attention. Walker and colleagues asked participants to indicate whether playing cards were red, which is more akin to a perceptual judgement task. Evidence would suggest that more complex cognitive functions are affected by heat stress to a greater extent than simple cognitive functions (Hancock and Vasmatzidis 2003; Hancock and Warm 1989; Taylor et al. 2015) and the current work supports this.

Further evidence for the impact of heat stress on complex tasks comes from the results of the Wisconsin Card Sorting Task (WCST). This task was used to measure cognitive flexibility, and whilst the effects of heat on cognitive flexibility have been investigated previously (e.g. Malcolm et al. 2018; Saini et al. 2017), the current work is the first study to explore this in a firefighter population. The results showed significantly more perseverative errors on exiting the live-fire training exercise compared to Baseline. There was no speed-accuracy trade-off as participants were also slower to make correct responses following the training exercise. Similar to the SART, performance returned to baseline 20-minutes post fire. This clearly shows reduced set-switching after exposure to high temperatures, consistent with the past research.

Together the findings from the SART and the WCST demonstrate that extreme temperatures faced by firefighters can lead to impairments in sustained attention and cognitive flexibility, but that cognitive performance returns to normal after 20-minutes. Analysis of core body temperature showed that 20 minutes after the live-fire training exercise participants had recovered to pre-fire levels, suggesting a relationship between core body temperature and cognition. This time period of recovery broadly aligns with the unpublished work of Williams-Bell, McLellan, and Murphy (2016) who asked participants to walk on a treadmill in a chamber heated to 35 °C and found that it took between 16 to 21 minutes for core body temperature to recover from 38.5 °C to 37.8 °C (and for cognitive processing to return to normal). Interestingly, they used active cooling whereby participants placed their hands in cold water, whereas in the current study, firefighters used a range of methods, as determined by their instructors. The impact of different cooling methods on the relationship between heat and cognition could be an area for future study.

The results regarding the effects of heat on working memory are less clear. Analysis of performance on the n-back task showed no effect of heat with no difference in accuracy and response times before and after the live-fire training exercise. It is impossible to draw any conclusions from this, primarily because participants were not completing the task in the correct way and did not make a response to every letter presented, leaving only a small proportion of trials that could be analysed. Added to this, past research measuring the impact of heat on working memory shows mixed findings. Malcolm et al. (2018) and Walker et al. (2015) found no effects of heat stress on working memory, although arguably the tasks they used to assess working memory were much simpler than the one used here (for example Walker and colleagues used a version of a 1-back task), and Hemmatjo et al. (2017) and Hemmatjo et al. (2020) found that heat impaired working memory, despite the fact that the environmental temperatures their participants were exposed to were substantially lower than those used in the current research.

Given the links between working memory and other aspects of executive functioning (e.g. McCabe et al. 2010) it is hard to reconcile the results from the three tests used in this experiment. Despite the non-significant effect of heat on working memory, the findings reported are consistent with the argument that exposure to extreme temperatures impairs higher-level cognitive processing. This could be due to the effects of heat on activity in the prefrontal cortex, as suggested by Taylor et al. (2015) and Liu et al. (2013). This is concerning because the challenging situations experienced by firefighters require goal-directed thinking and processing. Such higher-level processing requires more cognitive resources, and whilst firefighters in the UK are trained to use goal-directed thinking to encourage situational awareness and reflection (Cohen-Hatton and Honey 2015), if stressors such as heat compete for resources, or prevent the use of such resources, the ability to make effective decisions could suffer. To explore this in more detail, further work could measure activity in the prefrontal cortex following exposure to extreme heat (e.g. Coehoorn et al. 2020).

The issues with the n-back task would indicate that future research should provide more time for familiarising participants with the tasks. In the present experiment participants were given a practice with each of the tasks before they completed the tests at Baseline, however this may not have been sufficient, especially when participants have to complete a battery of tests. This issue is further evidenced by the slight improvement in performance over time across each of the tasks, potentially masking the impairment in performance at Time 0. Studies show that performance on these three cognitive tasks does not vary due to practice or experience with the procedure (e.g. Di Rosa et al. 2014; Hockey and Geffen 2004; Kopp, Lange, and Steinke 2019), yet this may be different when conducting research outside a laboratory environment with participants who are unfamiliar with psychology experiments.

Whilst the use of more traditional lab-based experimental tasks is unusual in a field setting, investigating cognition in a controlled manner within a realistic setting improves on previous research (e.g. Williams-Bell, McLellan, and Murphy 2016; Zhang et al. 2014) because it replicates the challenging situations that firefighters may face. Utilising a live-fire training exercise in the present study raises the ecological validity of the findings, although it also adds extraneous variables that cannot be controlled. Morley et al. (2012) point out that accidents that occur on a fireground could be due to heat stress, physical activity/fatigue, and psychological stress. As the current work made use of a realistic firefighting scenario, each of these sources of stress could have contributed to the impairment in cognition immediately following the training exercise. For instance, not only were participants exposed to temperatures ranging from 115 °C to 400 °C, they were also completing physically tiring tasks such as rescuing casualties and climbing stairs. Additionally, the firefighters were under pressure because their performance was being assessed. The present findings are attributed to heat stress, and the fact that cognition improves as core body temperature returns to normal supports this, but any of these factors could be having an influence. This is supported by a study comparing working memory pre and post firefighting activities in a live-fire training exercise, a typical training exercise, and a rescue from height (Zare et al. 2018). The researchers found greatest impairment in the rescue from height condition, suggesting that stress impacts on cognition, but this is not necessarily specifically heat stress.

There is an argument that the exact source of stress does not matter because each plays a role when fighting a live-fire and knowing the time course of recovery (regardless of the initial cause of impairment) is still beneficial. However, if the relative contribution of each stressor is unknown, it is impossible to effectively reduce stressors and reduce any negative impact on cognition. In future it would be prudent to make use of control groups, for example a group who engaged in physical activity but were not exposed to extreme temperatures, and/or a group who were exposed to high temperatures but did not have to complete any activities. It would also be beneficial to take measures of stress, such as cortisol or self-reported anxiety levels (i.e. Robinson et al. 2013).

A further issue is whether the impairments to cognition were due to the increase in core body temperature, or by the discomfort caused due to the high ambient environmental temperatures. Gaoua et al. (2012) found that cognitive decline can occur due to increases in skin temperature independent of core temperature. Given that in the current study cognitive processing returned to normal as core body temperature returned to normal, the negative impact on cognition can be linked to increased core body temperature, however it would be useful to include a subjective measure of comfort in future studies. This is particularly important because there are individual differences in tolerance to the heat (Wang et al. 2018), therefore if discomfort plays a role some firefighters may be disproportionately affected compared to others. There is some indication of individual differences in the current sample, for example, individual measures of core body temperature at Time 40 ranged from 34.30 °C to 39.20 °C. This could be due to inaccuracy of the pill but may also suggest individual responses to the heat. Future research could use a 'temperature change' measure to account for differences. This (given a larger sample) would also allow an investigation of the relationship between change in core body temperature and change in cognitive function.

Individual differences in the form of expertise may also interact with the effects of heat stress (e.g. Hancock and Vasmatzidis 2003). One limitation with past studies in this area is the use of low sample-sizes (e.g. Abrard et al. 2021; Canetti et al. 2022; Hemmatjo et al. 2017; Zare et al. 2018) and whilst the present study improves on this previous research by making use of a larger sample size, participants did vary in their level of firefighting expertise, from trainees to instructors. Added to this, cumulative exposure appears to compound the effects of heat stress on cognition, therefore depending on level of past exposure some individuals may be more impacted than others (Yi et al. 2021). This makes the effect of expertise more complex and difficult to account for. For instance, some firefighters may have worked in the fire and rescue service for many years but have relatively minimal exposure to extreme temperatures on a day-to-day basis, whereas others may have worked in the service for less time, but may see more active duty (for example, due to working in an area with high population density). Future research should consider expertise with regards to general firefighting expertise, and expertise in relation to exposure to high temperatures.

Despite these limitations, the current work advances the research in this field by measuring the effects of heat on complex cognitive processing following a real live-fire exercise. In addition to showing that extreme temperatures impaired cognitive flexibility and sustained attention, both important in firefighting due to the requirement to maintain vigilance and awareness and respond appropriately in dynamic settings, the research shows that the negative effects of heat on these processes dissipate within 20 minutes as core body temperature returns to normal. Currently there are no guidelines for how long UK firefighters should spend cooling before they can re-enter a fire or complete another task, and decisions are made based on physiological readiness and self-reported capability of the individual (National Fire Chiefs Council 2018). Impairments to cognition can occur before physiological tolerance limits are reached (Hancock and Vasmatzidis 2003) and it is not always easy to make an independent judgement of one's own capacity for thinking and decision making. The findings reported here suggest that re-entry decisions may benefit from a measure of cognitive readiness, and this should be targeted towards executive functioning. Further research could help in the development of a simple cognitive task that could be used in an operational environment to determine readiness and be used prior to firefighters re-entering fire situations. The findings also indicate that firefighters exposed to temperatures over 115 °C for eight minutes or longer should be given at least 20 minutes of cooling before completing any further task. Individual fire and rescue services adopt different cooling strategies, and it would be beneficial to investigate whether different strategies have any impact on cognitive recovery. Ongoing research would therefore help to determine optimal cooling durations.

This study measured the impact of extreme heat on cognitive functioning of firefighters and sought to investigate the time limits of any negative effects on cognition. Firefighters were exposed to temperatures, activities, and demands similar to what they would face in real-world situations, allowing for a realistic exploration of the impact of acute heat stress on cognitive functioning. The results show that the working temperatures experienced by firefighters have a detrimental effect on higher-level cognitive processing, specifically cognitive flexibility and sustained attention. Impairments to cognition do not appear to last beyond 20 minutes, however future research should take account of levels of expertise and cumulative exposure to heat and should also attempt to isolate the effects of heat stress from other sources of stress.

Disclosure statement

We have no conflicts of interest to disclose.

Funding

This work was funded by the Fire Service Research and Training Trust.

ORCID

Catherine Thompson http://orcid.org/0000-0002-7967-7019
Stephen J. Pearson http://orcid.org/0000-0003-1503-5452

Data availability statement

Data are available at the project's Open Science Framework page (https://osf.io/e49c6/?view_only=43a95d2248694a56b15474476b22a5ba).

References

Abrard, S., M. Bertrand, T. De Valence, and T. Schaupp. 2021. "Physiological, Cognitive and Neuromuscular Effects of Heat Exposure on Firefighters after a Live Training Scenario." *International Journal of Occupational Safety and Ergonomics: JOSE* 27 (1): 185–193. doi:10.1080/10803548.2018.1550899.

Beaufils, R., O. C. Koumar, P. A. Chapon, C. Chesneau, B. Sesboüé, S. Besnard, H. Normand, S. Moussay, and N. Bessort 2018. "Gastrointestinal Thermal Homogeneity and Effect of Cold Water Ingestion." *Journal of Thermal Biology* 78: 204–208. doi:10.1016/j.therbio.2018.10.002.

Berg, R. J., K. Inaba, M. Sullivan, O. Okoye, S. Siboni, M. Minneti, P. G. Teixeira, and D. Demetriades. 2015. "The Impact of Heat Stress on Operative Performance and Cognitive Function during Simulated Laparoscopic Operative Tasks." *Surgery* 157 (1): 87–95. doi:10.1016/j.surg.2014.06.012.

Bogerd, C. P., K. B. Velt, S. Annaheim, C. C. W. G. Bongers, T. M. H. Eijsvogels, and H. A. M. Daanen. 2018. "Comparison of Two Telemetric Intestinal Temperature Devices with Rectal Temperature during Exercise." *Physiological Measurement* 39 (3): 03NT01. doi:10.1088/1361-6579/aaad52.

Canetti, E. F. D., S. Gayton, B. Schram, R. Pope, and R. M. Orr. 2022. "Psychological, Physical, and Heat Stress Indicators Prior to and after a 15-Minute Structural Firefighting Task." *Biology* 11 (1): 104. doi:10.3390/biology11010104.

Coehoorn, C. J., L. A. Stuart-Hill, W. Abimbola, J. P. Neary, and O. E. Krigolson. 2020. "Firefighter Neural Function and Decision-Making following Rapid Heat Stress." *Fire Safety Journal* 118: 103240. doi:10.1016/j.firesaf.2020.103240.

Cohen-Hatton, S. R., and R. C. Honey. 2015. "Goal-Oriented Training Affects Decision-Making Processes in Virtual and Simulated Fire and Rescue Environments." *Journal of Experimental Psychology. Applied* 21 (4): 395–406. doi:10.1037/xap0000061.

Di Rosa, E., C. Hannigan, S. Brennan, R. Reilly, V. Rapčan, and I. H. Robertson. 2014. "Reliability and Validity of the Automatic Cognitive Assessment Delivery (ACAD)." *Frontiers in Aging Neuroscience* 6 (34): 34. doi:10.3389/fnagi.2014.00034.

Domitrovich, J. W., J. S. Cuddy, and B. C. Ruby. 2010. "Core-Temperature Sensor Ingestion Timing and Measurement Variability." *Journal of Athletic Training* 45 (6): 594–600. doi:10.4085/1062-6050-45.6.594.

Fan, J., B. D. McCandliss, T. Sommer, A. Raz, and M. I. Posner. 2002. "Testing the Efficiency and Independence of Attentional Networks." *Journal of Cognitive Neuroscience* 14 (3): 340–347. doi:10.1162/089892902317361886.

Fritz, C. O., P. E. Morris, and J. J. Richler. 2012. "Effect Size Estimates: Current Use, Calculations, and Interpretation." *Journal of Experimental Psychology. General* 141 (1): 2–18. doi:10.1037/a0024338.

Gaoua, N., J. Grantham, S. Racinais, and F. El Massioui. 2012. "Sensory Displeasure Reduces Complex Cognitive Performance in the Heat." *Journal of Environmental Psychology* 32 (2): 158–163. doi:10.1016/j.jenvp.2012.01.002.

Greenlee, T. A., G. Horn, D. L. Smith, G. Fahey, E. Goldstein, and S. J. Petruzzello. 2014. "The Influence of Short-Term Firefighting Activity on Information Processing Performance." *Ergonomics* 57 (5): 764–773. doi:10.1080/00140139.2014.897375.

Hancock, P. A., and I. Vasmatzidis. 2003. "Effects of Heat Stress on Cognitive Performance: The Current State of Knowledge." *International Journal of Hyperthermia: The Official Journal of European Society for Hyperthermic Oncology, North American Hyperthermia Group* 19 (3): 355–372. doi:10.1080/0265673021000054630.

Hancock, P. A., and J. S. Warm. 1989. "A Dynamic Model of Stress and Sustained Attention." *Human Factors* 31 (5): 519–537. doi:10.1177/001872088903100503.

Hemmatjo, R., M. Hajaghazadeh, T. Allahyari, S. Zare, and R. Kazemi. 2020. "The Effects of Live-Fire Drills on Visual and Auditory Cognitive Performance among Firefighters." *Annals of Global Health* 86 (1): 144. doi:10.5334/aogh.2626.

Hemmatjo, R., M. Motamedzade, M. Aliabadi, O. Kalatpour, and M. Farhadian. 2017. "The Effect of Various Hot Environments on Physiological Responses and Information Processing Performance following Firefighting Activities in a Smoke-Diving Room." *Safety and Health at Work* 8 (4): 386–392. doi:10.1016/j.shaw.2017.02.003.

Hockey, A., and G. Geffen. 2004. "The Concurrent Validity and Test-Retest Reliability of a Visuospatial Working Memory Task." *Intelligence* 32 (6): 591–605. doi:10.1016/j.intell.2004.07.009.

Home Office 2021. Fire and rescue workforce and pensions statistics: England, April 2020 to March 2021. Accessed 17 March 2023. https://www.gov.uk/government/statistics/fire-and-rescue-workforce-and-pensions-statistics-england-april-2020-to-march-2021/fire-and-rescue-workforce-and-pensions-statistics-england-april-2020-to-march-2021.

Horn, G. P., R. M. Kesler, S. Kerber, K. W. Fent, T. J. Schroeder, W. S. Scott, P. C. Fehling, B. Fernhall, and D. L. Smith. 2017. "Thermal Response to Firefighting Activities in Residential Structure Fires: Impact of Job Assignment and Suppression Tactic." *Ergonomics* 61 (3): 404–419. doi:10.1080/00140139.2017.1355072.

Huang, F., C. Magnin, and P. Brouqui. 2020. "Ingestible Sensors Correlate Closely with Peripheral Temperature Measures in Febrile Patients." *Journal of Infection* 80 (2): 161–166. doi:10.1016/j.jinf.2019.11.003.

Kopp, B., F. Lange, and A. Steinke. 2019. "The Reliability of the Wisconsin Card Sorting Test in Clinical Practice." *Assessment* 28 (1): 248–263. doi:10.1177/1073191119866257.

Liu, K., G. Sun, B. Li, Q. Jiang, X. Yang, M. Li, L. Li, S. Qian, L. Zhao, Z. Zhou, K. M. von Deneen, and Y. Liu. 2013. "The Impact of Passive Hyperthermia on Human Attention Networks. An fMRI Study." *Behavioural Brain Research* 243: 220–230. doi:10.1016/j.bbr.2013.01.013.

Malcolm, R. A., S. Cooper, J. P. Folland, C. J. Tyler, and C. Sunderland. 2018. "Passive Heat Exposure Alters Perception and Executive Function." *Frontiers in Physiology* 9: 585. doi:10.3389/fphys.2018.00585.

McCabe, D. P., H. L. Roediger, III, M. A. McDaniel, D. A. Balota, and D. Z. Hambrick. 2010. "The Relationship between Working Memory Capacity and Executive Functioning: Evidence for a Common Executive Attention Construct." *Neuropsychology* 24 (2): 222–243. doi:10.1037/a0017619.

Morley, J., G. Beauchamp, J. Suyama, F. X. Guyette, S. E. Reis, C. W. Callaway, and D. Hostler. 2012. "Cognitive Function following Treadmill Exercise in Thermal Protective Clothing." *European Journal of Applied Physiology* 112 (5): 1733–1740. doi:10.1007/s00421-011-2144-4.

National Fire Chiefs Council. 2018. Procedures for re-entry of a breathing apparatus team into the hazard area. Accessed: 12 April 2023. https://www.ukfrs.com/guidance/search/procedures-re-entry-breathing-apparatus-team-hazard-area.

Osborne, J. W., and A. Overbay. 2004. "The Power of Outliers (and Why Researchers Should ALWAYS Check for Them)." *Practical Assessment, Research, and Evaluation* 9 (6): 1–8. doi:10.7275/qf69-7k43.

Qian, S., M. Li, G. Li, K. Liu, B. Li, Q. Jiang, L. Li, Z. Yang, and G. Sun. 2015. "Environmental Heat Stress Enhances Mental Fatigue during Sustained Attention Task Performing: Evidence from an ASL Perfusion Study." *Behavioural Brain Research* 280: 6–15. doi:10.1016/j.bbr.2014.11.036.

Ramsey, J. D., C. L. Burford, M. Y. Beshir, and R. C. Jensen. 1983. "Effects of Workplace Thermal Conditions on Safe Work Behaviour." *Journal of Safety Research* 14 (3): 105–114. doi:10.1016/0022-4375(83)90021-X.

Robinson, S. J., J. Leach, P. J. Owen-Lynch, and S. I. Sünram-Lea. 2013. "Stress Reactivity and Cognitive Performance in a Simulated Firefighting Emergency." *Aviation, Space, and Environmental Medicine* 84 (6): 592–599. doi:10.3357/ASEM.3391.2013.

Saini, R., K. Srivastava, S. Agrawal, and R. C. Das. 2017. "Cognitive Deficits Due to Thermal Stress: An Exploratory Study on Soldiers in Deserts." *Medical Journal, Armed Forces India* 73 (4): 370–374. doi:10.1016/j.mjafi.2017.07.011.

Schmit, C., C. Hausswirth, Y. Le Meur, and R. Duffield. 2017. "Cognitive Functioning and Heat Strain: Performance Responses and Protective Strategies." *Sports Medicine (Auckland, N.Z.)* 47 (7): 1289–1302. doi:10.1007/s40279-016-0657-z.

Skagerlund, K., M. Forsblad, G. Tinghög, and D. Västfjäll. 2022. "Decision-Making Competence and Cognitive Abilities: Which Abilities Matter?" *Journal of Behavioral Decision Making* 35 (1): 1–18. doi:10.1002/bdm.2242.

Tawatsupa, B., V. Yiengprugsawan, T. Kjellstrom, J. Berecki-Gisolf, S. A. Seubsman, and A. Sleigh. 2013. "Association between Heat Stress and Occupational Injury among Thai Workers: Findings of the Thai Cohort Study." *Industrial Health* 51 (1): 34–46. doi:10.2486/indhealth.2012-0138.

Taylor, L., S. L. Watkins, H. Marshall, B. J. Dascombe, and J. Foster. 2015. "The Impact of Different Environmental Conditions on Cognitive Function: A Focused Review." *Frontiers in Physiology* 6 (372): 372. doi:10.3389/fphys.2015.00372.

Walker, A., C. Argus, M. Driller, and B. Rattray. 2015. "Repeat Work Bouts Increase Thermal Strain for Australian Firefighters Working in the Heat." *International Journal of Occupational and Environmental Health* 21 (4): 285–293. doi:10.1179/2049396715Y.0000000006.

Wang, Z., R. de Dear, M. Luo, B. Lin, Y. He, A. Ghahramani, and Y. Zhu. 2018. "Individual Difference in Thermal Comfort: A Literature Review." *Building and Environment* 138: 181–193. doi:10.1016/j.buildenv.2018.04.040.

Willi, J. M., G. P. Horn, and D. Madrzykowski. 2016. "Characterizing a Firefighter's Immediate Thermal Environment in Live-Fire Training Scenarios." *Fire Technology* 52 (6): 1667–1696. doi:10.1007/s10694-015-0555-1.

Williams-Bell, F. M., T. M. McLellan, and B. A. Murphy. 2016. *The Effects of Exercise-Induced Heat Stress on Cognitive Function in Firefighters*. PeerJ Preprints. doi:10.7287/peerj.preprints.2524v1.

Yi, F., T. Zhou, L. Yu, B. McCarl, Y. Wang, F. Jiang, and Y. Wang. 2021. "Outdoor Heat Stress and Cognition: Effects on Those over 40 Years Old in China." *Weather and Climate Extremes* 32: 100308. doi:10.1016/j.wace.2021.100308.

Zare, S., R. Hemmatjo, T. Allahyari, M. Hajaghazadeh, A. Hajivandi, M. Aghabeigi, and R. Kazemi. 2018. "Comparison of the Effect of Typical Firefighting Activities, Live-Fire Drills and Rescue Operations at Height on Firefighters' Physiological Responses and Cognitive Function." *Ergonomics* 61 (10): 1334–1344. doi:10.1080/00140139.2018.1484524.

Zhang, Y., G. Balilionis, C. Casaru, C. Geary, R. E. Schumacker, Y. H. Neggers, M. D. Curtner-Smith, M. T. Richardson, P. A. Bishop, and J. M. Green. 2014. "Effects of Caffeine and Menthol on Cognition and Mood during Simulated Firefighting in the Heat." *Applied Ergonomics* 45 (3): 510–514. doi:10.1016/j.apergp.2013.07.005.