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Original Article

The Effect of Various Hot Environments on Physiological Responses and Information Processing Performance Following Firefighting Activities in a Smoke-Diving Room

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ABSTRACT

Background: Fire service workers often implement multiple duties in the emergency conditions, with such duties being mostly conducted in various ambient temperatures.
Methods: The aim of the current study was to assess the firefighters' physiological responses, information processing, and working memory prior to and following simulated firefighting activities in three different hot environments. Seventeen healthy male firefighters performed simulated firefighting tasks in three separate conditions, namely (1) low heat (LH; 29–31°C, 55–60% relative humidity), (2) moderate heat (MH; 32–34°C, 55–60% relative humidity), and (3) severe heat (SH; 35–37°C, 55–60% relative humidity). It took about 45–50 minutes for each firefighter to finish all defined firefighting activities and the paced auditory serial addition test (PASAT).
Results: At the end of all the three experimental conditions, heart rate (HR) and tympanic temperature (TT) increased, while PASAT scores as a measure of information processing performance decreased relative to baseline. HR and TT were significantly higher at the end of the experiment in the SH (159.41 ± 4.25 beats/min; 38.22 ± 0.10°C) compared with the MH (156.59 ± 3.77 beats/min; 38.20 ± 0.10°C) and LH (154.24 ± 4.67 beats/min; 38.17 ± 0.10°C) conditions ($p < 0.05$). There was no significant difference in PASAT scores between LH and MH ($p > 0.05$). Nonetheless, there was a measurable difference in PASAT scores between LH and SH ($p < 0.05$).
Conclusion: These consequences demonstrate that ambient temperature is effective in raising the physiological responses following firefighting activities. It is therefore argued that further increase of ambient temperature can impact firefighters' information processing and working memory during firefighting activity.

1. Introduction

During fire suppression and rescue operation, firefighters often perform multiple strenuous physical tasks under unknown and demanding conditions. Firefighters are also exposed to hot and hostile environments, which can lead to the rise of physiological response and may cause impairment of cognitive function. Increases in physiological response during firefighting activities can be attributed to the combined effect of strenuous physical work and extreme thermal stress. Additional physiological strain is caused by the firefighting protective clothing (FPC), which is typically heavy, thick, multilayered, and massive [1,2]. Therefore, these agents (e.g. strenuous physical tasks, FPC, hot and hostile environments) suggest that firefighters must have appropriate physical and physiological capacity to perform firefighting and rescue operations as quickly as possible [3,4].

It is recognized that working in actual fire conditions creates greater heart rates (HRs) among firefighters, which may range from

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150 beats/min to 190 beats/min [5]. In addition, during simulated firefighting activities, a firefighter achieves a near maximal HR [6]. Gao et al [7] investigated physiological responses of six male firefighting trainees following 45.5 minutes treadmill exercise in a climatic chamber (air temperature 55°C, relative humidity 30%) and reported increase in HR to 155–160 beats/min following exercise, which was about 84–86% of the maximal HR and increase in rectal temperature to 1.2°C. Investigations by Watt et al [8] on fire service instructors' physiological responses to heat exposures after a 4-week training course showed acute effects of wear on the physiological strain index, core temperature, and measures of fatigue. Another study focused on physiological responses to wearing different FPC following at least 20 minutes of treadmill exercise in an environmental chamber (22°C, 50% RH) and reported increases in HR and skin temperature [9]. Previous studies also investigated the effects of thermal stressors on performance and reported impairments in work performance [10,11].

Although prior research has indicated that performing simulated firefighting tasks in the heat imposes notable physiological stress on the firefighters' body, there are no published studies clearly demonstrating the effects of physical activities and various hot environments on physiological responses throughout the course of firefighting operations. Moreover, existing studies have often used physical tasks, such as treadmill running or cycle exercise, to simulate firefighting activity. These physical tasks, however, are unsuitable because firefighters perform multiple firefighting activities during fire suppression and rescue operations [12–15].

One of the firefighters' primary task is smooth communication with commanders and other colleagues during firefighting and rescue operations. They also need to find their way in dismal, hot, and smoky buildings in order to help and rescue people who are trapped in fire scenes and/or escape in an emergency. It is further essential for firefighters to develop necessary skills to appropriately deal with stressful conditions and not to have excessively emotional reactions while facing heartbreaking and grievous scenes. Moreover, they should be able to process information instantly and make quick decisions while saving victims in stressful situations. To meet all these qualifications, firefighters must have high level of information processing and working memory during firefighting activities. The extent to which multiple firefighting activities and various hot environments may affect information processing performance and working memory during physical and strenuous work in fire scene has not been thoroughly examined. Smith et al [16] showed that firefighting activities could impair cognitive function capacity, speed, and accuracy. Research has also shown that 20-minute treadmill exercise in the environmental chamber (wet temperature: 31°C, dry: 45°C, globe temperature: 43°C; 40% relative humidity) severely impacts mood, but minimally influences cognitive function performance [15].

However, to the best of our knowledge, the impact of various hot environments as an environmental stressor on firefighters' physiological and information processing capacity during fire suppression and life-saving activities has not been investigated. Therefore, this study concentrated on the effect of various hot environments on firefighters' physiological responses and information processing performance following firefighting activities in the smoke-diving room. It is hypothesized that firefighters' physiological responses and information processing capacity would be negatively influenced during firefighting activities and exposure to various hot environments.

2. Material and Methods

2.1. Participants

Seventeen healthy male firefighters were requested to complete three trials. Participants' health status was tracked by reviewing their medical history. The participants were not engaged in the experiment if they had any record of cardiovascular disease or hypertension, mental health problems, and/or vision and hearing problems. Healthy participants were recruited in the light of the checkup results. Table 1 displays firefighters' physical characteristics. Prior to conducting the experiment, sufficient explanation was provided about the goals, risks, and discomforts of the study, followed by receiving written consent from all firefighters. This investigation was approved by the Research Ethics Committee of Hamedan University of Medical Sciences, Iran.

2.2. Smoke-diving room

Firefighting activities were simulated by the use of a smoke-diving room, which is an enclosed space comprising dark and nested rooms used for carrying out firefighting-related exercises. There are some differences among smoke-diving rooms in terms of their facilities (including nesting rooms, heating and cooling systems, and specialized ultra violet [UV] cameras), design, and physical space. The smoke-diving room used in this study was 3,000 m^2 and had black walls. A number of the walls had windows, very narrow roots for firefighters' crossing, and escape tunnels (Fig. 1). A separate part of the smoke-diving room (12 m^2 indoor space) was allocated to the control room, which had control devices such as monitors inside the control room. A heating and cooling system was employed to control temperature (22°C ambient temperature and 50% relative humidity) in the smoke-diving room. Given that the room was big, it was difficult to adjust its temperature and humidity. To address this challenge, numerous heating and cooling devices were installed in different parts of the smoke-diving room. As another measure to simulate the real environment, artificial smoke and steam (deionized water) generators were used to create fog. Firefighters' activity performance was recorded by the use of advanced UV cameras placed in different locations of the room. Considering physical space and available resources, more advanced facilities were employed in this study in comparison with similar studies that have focused on the impact of simulated firefighting activities on firefighters' physiological and cognitive function.

2.3. Paced auditory serial addition tests

Information processing and working memory are often assessed through paced auditory serial addition tests (PASAT) [17–19]. Following other studies' lead, the participants were requested to sit 38–60 cm from the computer monitor, with the center of the monitor being 2.5–5 cm below eye level. They were then invited to listen to 61 single digit numbers (varying from 1 to 9), with an interval of 3 seconds between every two numbers. They should subsequently calculate the sum of the last two numbers they had heard from the headphone and loudly announce the result into the microphone. The participants should utter the answer before the following digit was presented to them; otherwise, it would not be

Table 1
Anthropometric characteristics of firefighters ($N = 17$)

Characteristic	Mean ± SD	Minimum	Maximum
Age (y)	30.35 ± 4.51	23	38
Height (m)	1.79 ± 0.06	1.71	1.90
Weight (kg)	81.59 ± 15.13	65	120
BMI (kg/m^2)	25.21 ± 3.12	22.00	33.20
BSA (m^2)	2.02 ± 0.22	1.76	2.47

BMI, body mass index; BSA, body surface area.

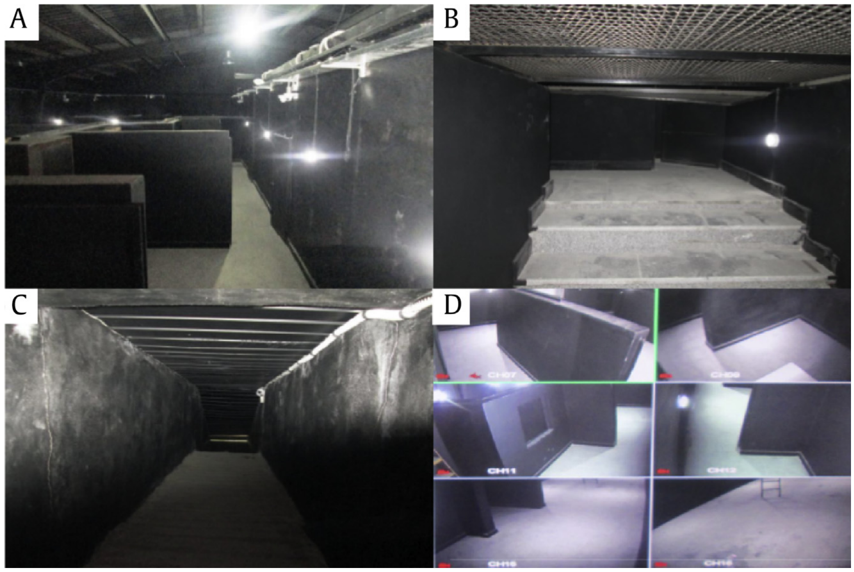

Fig. 1. (A) An overview of the smoke-diving room. (B) Very narrow routes for crossing. (C) Escape tunnel. (D) Control room.

regarded as a correct answer. For example, if 4 and 2 were presented consecutively, the participants should loudly say 6, which was the correct answer (Fig. 2). The rectangle on the computer screen was blank when the participants were taking the test. The highest score that the participants could gain (based on the number of correct answers) was 60. It took 3 minutes for the participants to complete the test.

2.4. Experimental design

To measure the integrated effect of multiple firefighting operations and various hot environments on firefighters' physiological response, information processing, and working memory, each firefighter completed three experiments in three hot environments in the smoke-diving room: (1) low heat (LH; 29–31°C ambient temperature, 55–60% relative humidity); (2) moderate heat (MH; 32–34°C ambient temperature, 55–60% relative humidity); and (3) severe heat (SH; 35–37°C ambient temperature, 55–60% relative humidity). The firefighters donned a full complement of FPC, self-contained breathing apparatus (SCBA), gloves, boots, helmet, and hood weighing 22–26 kg in total throughout the three experiments. The experiment was performed during about 1 month in three 10-day sections with no interval between them.

Prior to conducting the experiments, firefighters attended practice session in which they got familiar with the procedure for taking the defined firefighting tasks in the smoke-diving room. Furthermore, PASAT practice meetings were implemented to familiarize participants with the test. Training firefighters for the PASAT continued until they were able to take part in the PASAT using the provided equipment, including computer, headphone, and the installed software program. In general, the training course made it easy for the firefighters to execute the PASAT.

In line with the protocol, all firefighters wore a HR sensor after entering the control room, and their basic HR and tympanic temperature (TT) were gauged following 15–20 minutes of rest in the control room. They then completed PASAT test in the control room (12 m^2 indoor space, 22°C ambient temperature, and 50% relative humidity) prior to entering the smoke-diving room. Subsequently, each firefighter implemented simulated firefighting activities in the smoke-diving room for about 30 minutes (Fig. 3). After that, they again completed PASAT test in the control room. It took about 45–50 minutes for each firefighter to finish all defined simulated firefighting activities and the PASAT test.

The firefighters' HR was gauged in the control room prior to all experiments. Their HR was also measured during the activity by the use of an arm wrist Polar V800 watch (Polar, Kempele, Finland). All the participants donned a Polar HR sensor under protective clothing and, prior to the activity session, the HR sensor was paired with the HR monitor. It is important to be aware prior to selecting any temperature measurement options what the pros and cons might be for each option. An optimal infrared thermometer should have the following aspects; accurate body temperature (tympanic, forehead, and temporal) measurement, facility for use in a short time and the absence of potential risks. Since the infrared thermometer meets these principles, its use in the routine clinical practice and research purpose appears to be advantageous rather than or supplementary to the usual methods. Previous studies have found that infrared thermometers can measure the body temperature (tympanic and temporal temperature) up to an acceptable level for clinical practice and research purpose [20,21]. According to previous studies, in the present work TT was measured prior to and after performing simulated firefighting tasks in the three ambient temperatures using an infrared thermometer (Rossmax, Berneck, Switzerland).

2.5. Statistical analysis

SPSS 21 (SPSS Inc., Chicago, IL, USA) was used for data analysis. The Kolmogorov–Smirnov test was executed to analyze the

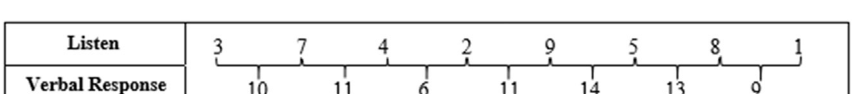

Fig. 2. The pattern of performing paced auditory serial addition test.

Pre-activity measurements	Simulated firefighting activities	Post-activity measurements
Physiological Heart rate Tympanic temperature **PASAT Test**	Hose pulling Ladder handling and climbing its stairs Passing through narrow routes Search and rescue operations Passing through escape tunnel Performing tasks in three various hot conditions, (1) low hot, (2) moderate hot and (3) severe hot.	**Physiological** Heart rate Tympanic temperature **PASAT Test**
Continuous measurement of heart rate during activity		

Fig. 3. Protocol timeline of simulated firefighting activities. Paced auditory serial addition test (PASAT).

normality of distribution of the data. Firefighters' physiological response and PASAT scores prior to and after the three experimental conditions were compared using a paired samples *t* tests. Also, the impacts of various hot environments on all measurements were analyzed by repeated measures analysis of variance (ANOVA) to find if there were any significant differences during firefighting tasks. The least significant difference (LSD) *posthoc test* was executed for pairwise comparisons of the three experiments. The statistical significance was set at ($p < 0.05$).

3. Results

3.1. Physiological responses

Compared with the baseline, HRs increased significantly following the firefighting activity period in the three environments (Fig. 4). Throughout the exercise periods, significant differences were observed between preexperiment and postexperiment in the HR mean scores ($p < 0.05$). The participants' HR mean scores prior to and after activity in the three hot environments were 70.4 ± 5.8 beats/min versus 154.2 ± 4.6 beats/min, 70.3 ± 5.4 beats/min versus 156.5 ± 3.7 beats/min, and 70.5 ± 5.9 beats/min versus 159.4 ± 4.2 beats/min for LH, MH, and SH, respectively.

The results of measuring firefighters' TT prior to and after the three different experiments are displayed in Fig. 5. The TT mean scores of firefighters prior to and after the activity were 37.11 ± 0.12 versus 38.17 ± 0.10°C, 37.11 ± 0.10 versus 38.20 ± 0.10°C, and 37.10 ± 0.10 versus 38.22 ± 0.10°C for LH, MH, and SH respectively. The results of the paired samples *t* test showed a significant difference in TTs between preexperiment and postexperiment in the three environments ($p < 0.05$).

Table 2 displays the results of pairwise comparisons of the impact of various hot environments on physiological responses. The repeated measures analyses of variance revealed significant differences in HR among the three various conditions. The LSD *posthoc* test was used for pairwise comparisons to examine the effect of various hot environments on the physiological responses. According to the table, there was a significant difference in HR between LH and MH ($p < 0.05$). Furthermore, the HR values significantly increased for the SH compared with the LH and MH conditions ($p < 0.05$). In addition, there was a small rise in TT among various hot environments; however, the LSD *posthoc* revealed significant differences in TT among the three various hot environments ($p < 0.05$).

3.2. PASAT

Fig. 6 illustrates the effect of various hot environments on PASAT scores (correct response, CR). Before and at the end of the experimental period, the mean PASAT scores were 50.41 ± 1.17 versus 48.18 ± 1.17 CR, 50.35 ± 1.15 versus 47.71 ± 1.31 CR, and 50.47 ± 1.58 versus 47.29 ± 1.10 CR for LH, MH, and SH respectively. The results of paired samples *t* tests demonstrated a significant difference in PASAT scores (CR) between preexperiment and postexperiment ($p < 0.05$).

Pairwise comparisons of the effect of various hot environments on information processing performance and working memory are

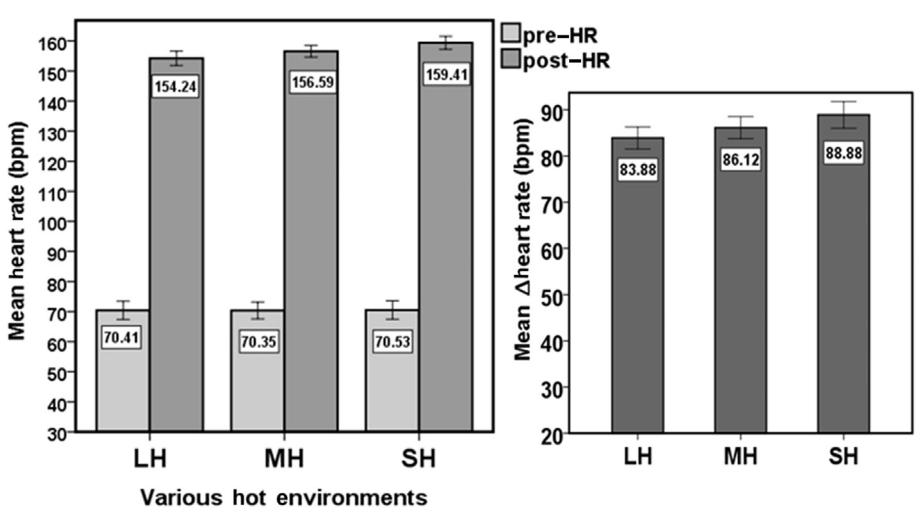

Fig. 4. Heart rate mean scores prior to (pre-HR) and after (post-HR) activity in the three hot environments: (1) low heat (LH), (2) moderate heat (MH), and (3) severe heat (SH). bpm, beats per minute; Δ Heart rate, difference of preexperiment and postexperiment.

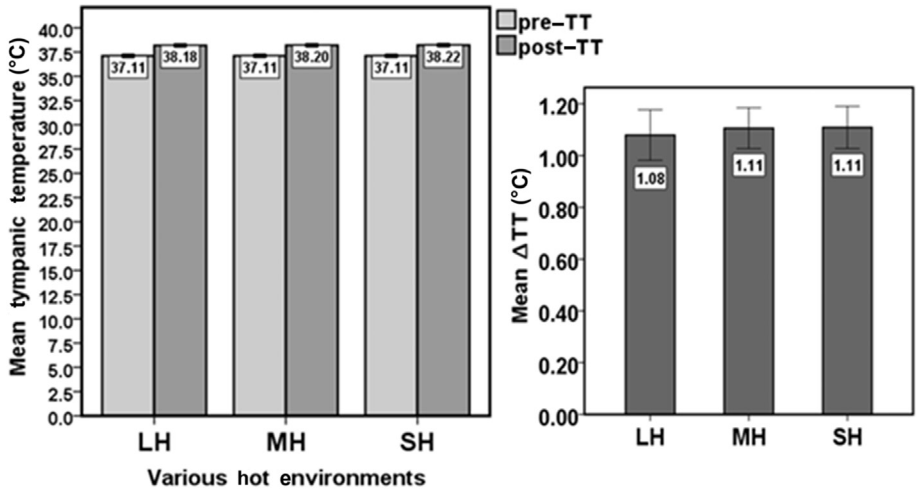

Fig. 5. Tympanic temperature mean scores prior to (pre-TT) and after (post-TT) activity in the three hot environments: (1) low heat (LH), (2) moderate heat (MH), and (3) severe heat (SH). ΔTT, difference of preexperiment and postexperiment.

Table 2
Pairwise comparison of the effect of various hot environments on physiological responses

Comparison of environment	HR		TT	
	Mean difference ± SE	*p*	Mean difference ± SE	*p*
LH vs. MH	2.3 ± 0.4	0.00	0.021 ± 0.006	0.004
LH vs. SH	5.1 ± 0.6	0.00	0.038 ± 0.008	0.000
MH vs. SH	2.8 ± 0.3	0.00	0.018 ± 0.006	0.009

HR, heart rate; LH, low heat; MH, moderate heat; SE, standard error; SH, severe heat; TT, tympanic temperature.

Table 3
Pairwise comparison of the effect of various hot environments on the paced auditory serial addition test (PASAT)

Comparison of environment	PASAT		
	Mean difference	SE	*p*
LH vs. MH	0.47	0.45	0.31
LH vs. SH	0.88	0.38	0.03*
MH vs. SH	0.41	0.38	0.30

* $p < 0.05$.
LH, low heat; MH, moderate heat; SE, standard error; SH, severe heat.

demonstrated in Table 3. The results of ANOVA revealed significant differences in PASAT scores among the three conditions. The LSD *posthoc* test was used for pairwise comparisons to examine the effect of various hot environments on information processing performance and working memory. There was no significant difference in PASAT scores between LH and MH ($p > 0.05$), or between MH and SH ($p > 0.05$), but there was a measurable difference in PASAT scores between LH and SH ($p < 0.05$).

4. Discussion

Fire service workers are under additional pressure due to sudden alarm calls, night-shift schedules, and stressful incidents [22–27]. Aside from distinct stressors and hazards, a fireman is exposed to environmental heat from natural environments or combustion products during firefighting. There is a considerable lack of knowledge about the effect of various hot conditions on firefighters' physiological responses and cognitive functions (e.g.

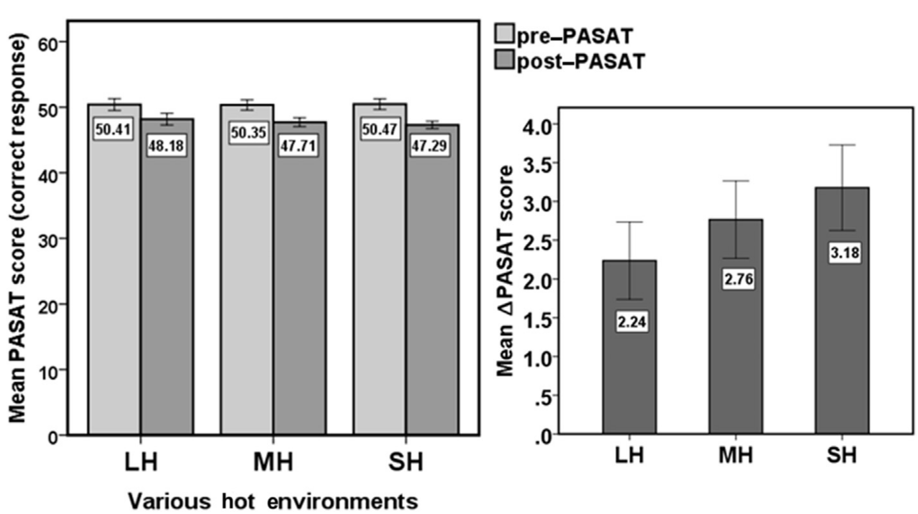

Fig. 6. Mean PASAT scores prior to (pre-PASAT) and after activity (post-PASAT) in three hot environments: (1) low heat (LH), (2) moderate heat (MH), and (3) severe heat (SH). ΔPASAT, difference of preexperiment and postexperiment.

information processing and working memory) during firefighting activities. As an effort to fill this gap partially, we investigated the effect of various hot conditions on firefighters' physiological responses as well as cognitive functions during firefighting activities. In addition, to study the effect of multiple physical activity and various hot environments, it is required to investigate firefighters' physiological responses, information processing, and working memory in a condition that resembles a real fire scene. For this purpose, we implemented the current study in an advanced smoke-diving room, constructed to prepare fire service workers for firefighting and emergency operations.

The results displayed increases in HR and TT for 17 firefighters after implementing simulated firefighting activities in the three hot conditions. This is in line with the results of previous investigations, which have reported physiological responses (such as higher HRs as well as increase in skin and core temperature) when conducting treadmill exercise or performing simulated firefighting work while wearing FPC and SCBA [16,28,29]. Following treadmill exercise in a climatic chamber with constant ambient temperature, HR increased to 155–160 beats/min, which was about 84–86% of the maximal HR. Moreover, the rectal temperature increased 1.2°C after treadmill exercise [7]. It has also been shown that the HR went up to 174 beats/min after crawling search activity [30]. In the current work, increases in HR were lower following the firefighting activities in the LH compared with the MH condition and increases in HR were higher for the SH compared with the LH and MH conditions. On the other hand, the results of the ANOVA revealed significant differences in HR among the three various ambient temperatures. The results also showed that, at the end of the firefighting activity, TT increased in the LH, MH, and SH conditions relative to baseline. Further, a greater increase was observed in TT for the SH compared with the LH and MH conditions, after conducting firefighting tasks. The findings of the present work back previous studies reporting that high ambient temperatures are effective in enhancing the physiological responses during firefighting and life-saving operations while wearing FPC [14–16,31].

Because of lack of empirical studies, little is known about changes in information processing and working memory during firefighting activity [15,32]. Previous work has investigated cognitive functions such as sustained attention by visual continuous performance test during simulated firefighting and rescue operations [16,33,34]. Morley et al [35] studied non-firefighter participants' cognitive functions with PASAT test after treadmill exercise in a heated room (33–35°C) while wearing thermal protective clothing and SCBA, reporting decrements in working memory following experiment. Another work studied the influence of heat stress induced dehydration on mental performance outside of the fire service, with the results indicating a 2% and 3% level of early dehydration results in a considerable decline in mental performance [36].

In the current research, we were interested in finding out how much firefighters' information processing and working memory can alter after performing firefighting tasks in various ambient temperature. As expected, the results showed reductions in PASAT scores after performing firefighting activities in three various ambient temperature as compared with prior to activity. Because of decreases in PASAT scores (correct response) after performing defined firefighting tasks in the three ambient temperatures, one can conclude that firefighters' information processing and working memory was impaired in all conditions after firefighting activity. Comparison of changes in PASAT mean scores by a repeated measures ANOVA showed no significant differences between the LH and MH conditions. There was also no significant difference between the MH and SH environments. However, the response to SH condition in the smoke-diving room resulted in significantly lower PASAT scores (47.29 vs. 48.18 CR), compared with firefighting activities in the LH condition. Therefore, PASAT scores decline to a greater extent in high ambient temperature. It is thus concluded that the increase of ambient temperature negatively impacts firefighters' information processing and working memory during firefighting and life-saving operation while wearing firefighting protective clothing.

The various occupational and environmental stressors that firefighters deal with cause physiological and psychological stress [16,33,37–39]. In the present study, physiological response values increased significantly throughout the exercise. During firefighting operations, the physiological responses and stress level goes up, making it necessary for the body to deal with it. This may cause reduction in the capacity of information processing and decision-making [32]. According to the results information processing and working memory impairment increased significantly following firefighting activities throughout the exercise. This can be clarified in the light of the physiological responses and stress hormones that are secreted as a consequence of various stressors; that is, stressful conditions lead to the production of steroids which can quickly overcome the blood–brain barrier and arrive in the brain. They can then influence learning and memory by binding to receptors located in various areas of the brain which are responsible for learning and memory [40]. It is thus deduced that the rise of physiological strain negatively impacts firefighters' information processing and working memory during firefighting activities while wearing personal protective equipment.

These findings prove that multiple strenuous duties during fire and rescue operations have considerable impact on a firefighter's physiological response. In conclusion, it can be argued that firefighters' physiological responses are affected by the change of ambient temperature during firefighting activities. Our results also suggest that cognitive functions such as information processing and working memory alter as a result of conducting simulated firefighting activities. Moreover, further increase of ambient temperature can affect firefighters' information processing and working memory during firefighting and life-saving operations. Finally, the rise of physiological responses and impairments of information processing and working memory among fire service and emergency workers may increase risks of injuries and accidents during firefighting and emergency operation.

Conflicts of interest

There are no conflicts of interest.

Acknowledgments

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