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# Firefighter neural function and decision-making following rapid heat stress<sup>☆</sup>

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## ABSTRACT

In the present experiment we evaluated the impact of rapid heat stress on decision-making and neural function. Previous work has demonstrated that heat stress has an impact on cognitive and neural function. Here, we hypothesized that a rapid increase in heat stress would result in reduced decision-making ability evidenced by a reduction in frontal theta electroencephalographic (EEG) power. Fifteen participants performed an incremental exercise test to a termination criterion (volitional maximum, core temperature = 39.5 °C, or a 2-h time cap) with or without fire-fighting gear (selection was randomized) in a laboratory with an ambient temperature of 25–26 °C. Immediately following the exercise test, participants completed a Go/No-Go task and we observed an increase in incorrect responses when the subjects were wearing fire-fighting gear; no change was observed without gear. Additionally, an analysis of frontal EEG revealed a decrease in theta power when comparing pre- and post-exercise values with fire-fighting gear on; no change was observed without gear. Importantly, our results suggest that rapid heat stress and the resulting increase in physiological strain causes a decrease in cognitive control that could result in serious consequences in life-saving occupations that require contemplative, effortful decision-making.

## 1. Introduction

Each day at work firefighters must make decisions that require them to process multiple alternatives and ultimately choose an optimal course of action [1]. Some of these decisions are gut-hunch decisions that require little processing, while others require more effortful thinking and the outcome may result in life or death. At least one prominent theory posits that human beings use two systems to navigate simple or complex decision-making [2]. Specifically, System One (or “fast”) decisions are automatic judgements based on patterns that are familiar. Alternatively, System Two (or “slow”) decisions take more effort, require focus, and are more analytical [2,3]. As humans, we mostly rely on System One decisions as they are fast, efficient, and allow us to navigate most of the choices we face each day. When faced with more challenging scenarios, we rely on System Two which uses effortful thinking and increased cognitive control. The interplay between System

One and System Two decisions can be observed in real-world situations such as firefighting. When a veteran firefighter approaches a typical house fire, they rely on System One processing to navigate a series of familiar decisions; however, once they encounter a situation that is atypical (e.g., a beam falls on a crew member or another oxygen source comes in contact with the fire), they engage System Two processing in order to make important, effortful decisions with cognitive control to save a life or remediate a more intense fire. If System Two becomes compromised in these situations, it could result in a catastrophic scenario.

One factor that could compromise cognitive control is stress [4]. Heat stress has specifically been shown to have a detrimental effect on cognition [5–8]. A meta-analysis of performance response under thermal stressors demonstrated that thermal stress causes individuals to reallocate attentional resources to appraise and cope with the thermal threat and reduces one’s ability to process task-relevant information [9].

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Hyperthermia additionally has a negative effect on response processing speed [7] limiting one's ability to make rapid decisions. Indeed, studies examining the effects of heat stress on decision-making report a negative effect. Warm temperatures deplete extensive processing resources, increase the incidence of System One processing, and have a negative impact on performance during complex choice tasks [5].

Functional neuroimaging has shown that many cortical and subcortical structures associated with the cognitive processes are adversely affected by heat stress. For instance, Sun et al. [10] identified several changes in connectivity correlations. Specifically, they showed a total of 50 decreased functional connectivities during hyperthermia trials (50 °C for 1 h) when compared to control trials (25 °C for 1 h). When examining the locus of the decreased connectivities, Sun and colleagues found the majority involved the medial orbitofrontal cortex, temporal lobe, and occipital lobe suggesting the potential for diminished decision-making capability. In addition to the findings by Sun et al. [10], Jiang et al. [11] also demonstrated that hyperthermia changes activity in the dorsolateral prefrontal cortex (DLPFC) which plays a major role in the decision-making process. In terms of persisting effects after hyperthermia, actual neural tissue damage has been reported in the cerebral cortex and the basal ganglia [12]. Interestingly, when analyzing literature related to the impact of heat stress on cognitive and neural function [5–8,13–16], no differentiation can be found between gradual (compensable) heat stress and uncompensable rapid heat stress.

Neuroimaging, and specifically electroencephalography (EEG), provides a way to quantify decision-making within the prefrontal cortex (PFC). For example, studies using EEG have demonstrated that it is possible to gauge the extent of engagement of cognitive control processes within the prefrontal cortex [17–20]. In particular, frontal theta power seems to be related to the engagement of cognitive control [20] with generic and reactive medial prefrontal processes represented by changes in theta band power [21]. Moreover, theta synchronization has been proposed to act in organizing decision points and specifically it has been proposed to play an important role in the selection of a choice during goal-directed behavior [22]. Indeed, frontal theta has been suggested to play an important role in implementing cognitive control during an array of scenarios [23], and theta dynamics have been shown to enhance following events that require increased cognitive control [21]. Recently, it has been proposed that frontal theta power is indicative of System Two decision-making given the underlying need for cognitive control in these instances [20]. With all of this in mind, measuring frontal theta power via EEG is a reasonable methodology for probing decision-making processes.

In the present study we examined the impact of heat stress on decision-making in the prefrontal cortex. Here, participants performed a graded exercise protocol in both uncompensable (while wearing fire-fighting gear: GEAR) and compensable (while not wearing firefighting gear: NOGEAR) rapid heat stress scenarios. To gauge the extent to which cognitive control was impacted by heat stress with and without gear we had participants perform a Go/No-Go task while EEG data were recorded prior to and after the rapid heat stress scenarios. We hypothesized that an uncompensable rapid heat stress scenario would result in reduced behavioral performance and a reduction in prefrontal theta activity relative to the compensable heat stress scenario.

## 2. Methods

### 2.1. Participants

Fifteen healthy male adults (age:  $32.7 \pm 12.2$  years; height:  $181.4 \pm 7.6$  cm; body mass:  $83.9 \pm 9.1$  kg;  $VO_{2max}$ :  $51.3 \pm 6.7$  mL kg<sup>-1</sup> min<sup>-1</sup>) participated in this study. Participants were healthy and had no barriers to physical activity based on the Physical Activity Readiness Questionnaire (PAR-Q). Additionally, participants did not have esophageal constriction which could contribute to inability to swallow a core temperature capsule (VitalSense, Health Canada License # 70,240). Further,

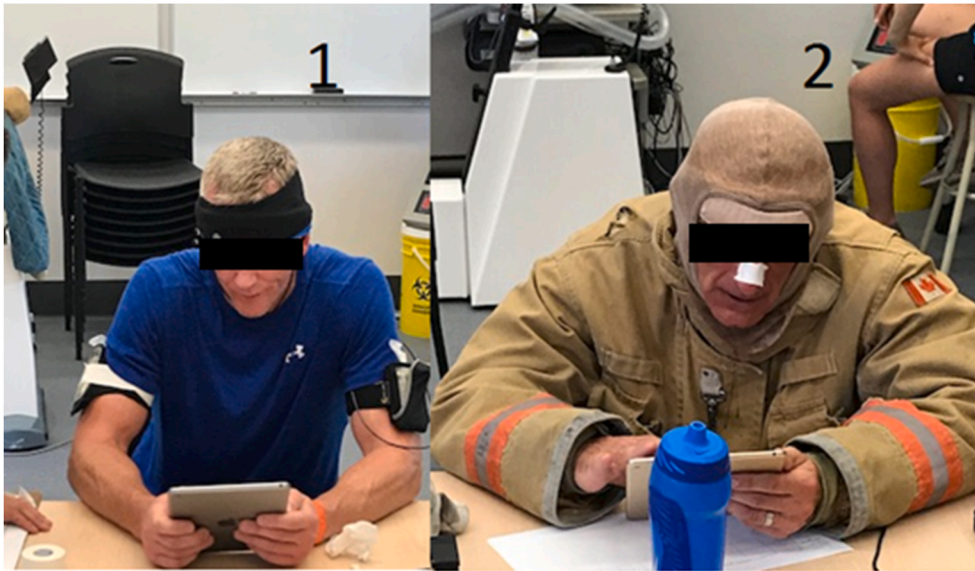
any subject with a relative  $VO_{2max}$  of less than 35 mL kg<sup>-1</sup> min<sup>-1</sup> was excluded from participation in the study. The Human Research Ethics board at the University of Victoria (Ethics Protocol #: 17–236) approved this research study and each participant provided written informed consent.

### 2.2. Experimental design

All participants came to the laboratory for three separate sessions ( $VO_{2max}$  determination, NOGEAR, and GEAR). The NOGEAR and GEAR training sessions were completed following the  $VO_{2max}$  determination session in a random, counterbalanced order to prevent crossover effects. All subjects underwent a familiarization period with the fire-fighting gear prior to the GEAR session. Additionally, NOGEAR and GEAR were scheduled at the same time of day to maintain consistency and to limit the potential diurnal effects. The participants all followed a specific pre-testing exercise protocol for NOGEAR and GEAR testing sessions. This pre-testing protocol had the participants refrain from caffeine, alcohol, and nicotine intake for 12 h prior to testing. In addition to this, the subjects followed a pre-testing dietary protocol. The subjects drank at least 3.7 L of water in the 24-h period prior to testing, and also drank at least 500 mL of water 2 h prior to the testing protocol (see Ref. [24]). Participants were additionally instructed to eat their last meal a minimum of 2 h prior to a testing session. Participants were also instructed to completely void their bladders prior to NOGEAR and GEAR testing sessions.

Upon arrival to the laboratory for NOGEAR and GEAR testing, the subject's anthropometric values were measured. Height was measured using a stadiometer (Tanita, USA) and body mass was measured pre- and post-exercise with a scale (Health-o-meter, Continental Scale Corporation, USA). Following these measurements, participants were fitted with the Equivital Integrated physiological monitoring system for heart rate (HR) measurement and were also given a Jonah core temperature capsule (VitalSense, Health Canada License # 70,240) to ingest for real-time core-temperature observation and analysis. It should be noted that human brain temperature is on average at least 0.2 °C higher than core temperature during prolonged exercise [25,26]. Physiological strain index (PSI) was derived using the core temperature and HR data. To increase thermal stress, the laboratory was kept at an ambient temperature of 25–26 °C during both the NOGEAR and GEAR sessions.

Participants began each testing session with a 10-min rest period lying in a supine position. After the initial rest period, participants completed a Go/No-Go task on an Apple iPad while electroencephalographic data was recorded via a MUSE EEG headband (see Fig. 1). Subsequent to performing the Go/No-Go task, participants completed a treadmill graded-exercise protocol. The treadmill graded-exercise protocol included an initial 5-min stage at 3.5 mph and a 0% grade, the second stage was 5-min at 3.5 mph at 4% grade, the third stage was 50-min at 3.5 mph and an 8% grade, and the final stage was 1-h at 3.5 mph and a 12% grade. HR was recorded at each 0.5 °C increase in core temperature during the treadmill graded-exercise protocol. The treadmill graded-exercise protocol was terminated at the onset of any of the following three termination criteria: (1) core-temperature reached 39.5 °C ( $n = 1$  during NOGEAR;  $n = 6$  during GEAR) (2) the subject reached a volitional maximum ( $n = 12$  during NOGEAR;  $n = 9$  during GEAR) (3) the participant reached the 2-h time limit ( $n = 2$  during NOGEAR). Volitional maximum was defined as the inability of the participant to maintain exercise intensity and thereby voluntarily stepping off the treadmill. Immediately following treadmill exercise, participants completed the Go/No-Go task again followed by another 10-min supine rest period. The participants wore shorts, t-shirt, socks, and running shoes in the NOGEAR session, and firefighter personal protective equipment (coat, pants, balaclava, gloves, and running shoes) in the GEAR session. Firefighter helmets were not worn during testing due to the need to wear headgear for metabolic analysis and EEG recording. Participants wore shorts and a t-shirt during the rest periods



**Fig. 1.** The difference between the attire in NOGEAR and GEAR. (1) The subject is wearing shorts and a t-shirt; (2) The subject is wearing the full firefighter personal protective equipment. The MUSE headband is under a black headband, which is secured by a tensor bandage.

in both the NOGEAR and GEAR sessions. To match the mass of the firefighter personal protective equipment, during the NOGEAR session participants wore a backpack with mass equal to the mass of firefighter personal protective equipment. The backpack (NOGEAR)/firefighter personal protective equipment (GEAR) was added following the initial 10-min rest period and removed prior to the final 10-min rest period.

### 2.3. Electroencephalography (EEG) data collection

Participants performed a Go/No-Go task on an Apple iPad using the PEER iOS research application (Suva Inc., Victoria, B.C.) while EEG data were recorded via a MUSE (Interaxon Inc., Toronto, ON.) EEG headband.<sup>1</sup> Effortful control is correlated to Go/No-Go task performance [28, 29]; therefore, the Go/No-Go task is relevant for System One and System Two analysis. While performing the Go/No-Go task participants saw a series of green and blue circles (70% probability versus 30% probability each trial) preceded by a fixation cross and were instructed to tap the screen of the iPad each time one of the green (Go) circles appears and to not respond when one of the blue (No-Go) circles appeared. Within each trial, the fixation cross was on screen each trial for 400–600 ms and was followed by a colored circle that was on screen for 800 ms. Participants completed four blocks of 50 trials of the Go/No-Go task. Presentation order of the circles was completely random and the meaning of the circles (Go/No-Go) was randomly counterbalanced between sessions. The Go/No-Go task was done in a quiet room with limited visual and auditory stimuli.

The PEER application recorded stimulus locked EEG data from a MUSE EEG headband during performance of the Go/No-Go task at a sampling rate of 256 Hz. The MUSE EEG headband has five EEG electrodes (AF7, AF8, Fpz, TP9, TP10) with electrode Fpz used as the recording reference. Prior to commencement of the Go/No-Go task the EEG signal was checked using the PEER application via a method that uses the variance per second for each channel of EEG data to determine signal quality (see Refs. [27] for more on this method). Signal quality was monitored throughout the Go/No-Go task by the PEER application.

### 2.4. EEG data processing

Post experiment the EEG data from the PEER application was imported into Brain Vision Analyzer 2 software (Version 2.1.1, Brain-products, GmbH, Munich, Germany) using custom MATLAB software (see <http://www.krigolsonlab.com/data-analysis.html>). First, the EEG data were filtered with a zero-phase shift Butterworth filter with a passband of 0.1 Hz–30 Hz in addition to a 60 Hz notch filter. The data front EEG channels (AF7, AF8) were referenced to the after of the two posterior channels (TP9, TP10). The two posterior EEG channels were left referenced to the recording reference of Fpz. Next, the EEG data were epoched using a window from –200 ms to 800 ms after the onset of the circle stimuli. To ensure the EEG data was artifact free, epochs with an absolute difference of more than 75  $\mu$ V were discarded with no participants being removed as a result of this procedure (mean data loss =  $34\% \pm 4\%$ ). Following the artifact rejection procedure, a Fast Fourier Transformation (FFT) was used to extract EEG power using maximum resolution, non-complex output, on the full EEG power spectrum with a Hanning Window, a 10% taper, and a resolution of 0.48 Hz. Epochs were zero-padded for a length of 1024 ms generating 512 data points. Power was determined for each individual epoch and was averaged across epochs for each frequency (1–30 Hz), for each condition (Go/No-Go), for each participant. Mean power was computed for the theta frequency band (theta: 4–7 Hz) and the difference in power (No-Go minus Go) was computed for each participant.

### 2.5. Statistical analysis

Pre- and post-test results for Go/No-Go difference in the error rate and spectral power difference scores for the theta frequency band were directly compared using Bayesian single sample tests [30] for both experimental conditions. The physiological strain index (PSI) differences between experimental conditions were also compared using Bayesian single samples tests [30]. A Cauchy prior was assumed. Bayes factor was used to determine effect [31]. Further affirmation of these tests was provided by visual comparison of 95% within subject confidence intervals [32]. All statistical analyses were conducted in R Studio (Version 1.1.456 – © 2009–2018 RStudio, Inc.).

<sup>1</sup> It is important to note that the ability of the MUSE EEG headband to measure event-related potential (ERP) data has been validated – see Ref. [27].

### 3. Results

#### 3.1. Behavioral performance and neural function

A Bayesian single sample test of error rate revealed more incorrect responses were made in the GEAR condition between pre- and post-exercise Go/No-Go tests (Mean = 13.02, 95% CI [6.77, 19.41]) - a decisive effect [31] (BF = 107.10). No difference was observed in the number of incorrect responses made in the NOGEAR condition between the pre and post-exercise Go/No-Go tests. Visual inspection of the results using with 95% confidence intervals affirmed the results of these tests (see Fig. 2).

Given our apriori hypotheses about frontal theta power our analysis was focused entirely on this frequency band. Our analysis revealed a decrease in frontal theta EEG power in the GEAR condition in the post-exercise test relative to the pre-exercise test, (Mean = 0.51, 95% CI [0.16, 0.87]) - a substantial effect [31] (BF = 6.75). Again, no difference was observed in the NOGEAR condition. As with our behavioral data, visual inspection of our results for frontal theta power using with 95% confidence intervals affirmed the results of these tests (see Fig. 3).

#### 3.2. Rate of thermal acquisition

The rate of thermal acquisition in GEAR (0.04 °C/min) was double that of NOGEAR (0.02 °C/min). Termination of exercise occurred later in NOGEAR (Mean = 77.3 min, 95% CI [64.7, 89.9]) when compared to GEAR (Mean = 50.3 min, 95% CI [43.4, 57.2]). The post-exercise Go/No-Go test occurred during a period of core temperature stability. No difference was observed between core temperature at the termination points and core temperature during the post-exercise Go/No-Go tests in both NOGEAR and GEAR (see Fig. 4).

#### 3.3. Physiological response

The physiological impact of the rate of thermal acquisition was calculated using PSI [33]. PSI was higher in GEAR at core temperature 37.5 °C (Mean = 0.72, 95% CI [0.10, 1.32]) - a substantial effect [31] (BF = 3.69), core temperature 38 °C (Mean = 0.95, 95% CI [0.54, 1.36]) - a decisive effect [31] (BF = 223.68), and end of exercise (Mean = 1.74, 95% CI [0.67, 2.82]) - a strong effect [31] (BF = 18.20).

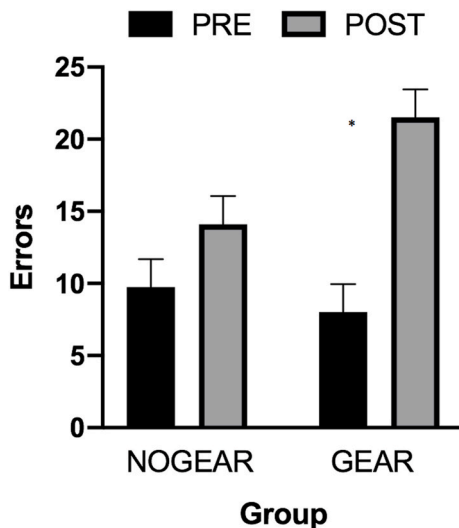


Fig. 2. Mean incorrect responses during Go/No-Go test pre- and post-exercise in the NOGEAR and GEAR conditions. Error bars reflect 95% within subject confidence intervals. \* indicates that the posterior distribution did not include zero.

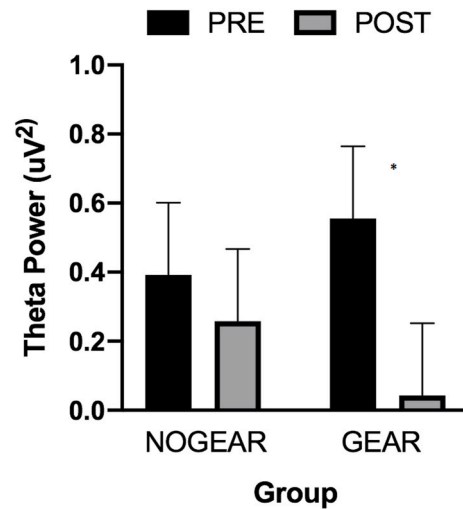


Fig. 3. Mean theta power from the pooled frontal electrodes for the difference between No-Go and Go stimuli for the pre- and post-exercise in NOGEAR and GEAR conditions. Error bars reflect 95% within subject confidence intervals. \* indicates that the posterior distribution did not include zero.

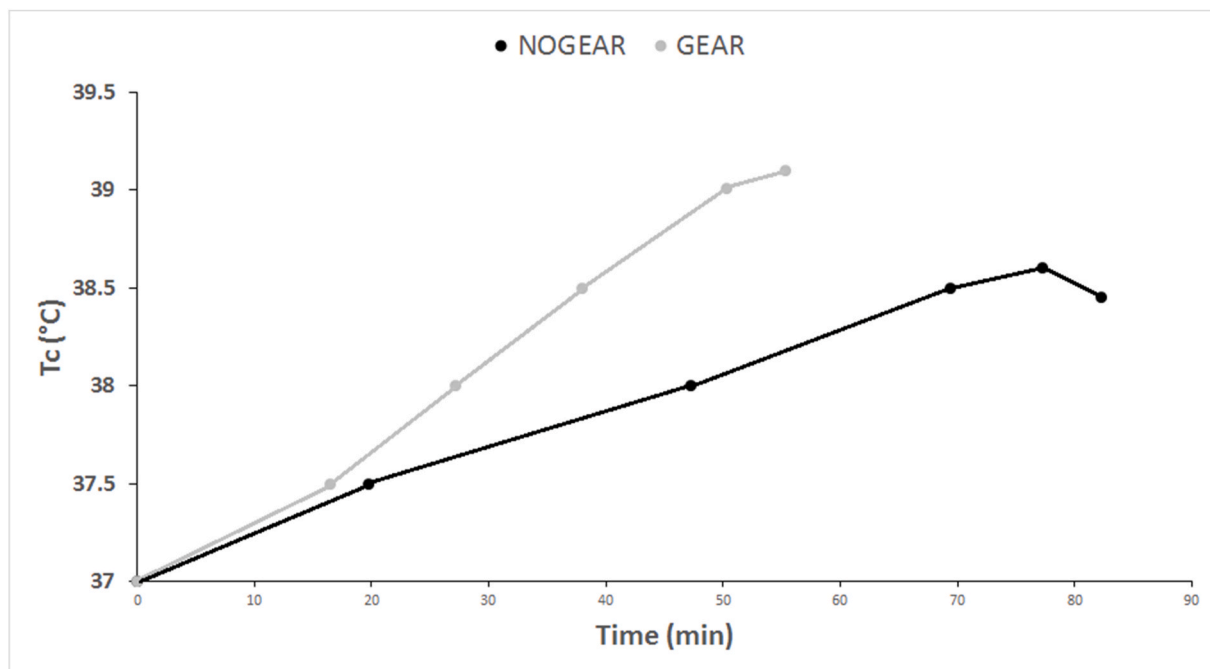
### 4. Discussion

The present study sought to determine the effect of rapid heat stress on neural function and decision-making ability. Our results revealed that participants in the GEAR condition made more incorrect responses and had a reduction in frontal theta EEG power following the heat stress exercise intervention, a pattern of results that was not present in the NOGEAR condition. Our behavioral findings support previous research demonstrating that hyperthermia has an effect on cognition [5,6,8,34]. Our results also highlight a novel result in that rate of thermal acquisition resulting in increased physiological strain has an effect on decision-making performance. Specifically, participants in the GEAR condition had double the core temperature acquisition per minute during exercise when compared to the NOGEAR condition. The difference in rate of thermal acquisition resulted in increased PSI at each temperature measurement point. Importantly, this increase rate of core temperature acquisition resulted in an increased number of errors made during decision-making during performance of the Go/No-Go task. It should be noted that there was no difference between core temperature at the termination points in GEAR and NOGEAR and core temperature during the post-exercise Go/No-Go tests. This means that core temperature did not drop during the test and therefore did not alter the impact of heat stress on the neural function and decision-making ability results.

As noted above, we also observed a reduction in frontal theta power during the post-exercise Go/No-Go test in the GEAR condition while we observed no reduction in frontal theta power in the post-exercise Go/No-Go test in the NOGEAR condition. Previous research has shown that there is a proportional relationship between frontal theta power and cognitive control [21]. More recently, Williams et al. [20] extended this and proposed that frontal theta power is a relative of index of System Two decision-making given the importance of cognitive control in this decision-making process. As such, decreased cognitive control, as indicated by decreased frontal theta power in the GEAR condition, would have implications for the top-down cognitive processing in the pre-frontal cortex. For instance, decreased cognitive control would impact one's ability to recruit System Two decision processes during scenarios that require more methodical decision-making (i.e., Williams et al. [20]).

Decreased decision-making performance during rapid heat stress as evidenced here as an increase in response errors and a reduction in frontal theta EEG power has a far-reaching impact on individuals, such as firefighters, who need to make decisions during rapid heat stress





**Fig. 4.** Rate of thermal acquisition in NOGEAR and GEAR conditions. The second to last value in each condition represents the termination of exercise and the last value in each condition represents the period during the post-exercise Go/No-Go test. Tc = Core Temperature.

scenarios. For example, decreased decision-making performance in these scenarios puts lives at risk. Approximately, 40% of all deaths are associated with decision-making deficits at the most basic level of self-regulation [35]. Additionally, the results of this study should cause concern with safety at work organizations. Decreased decision-making performance among firefighters most likely contributes to increased occupational work claims.

## 5. Conclusions

The present study demonstrated that uncompensable rapid heat stress results in more behavioral decision-making errors and a reduction in frontal theta power. Given that frontal theta power is associated with cognitive control [20], a reduction in frontal theta power suggests that rapid heat stress reduces decision-making efficacy, at least in terms of System Two decision-processes. As such, rapid heat stress and the resulting physiological strain therefore results in an increased reliance on System One decision processes which may result in decision errors being made when analytical thought is required in scenarios when rapid heat stress is an issue (e.g., while firefighting). It is important to for future research endeavors to find a solution to problem of uncompensable rapid heat stress. Personal protective equipment manufacturers need to come up with a solution to delay core temperature acquisition in occupations that require personal protective equipment and work in high ambient temperatures.

## Author statement

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## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The lead author is the co-founder and Chief Science Officer of Suva Technologies. Suva Technologies supplies and develops the PEER iOS research application (Suva Inc., Victoria, B.C.). Suva Technologies markets this system as a method of assessing cognitive function. The hardware and software was supplied for this study free of charge.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.firesaf.2020.103240>.

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