The effects of exercise-induced heat stress on cognitive function in firefighters

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Background. Firefighting requires tremendous cognitive demands including assessing emergency scenes, executing critical decisions, and situational awareness of their surroundings. The aim of this study was to determine the effects of differing rates of increasing core temperature on cognitive function during exercise-induced heat stress.

Methods. Nineteen male firefighters were exposed to repeated cognitive assessments, randomized and counter-balanced, in 30°C and 35°C and 50% humidity. Participants performed treadmill walking (4.5 $km \cdot h^{-1}$ and 2.5% grade) with cognitive function assessed before exercise (PRE), after mounting the treadmill (Cog 1), at core temperatures of 37.8°C (Cog 2), 38.5°C (Cog 3), and 39.0°C (Cog 4), after dismounting the treadmill (POST), and following an active cooling recovery to a core temperature of 37.8°C (REC). The cognitive tests implemented at PRE and POST were spatial working memory (SWM), rapid visual information processing (RVP), and reaction time (RTI) while paired associates learning (PAL) and spatial span (SSP) were assessed at Cog 1, Cog 2, Cog 3, and Cog 4. All five cognitive tests were assessed at REC.

Results. Planned contrasts revealed that SSP and PAL were impaired at Cog 3, with SSP also impaired at Cog 4 compared to Cog 1. REC revealed no difference compared to Cog 1, but increased errors compared to Cog 2 for PAL.

Conclusions. The decrements in cognitive function observed at a core temperature of 38.5°C are likely attributed to the cognitive resources required to maintain performance being overloaded due to increasing task complexity and external stimuli from exercise-induced heat stress. The addition of an active cooling recovery restored cognitive function to initial levels.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2524v1 | CC BY 4.0 Open Access | rec: 14 Oct 2016, publ: 14 Oct 2016

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ABSTRACT

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Introduction

Firefighting requires tremendous physical and cognitive resources to perform safe and effective operations (Barr et al. 2010). Cognitive demands for firefighters include assessing and executing critical decisions along with situational awareness to determine the safest means of exiting the emergency scene (Barr et al. 2010). Research about the effects of thermal stress on cognitive function for firefighters is limited.

A limitation of previous work using simple cognitive tasks is they are not sensitive to the changes in cognitive function that occur during or following firefighting activities in the heat (Smith & Petruzzello 1998). One study addressed this by using a standardized testing battery, the Cambridge Neuropsychological Test Automated Battery (CANTAB), which assesses more complex cognitive tasks, such as sustained attention and working memory capacity, as well as reaction time (Rayson et al. 2005). No impairments in cognitive function were revealed with the live-fire simulation, however, the cognitive tests were administered 30-min after the heat stress protocol, which may have allowed any negative effects of heat stress to dissipate (Rayson et al. 2005).

Despite limited research on firefighters, numerous studies have examined the effect of heat stress on cognitive function within the general population. Early data suggested it was the dynamic change in core temperature that limited cognitive function and not the absolute core temperature attained (Allan & Gibson 1979). Further, it appears that task complexity is a major factor on performance in the heat (Hancock & Vasmatzidis 2003). In a subsequent review, Hancock & Vasmatzidis (2003) suggested that more complex tasks including vigilance, tracking, and multiple tasks conducted simultaneously are more vulnerable to heat stress than simple tasks, such as reaction time and mental transformation.

Cognitive function is an important factor when combating highly demanding job tasks in rapidly changing environments experienced by firefighters (Walker et al. 2015). The cognitive tasks required of firefighters include assessing and executing critical decisions, situational awareness of their surroundings to determine the safest means of exiting the emergency scene (Barr et al. 2010). The emergency environments faced by firefighters involve a dynamic environment (Walker et al. 2015) in short durations that can place large demands on working memory. As previous work has focused primarily on reaction time (Smith & Petruzzello 1998), more complex tasks that are indicative of firefighting, such as sustained attention, working memory capacity, new learning, are required. In other populations, increasing T_{core} resulting in elevated levels of dehydration have been associated with a decline in cognitive performance (Cian et al. 2001). Dehydration can lead to a reduction in body mass, which at levels of 2% or more, has been linked to reductions in mental concentration and working memory (Sharma et al. 1986). Therefore, reducing the influence of dehydration on cognitive function is important to determine the specific effects of increasing levels of T_{core}.

This study aimed to examine the effects of exercise-induced heat stress (EIHS) on cognitive function using core temperature (T_{core}), rather than time of exposure, as the independent variable (Wright et al. 2012). The impact of different environmental temperatures were studied together with an active cooling recovery similar to that recommended by NFPA 1584, which indicates a minimum of 10-min but states a preferred duration of 20-min for active cooling (Association 2015; Selkirk et al. 2004). We hypothesized that aspects of cognitive function relevant to firefighting would be impaired with increasing levels of T_{core} and subsequently restored following active cooling recovery.

Methods

The research protocol was approved by the Office of Research Ethics at the University of Ontario Institute of Technology (REB #12-076) and informed written consent was obtained prior to participation in the study. Nineteen male firefighters were recruited to take part in each phase of testing. Participants were requested to refrain from vigorous exercise, alcohol, non-steroidal anti-inflammatories, and sleep medication in the 24 hours prior to testing and to refrain from consuming alcohol or nicotine 12 hours prior to arrival. Mean values for age, years of firefighting service, body mass, height, body mass index (BMI), and percent body fat were 35.6 ± 2.0 years, 10.0 ± 2.1 years, 85.1 ± 12.6 kg, 1.76 ± 0.07 m, 27.3 ± 3.2 $kg{\cdot}m^{-2}$, and 16.7 ± 5.8%, respectively. Inclusion criteria were (1) incumbent firefighter, (2) age less than 50 years, (3) not currently taking medication, and (4) urine specific gravity (USG) less than 1.030 (Casa et al. 2000), (values higher indicate serious dehydration), prior to the EIHS protocol.

Testing was conducted on 3 separate days, 1 day for familiarization of the CANTAB battery, and 2 days for the EIHS and cognitive function protocols. All EIHS trials were conducted at the University of Ontario Institute of Technology's ACE climate chamber at 30°C or 35°C and 50% relative humidity, with wind speed maintained at ≤ 0.1 $m{\cdot}s^{-1}$. The EIHS trials were randomized and at least 28 days apart during the winter months (January through April) to limit any potential effects of acute heat acclimation by the firefighters (Selkirk & McLellan 2004).

Nine participants attended the climate chamber at 0800 h and 10 participants began testing at 1200 h on both testing days after ingesting a core temperature (T_{core}) radio-pill (HQ Inc, Palmetto, FL) approximately 6 to 9 hours prior to attending the EIHS trials. Upon arrival, each participant had their nude body mass measured on a digital scale (Tanita, Arlington Heights, IL) to 0.1 kg and USG analyzed (Atago Co., LTD., Tokyo, Japan). Physiological measurements included T_{core}, heart rate (HR) using a transmitter (Polar, Kempele, Finland) attached around the chest with a wearable strap, and percent body fat was evaluated by four skinfold sites (triceps, subscapular, abdomen, and thigh) and then calculated using a specific formula developed by Jackson et al. (1980).

An illustration of the experimental protocol is provided in Figure 1. Once instrumented, participants (wearing station gear consisting of pants and short-sleeved t-shirt) donned their bunker pants (PPC1) and completed the pre-test (PRE) cognitive assessment. Then, participants donned their jacket, flash hood, gloves, helmet, and self-contained breathing apparatus (SCBA) wearing their face-piece (PPC2) but not breathing through the cylinder "on-air". Participants began treadmill walking at 4.5 $km \cdot h^{-1}$ and 2.5% grade while performing Cog 1. Treadmill walking continued until they either completed: (i) 30 min of exercise, at which time they would receive a 5-min rest break (in the test condition environment) and wear PPC1 and jacket or (ii) reached a level of 37.8°C where they would then complete Cog 2. Following Cog 2, participants were seated for 10-min wearing only PPC1 and jacket. After, participants donned PPC2 and completed the same work to rest ratio until T_{core} reached levels of 38.5°C (Cog 3) and 39.0°C or declaring 10-min of exercise remaining until volitional fatigue (Cog 4). Participants removed PPC2 and performed the post-test (POST) while seated. Next, participants were placed in active cooling recovery (in the test condition environment) by sitting in a chair (DQE, Inc., Fishers, IN) and submerging their hands and forearms in 15-20°C water until their T_{core} returned to 37.8°C and then completed the recovery (REC) cognitive assessment trial. Previous work has suggested that the final T_{core} of firefighters in similar ambient conditions may reach approximately 39.0 °C (Selkirk & McLellan 2004). This study utilized T_{core} as the independent variable rather than time of exposure (Wright et al. 2012) with similar targets of T_{core} as investigated by Gaoua et al. (2011).

Due to volitional fatigue, only 13 and 12 participants were able to reach Cog 4 in the 30°C and 35°C conditions, respectively. To mitigate the potential for dehydration, participants were given 5 $mL{\cdot}kg^{-1}$ (Selkirk & McLellan 2004) of warm water (37°C) before PRE and following Cog 2, 3, 4, and active cooling recovery to avoid influencing measurements with the radio-pill. This specific hydration protocol was utilized to eliminate the confounding impact that dehydration has on cognitive performance in order to understand the effects of increasing T_{core} on cognitive function. Upon completion of REC, participants removed their PPC within 5-min and toweled off any remaining sweat to determine final nude mass.

Cognitive function was assessed using the CANTAB battery (Cambridge Cognition, Cambridge, UK), specifically (i) visual episodic memory, PAL (paired associates learning), ii) processing and psychomotor speed, RTI (reaction time), (iii) visuospatial working memory, SSP (spatial span), iv) working memory and strategy, SWM (spatial working memory), and v) sustained attention, RVP (rapid visual information processing). These cognitive tests represent the nature of the cognitive demands of firefighting including spatial awareness, attention, integrating new information (working memory), and rapidly processing information. During exercise (Cog 1, 2, 3, 4) only PAL and SSP were assessed, whereas before (PRE) and after exercise (POST and REC) the complete CANTAB battery was performed. A more comprehensive description of each cognitive assessment can be found in Bourke et al. (2012) and Rayson et al. (2005).

Statistical analysis was conducted using IBM SPSS Statistics for Windows (Version 23.0, IBM Corp., Armonk, NY). There was no main effect of time of day on the performance of cognitive function. As a result, all participants were grouped together for subsequent analyses. Normality for each of the dependent variables was confirmed using the Shapiro-Wilks test. A one-within (cognitive trial) and one-between (condition) repeated measures ANOVA was conducted on dependent measures for RTI, SWM, RVP, and overall $\Delta T_{core.}$ Simple effects analysis using a Bonferroni correction was conducted when a significant interaction effect was found. Partial eta-squared (η^2_p) was calculated, as a measure of effect size, with values for small, medium, and large effect size set at 0.01, 0.06, and 0.14, respectively (Fritz et al. 2012). Linear mixed model (LMM) analysis was performed for PAL, SSP, and ΔT_{core} during each cognitive trial. Condition and cognitive trial were entered into the model as fixed factors, with subjects entered as a random factor for the PAL andSSPanalysis, whereas condition and time were entered as fixed factors for ΔT_{core}. The covariance structure for repeated measures was auto-regressive (AR1) with the interaction removed from the final model when nonsignificant. *A-priori* planned contrasts were analyzed compared to PRE (for SWM, RVP, RTI) or Cog 1 (for PAL, SSP) for each cognitive assessment trial and Cog 2 for all trials to determine effects of active cooling recovery.

The dynamic change in T_{core} (ΔT_{core}), the initial $T_{core,,}$ the final T_{core}, pre-nude body mass, percent change in body mass, hydration, USG, and end-point HR were each compared between conditions using paired t-tests. Statistical significance for all analyses was set at an alpha level of ≤ 0.05. Data are presented as the mean ± standard error of the mean.

Results

Data for initial and final T_{core}, ΔT_{core}, T_{core} at the start of each cognitive trial, exposure time, work duration, end-point HR, change in body mass, and fluid intake are depicted in Table

1. Final T_{core}, ΔT_{core}, exposure time, and work duration were all significantly greater in 35°C ($p \leq 0.05$). Figure 2 reveals data for ΔT_{core} (normalized to the percent of the protocol completed to account for varying exposure times between participants) over the duration of heat exposure (Figure 2A) and during the individual cognitive trials (Figure 2B). ΔT_{core} over the duration of heat exposure revealed an interaction effect (condition x cognitive trial) with simple effects revealing 35°C was elevated at 40, 50, 60, and 70% of the protocol completed ($p \leq 0.05$). Individual LMMs of ΔT_{core} at each cognitive trial revealed a main effect of condition with 35°C greater at Cog 2, 3, 4, and POST ($p \leq 0.05$). The rate of change in T_{core} during the active cooling forearm immersion was not different between the 30 °C (-2.98 $°C \cdot hr^{-1}$) and 35 °C (-3.43 $°C \cdot hr^{-1}$) conditions with average active cooling recovery times of 16.7 and 21.1-min, respectively.

Simple reaction time (Figure 3A) revealed a main effect of cognitive trial ($p \leq 0.01$; $\eta^2_p = 0.26$) with planned contrasts revealing a faster reaction time at POST ($p \leq 0.05$). SWM token search time (Figure 3B) revealed a main effect of cognitive trial ($p \leq .05$; $\eta^2_p = 0.20$). Total correct rejections (Figure 3C) for the RVP test revealed a main effect of cognitive trial ($p \leq 0.01$; $\eta^2_p = 0.34$) with planned contrasts showing increases in correct rejections at POST ($p \leq 0.001$: $\eta^2_p = 0.60$) compared to PRE. RVP latency (Figure 3D), indicating the time to respond following a correctly identified three-digit sequence, revealed a main effect of cognitive trial ($p \leq 0.001$; $\eta^2_p = 0.48$) with planned contrasts indicating a faster latency at POST ($p \leq 0.001$; $\eta^2_p = 0.53$) compared to PRE.

PAL total errors at the 8-object level, adjusted for test termination prior to this level, (Figure 3E) revealed a main effect of cognitive trial ($p \leq 0.001$) with planned contrasts indicating at Cog 3 there were significantly more errors compared to Cog 1 ($p \leq 0.01$). Planned contrasts revealed a difference between Cog 2 and REC ($p \leq 0.05$) with no difference between Cog 1 and

REC. Span length (Figure 3F) observed during the SSP test revealed a main effect of cognitive trial ($p \leq 0.01$) with planned contrasts indicating a significantly shorter length achieved at Cog 3 and Cog 4 ($p \leq 0.05$) compared to Cog 1. All other cognitive variables revealed no main effects.

Discussion

This study found impairments in visuospatial working memory, visual episodic memory, and executive function once a core temperature of 38.5°C was attained at two different rates of increasing T_{core} (0.85 and 1.40 $°C \cdot hr^{-1}$), with accompanying elevations in HR.. The implementation of an active cooling recovery restored cognitive function to initial levels. Previous work has utilized time as the independent variable, which results in varying T_{core} between individuals performing the cognitive assessments (Caldwell et al. 2012; Morley et al. 2012; Radakovic et al. 2007). The use of T_{core} as the independent variable in the current study is a unique methodological approach along with conducting cognitive assessments during physical activity, which is indicative of the situation firefighters are required to perform cognitive tasks during an emergency scenario. Firefighters performing moderate-intensity activities at an emergency scene in a hot, humid environment will be challenged with increased metabolic rate, impaired thermoregulation due to PPC, as well as elevated T_{sk} and HR. The current data reveal that reaching a core temperature of 38.5°C may impair aspects of cognitive function.

One explanation for the impairments observed in cognitive function is the Global Workplace Theory (GWT) suggested by Baars (Baars 2005). The GWT suggests that the cognitive capacity of humans is limited by the various external stimuli constantly competing for the limited conscious processes available to successfully execute the proper outcome of a task [16].

Similarly, the inclusion of a motor task (i.e. treadmill walking in the current study) during the SSP and PAL tests resulted in a motor plus cognitive task. Dietrich [17] proposed the transient hypofrontality theory, stating that dynamic movements of the body require an increase in brain activation, which appears to specifically affect the prefrontal cortex by reallocating neural resources to perform cognitive tasks. Previous studies have shown that the Corsi Block Test, analogous to the SSP test, generates significant activation in the ventro-lateral prefrontal cortex [18] as well as a neural network encompassing the visual occipital, posterior parietal, and dorsolateral prefrontal cortices [19], including the hippocampus during encoding of spatial locations [20]. The potential reallocation of neural resources from the prefrontal cortex may provide an explanation for the impaired performance in the SSP test.

In addition, the PAL test has been shown to elicit increased activity in the hippocampus (during encoding of a newly shown object) and parahippocampal gyrus (during retrieval of the location of the object) with increasing task complexity [21]. Previous research has found that exercise and hyperthermia resulted in reduced middle cerebral blood flow (Nybo & Nielsen 2001) with regional decreases in the hippocampus and prefrontal cortex (Qian et al. 2014). However, subsequent research showed that the reduction in global cerebral blood flow (gCBF) during exercise, producing an absolute increase in T_{core} of 1.6°C, resulted in a 7% increase in cerebral oxygen uptake, likely attributed to a Q_{10} effect of higher tissue temperature (Nybo et al. 2002). In addition, Qian et al. (2014) found regional blood flow decreases in the hippocampus and prefrontal cortex following passive heat stress in 50°C. The current findings suggest the increase in cognitive resources required to perform the SSP and PAL tests at a T_{core} of 38.5°C combined with exercise resulted in the impaired cognition.

Active cooling recovery to a T_{core} of 37.8°C resulted in restoration of visuospatial memory and visual episodic memory to initial levels. Previous work has reported decrements in memory recall 60 and 120-min following treadmill exercise at 33-35°C (Morley et al. 2012) as well as impairments impairments have been reported in working memory 20-min following a 60-min live fire simulation (Robinson et al. 2013). However, Morley et al. (2012) implemented a passive cooling recovery without PPC but with the administration of water every 5-min for 20-min prior to the post heat stress cognitive assessments. The latter study conducted by Robinson et al. (2013) did not report they specific recovery procedure or whether the participants wore their PPC during the post-simulation cognitive assessment. The result in the current study different from Robinson et al. (2013) and Morley et al. (2012) in that no impairments were observed in any aspect of cognition assessed immediately following the EIHS protocol or after active cooling recovery. This suggests that active cooling recovery with forearm immersion may be capable of restoring certain aspects of cognitive function that do not return to pre-exercise levels with passive recovery. Without proper rehabilitation, cognitive impairments following an emergency scenario can put firefighters in increased danger upon performing additional duties, re-exposure at the scene, or emergency calls later in their shift. The data from the current study reveal the importance of an active cooling recovery protocol not only to reduce physiological strain but also improve cognitive function to perform duties within the same work shift.

The direction of T_{core} declined during the POST and REC cognitive assessments. Allan & Gibson (1979) have shown that the direction of T_{core} may have a substantial impact on cognitive function, with greater impairments observed when T_{core} is rising compared to falling between a T_{core} of 37.9 and 38.5°C. In their study, the cognitive task implemented took 60s to complete, and, although not specifically stated by the authors, T_{core} may have been falling up to 0.3°C during each assessment, similar to the changes in the current study. A recent study by Walker et al. (2015) reported no changes in certain aspects of cognitive function (processing speed, visual attention, and working memory) following consecutive 20-min live fire simulations separated by a 10-min passive recovery period. However, the observations by Walker et al. (2015) differ from the current study possibly due to cognitive function being assessed following the second simulation, outside of the hot environment, where T_{core} was not reported throughout the duration of the cognitive assessment and may not have continued to rise. In addition, Hancock (1986) has also suggested that achieving heat balance, separate from the degree of T_{core} increases, can result in restoration of cognitive function. In contrast, similar to previous findings, simple reaction time (Smith & Petruzzello 1998) and latency reaction time on the RVP (Schlader et al. 2015) test were faster immediately post-heat stress and then returned to initial levels following active cooling recovery.

The findings in this study have potential applications for Incident Commanders who are in charge of strategic and tactical planning while at an emergency scenario. Based on the "Incident Commander's Guide" developed by McLellan and Selkirk (McLellan & Selkirk 2006), firefighters performing moderate-intensity work (such as primary search, overhaul, ladder setup, and vehicle extrication) at 35°C and 50% humidity would attain a T_{core} of 38.5°C in 53-min. Firefighters in the current study required 58.2 ± 4.5-min to reach a T_{core} of 38.5°C. These findings suggest that aspects of cognitive function are impaired after performing specific job tasks in this condition for approximately 50 to 60-min. With this knowledge, Incident Commanders will be able to move firefighters to an active cooling recovery station before sending them back into the emergency scenario. Furthermore, this is the first study to show that cognitive function appears to be restored to initial levels after an active cooling recovery following EIHS in firefighters, emphasizing the need for active cooling recovery during firefighting job tasks in hot environmental conditions (Selkirk et al. 2004).

Conclusion

This study found that at two different rates of increasing T_{core} visuospatial working memory, visual episodic memory, and executive function, were impaired when T_{core} reached a level of 38.5°C, with continued impairments in visuospatial working memory and executive function at T_{core} of 39.0°C. These data, combined with previous findings, can be applied to any emergency scenario while working in the heat to provide the Fire Service with information regarding the length of time firefighters can perform job tasks before reaching levels that may result in impaired cognition. This study confirms the necessity of an active cooling protocol following work in the heat to not only reduce T_{core} but to simultaneously reduce the impact on cognitive function before performing further job tasks.

Acknowledgements

The authors would like to thank members of the Toronto Fire Services' including Chief William Stewart, Chief Jim Sales, Commander Andrew Kostiuk, Captain Geoff Boisseau and Acting Captain John McGill for their support and assistance with the project, and statisitcal consultant Anton Svedrovski for his help with data analyses. A special thanks to all of the firefighters who graciously participated in this research study and to all of the undergraduate and graduate research assistants.

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Figure 1 (on next page)

Illustration of the exercise-induced heat stress (EIHS) protocol in both hot, humid environmental conditions of 30 °C, 50% humidity and 35 °C, 50% humidity eliciting at rate of rise in T_{core} of 0.85 ± 0.1 $°C \cdot h^{-1}$ and 1.40 ± 0.

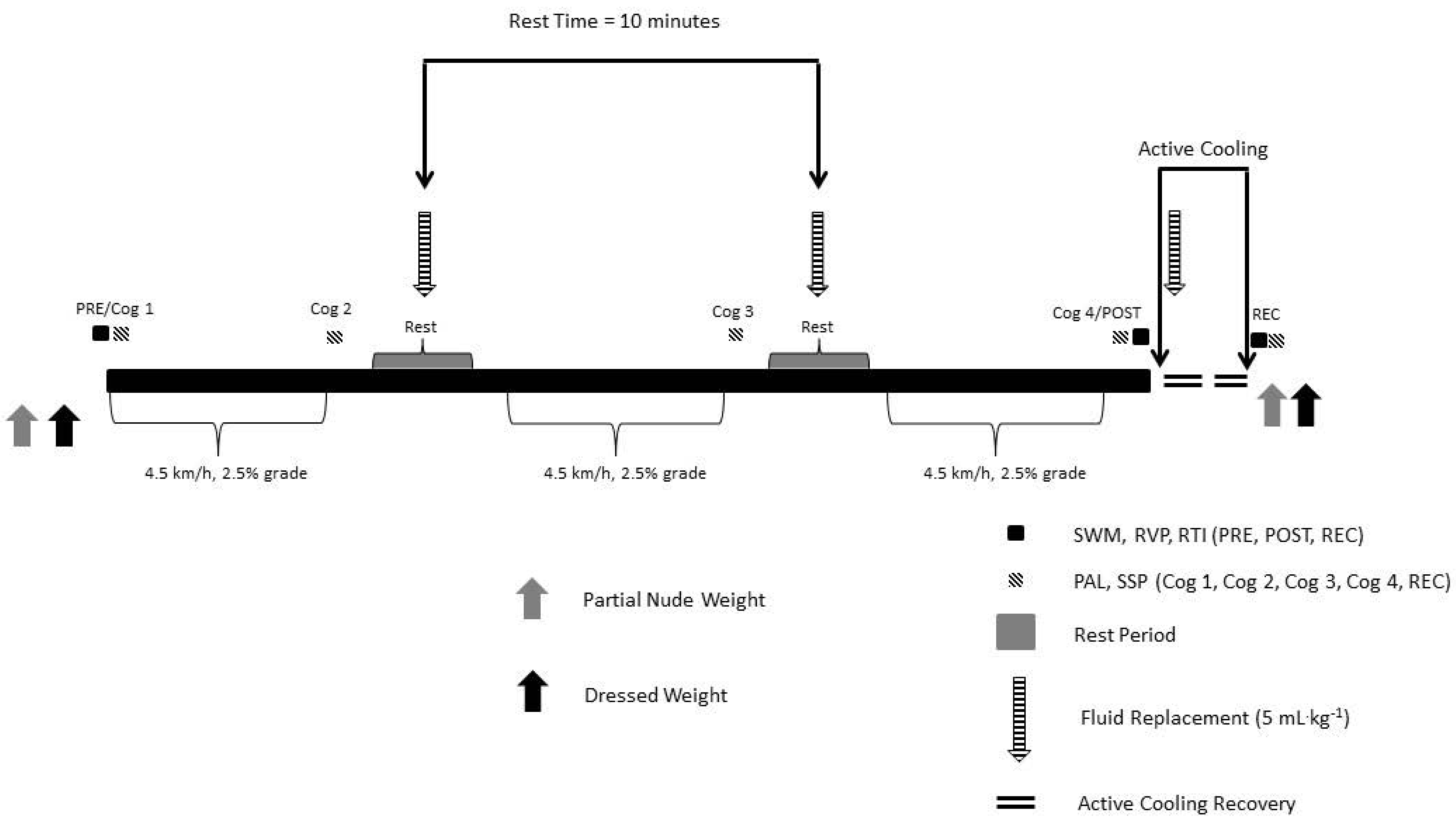
Rest Time = 10 minutes
Active Cooling
PRE/Cog 1
Cog 2
Rest
Cog 3
Rest
Cog 4/POST
REC
4.5 km/h, 2.5% grade
4.5 km/h, 2.5% grade
4.5 km/h, 2.5% grade
SWM, RVP, RTI (PRE, POST, REC)
PAL, SSP (Cog 1, Cog 2, Cog 3, Cog 4, REC)
Partial Nude Weight
Rest Period
Dressed Weight
Fluid Replacement (5 mL·kg-1)
Active Cooling Recovery

Figure 2

Physiological data for ΔT_{core} (A; normalized to percent of protocol completed) and ΔT_{core} (B) during each of the cognitive assessment trials (normalized from 0 – 100% of trial completed).

*indicates different from 30°C ($p \leq 0.05$)

**indicates main effect of condition ($p \leq 0.05$).

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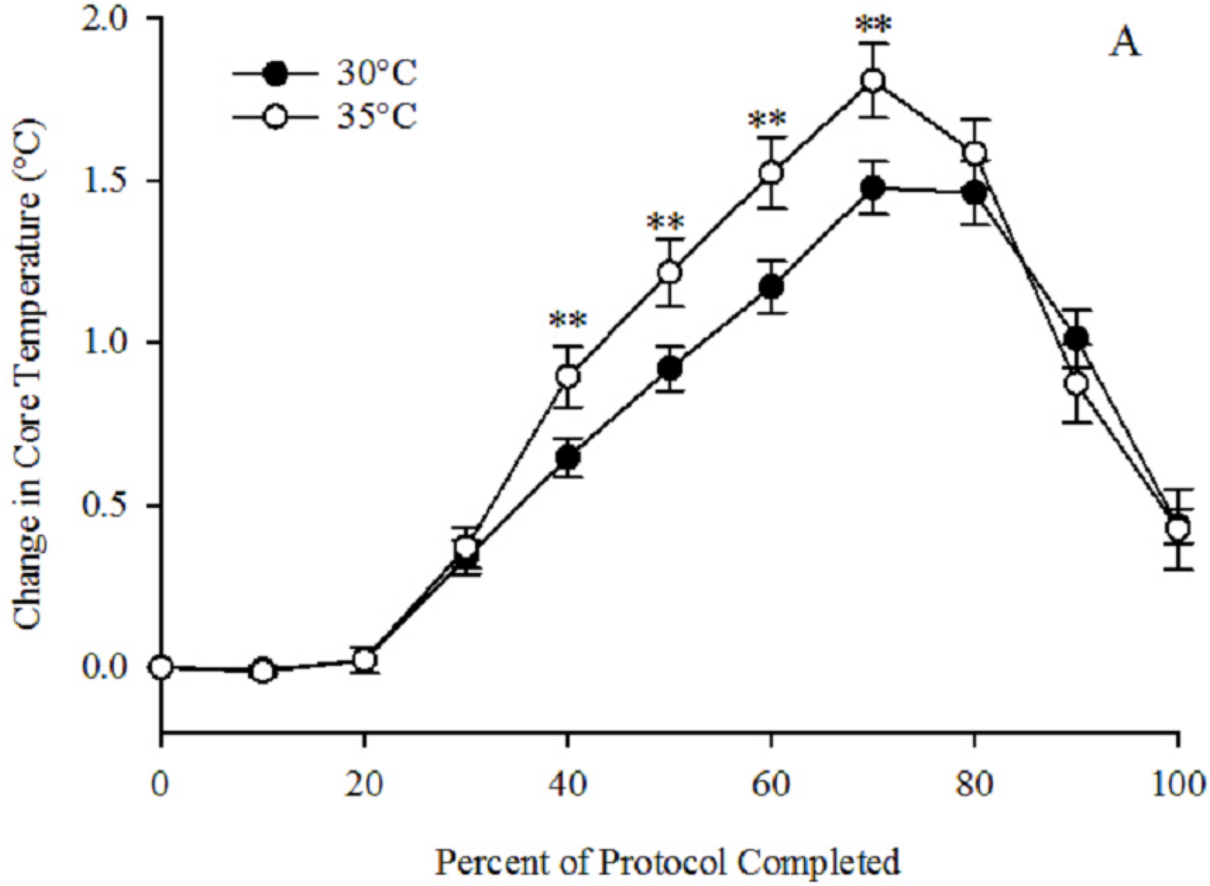

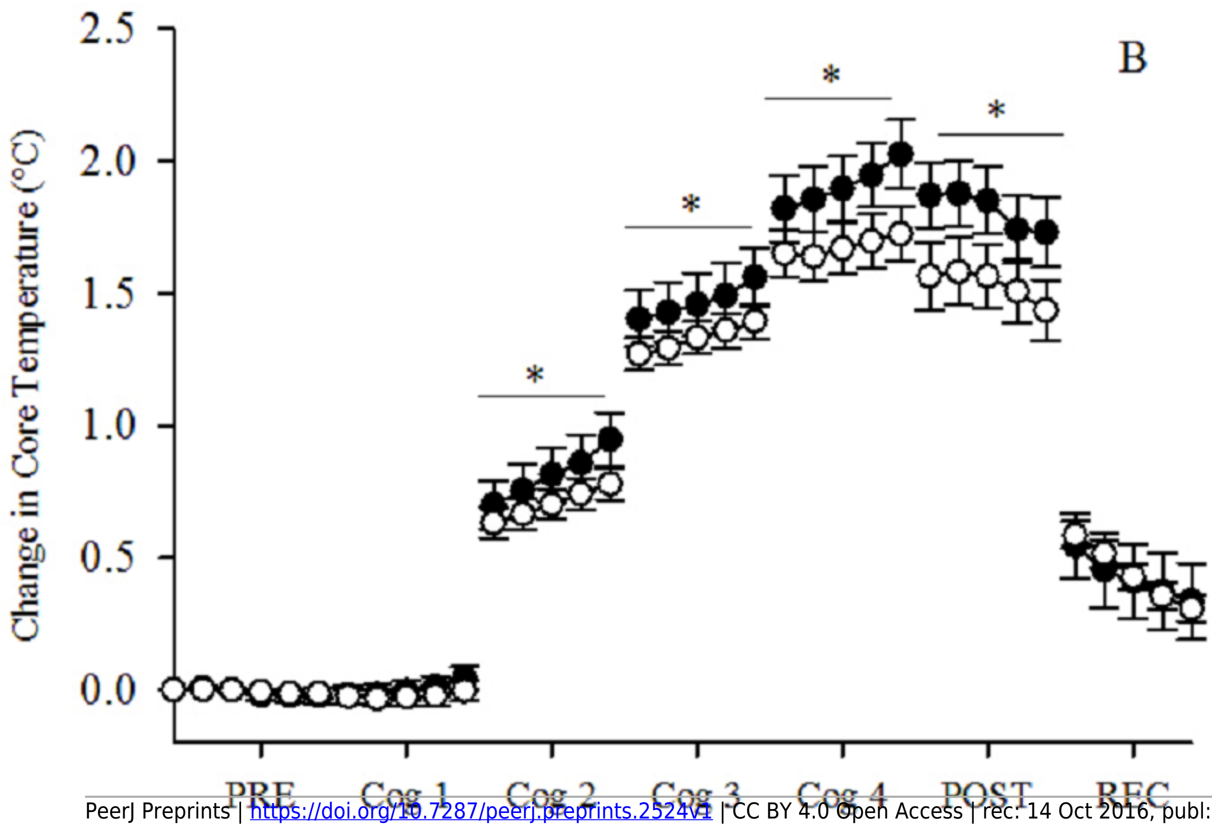

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Figure 3

Data from the simple reaction time (RTI) test (A), spatial working memory (SWM) test (B), rapid visual information processing (RVP) test (C and D), PAL test (E), and SSP test (F) for the 30°C (closed circles) and 35°C (open circles) conditions. body� �z

*indicates main effect of cognitive trial ($p \leq 0.05$) with planned contrasts revealing different from PRE or Cog 1 ($p \leq 0.05$).

¥indicates main effect of cognitive trial ($p \leq 0.05$)

**indicates planned contrasts different from Cog 2 ($p \leq 0.05$)

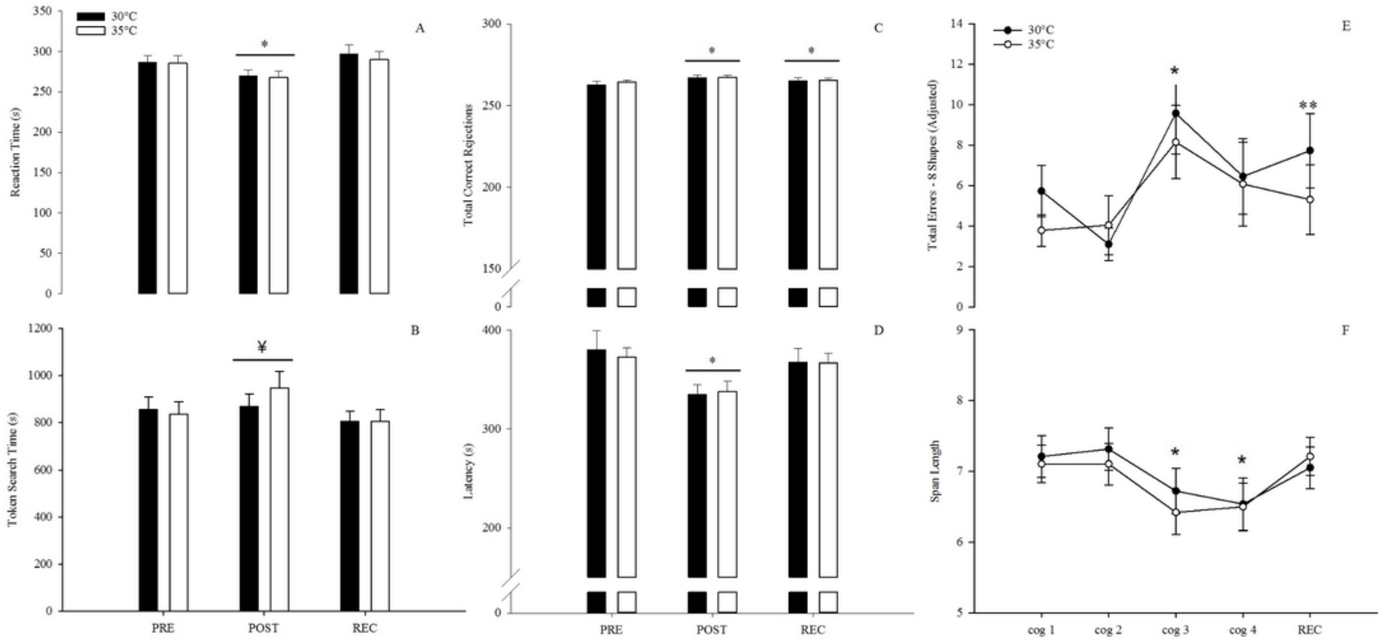

Table 1 (on next page)

Data for T_{core}, starting T_{core} at each cognitive trial, total exposure time, work duration, end-point HR, Δbody mass, and fluid intake.

[a]denotes significantly different from 30°C & 50% humidity condition ($p \leq 0.05$) T_{core} = core temperature

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Measurement	30°C & 50% Humidity	35°C & 50% Humidity
Initial T_{core} (°C)	37.2 ± 0.1	37.1 ± 0.1
Final T_{core} (°C)	38.8 ± 0.1	39.1 ± 0.1[a]
ΔT_{core} (°C·hr^{-1})	0.85 ± 0.1	1.40 ± 0.1 [a]
PRE (°C)	37.2 ± 0.1	37.2 ± 0.1
COG 1 (°C)	37.2 ± 0.1	37.1 ± 0.1
COG 2 (°C)	37.8 ± 0.01	37.8 ± 0.01
COG 3 (°C)	38.5 ± 0.02	38.5 ± 0.03
COG 4 (°C)	38.8 ± 0.1	39.0 ± 0.03
POST (°C)	38.8 ± 0.1	39.1 ± 0.1
REC (°C)	37.8 ± 0.04	37.8 ± 0.03
Exposure time (min)	122.3 ± 6.0	85.2 ± 3.8[a]
Work duration (min)	84.3 ± 3.2	62.0 ± 3.5[a]
End-point HR (bpm)	156 ± 4	163 ± 4
Δbody mass (%)	-1.1 ± 0.2	-1.1 ± 0.3
Fluid Intake (%)	94.4 ± 2.9	92.9 ± 3.9

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