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Effects of Acute Noxious Heat Exposure on The Attention Required by Tasks of Three Levels of Difficulty in Young Healthy Men

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ABSTRACT

Background: This article discusses the current knowledge on the effects of heat stress on cognitive abilities. Whole-body hyperthermia (WBH) has a negative effect on mental performance. In this study, we investigated whether short-term whole-body immersion in water at 45°C (HWI-45°C), which induces a strong neurotransmitter and temperature flux without inducing whole-body hyperthermia, would impair mental performance in humans.

Methods: Fourteen men (aged 25±6 years) were enrolled in this study and participated in three experiments: (i) a brief (5-min) immersion of the whole body in 37°C water (WI-37°C); (ii) a brief (5-min) immersion of the whole body in 45°C water (HWI-45°C); and (iii) a control trial in a thermoneutral condition at an ambient temperature of 24°C and 60% relative humidity. Before and after immersion, cognitive performance was tested. All tests were performed in a quiet and semi-darkened laboratory.

Results: Baseline simple, 2-choice and procedural reaction time and percentage of correct answers did not differ significantly across all trials. 2-choice reaction time was reduced (i.e. faster reaction) only after immersion to 37°C water. Interestingly, only whole-body immersion to 45°C was a sufficient trigger to reduce procedural reaction time.

Conclusion: young healthy men do not deteriorate in response to whole-body hot water immersion for a short duration. By contrast, we here show faster reaction time in procedural reaction task, which was the most difficult of the three to perform.

Keywords: Heat stress, hot water immersion, cognitive performance.

INTRODUCTION

The physiological responses of the human body to heat are well understood, modelled, and documented. However, despite a growing body of experimental studies in this area, the effects of heat stress on human cognitive abilities are less well understood (Hancock et al., 2003). Better understanding of cognitive functioning (behaviour) in response to high environmental and body temperature is of critical importance for people's occupational and recreational safety, health, and well-being. Although most studies have reported cognitive performance decrement in heat, several studies have reported no effects of heat stress on mental performance (Bell et al., 1964; Chiles et al., 1958; Nunneley et al., 1979), or even performance improvement upon initial exposure to heat (Colquhoun et al., 1972; Lovingood et al., 1967; Poulton et al., 1965). Task complexity and thermal state appears to be the primary factor (Hancock et al., 2003).

Heat affects cognitive performance differently, based on the type of cognitive task. Analyses of thermal stress on cognitive performance have made a clear distinction based on the type of task, with less

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attention-demanding tasks being less vulnerable to heat stress effects than more attention-demanding tasks (Hancock et al., 1998; Grether et al., 1973; Hancock et al., 1982; Hancock et al., 2003). Based on these previous assumptions, in the present study, we aimed to stress attention-demanding resources by applying computer-controlled cognitive (simple, 2-choice and procedural reaction) tests of three different difficulty levels (Reeves et al., 2010) and to investigate whether acute noxious heat stress would be a sufficient trigger to affect the response time and accuracy of an individual.

Evidence indicates that exposure to acute noxious heat (i.e. whole-body immersion in 45°C (vs. ≤41°C) for 5 min) evokes an acute cardiorespiratory shock response, and was an effective trigger in evoking neuromuscular excitability including accelerated electrophysiological motor drive transmission and muscle contractility properties (made it faster) (Eimantas et al., 2022). However, it is unknown whether short-duration (5-min) whole-body immersion in noxious 45°C water, which produces a strong neural and temperature flux without inducing the whole-body hyperthermia, would deteriorate cognitive performance. Therefore, in the present study, we hypothesise that exposure to noxious heat would accelerate neural drive along with faster reaction time to a simple target and that reaction time and accuracy will be compromised by the task difficulty.

MATERIALS AND METHODS

Participants

Eighteen male volunteers were assessed for eligibility. Participants were excluded if they smoked or had Raynaud's syndrome, asthma, a neurological pathology, or another condition that could be worsened by acute exposure to hot (45°C) water. The inclusion criteria were as follows: (i) aged 20–30 years; (ii) no excessive regular sport activities (i.e. <3 times per week and <150 min of moderate intensity or <75 min of vigorous intensity activity per week); (iii) no involvement in any temperature-manipulation programme or extreme temperature exposure for 3 months; (iv) no medications or dietary supplements that could affect experimental variables; (v) regular sleep schedule (7–9h of sleep per night). Fourteen men met the inclusion criteria and agreed to participate in this study. The physical characteristics of the participants are presented in Table 1. Written informed consent was obtained from all participants after explanation of all details of the experimental procedures and the associated discomforts and risks. All procedures were approved by the Human Research Ethics Committee (No. BE-2-30) and were conducted according to the guidelines of the Declaration of Helsinki. The participants were in self-reported good health, which was confirmed by a medical history and physical examination.

Table 1. **Physical characteristics of the participants in the study**

Number of participants	14
Age, yr	24 ± 5
Height, cm	186.29 ± 6.09
Mass, kg	87.48 ± 6.98
Body mass index, kg m^{-2}	24.98 ± 2.05
Body fat, %	18.03 ± 4.51
Mean skinfold thickness, mm	11.15 ± 4.97
Body surface area, m^2	2.11 ± 0.58

Values are expressed as the mean ± standard deviation.

Familiarisation trial

The subjects were familiarised with the procedures over 3 days. One week before the experiment, participants were introduced to the experimental procedures and cognitive testing and informed of the known risks of the study. On each day, the subjects performed the cognitive test battery. Participants attended the laboratory at the same time of day within the time frame of 8:00–10:00 a.m. to avoid circadian fluctuations in body temperature. They were instructed to sleep for a minimum 7–8h on the night before the experiment; to refrain from alcohol, heavy exercise, and caffeine for at least 24h; and to refrain from consuming any food for at least 12h before arrival at the laboratory. To standardise the morning state of hydration, subjects were allowed to drink still water as desired until 60min before the experiment. The study was performed at a room temperature of 24°C and 60% relative humidity.

Experimental protocol

The study consisted of experiments with (i) a brief (5min) immersion of whole body in 37°C water (WI-37°C trial); (ii) a brief (5-min) immersion of whole body in hot 45°C water (HWI-45°C trial); and (iii) a brief (5min) control trial (CON) in an empty bath in thermoneutral conditions at an ambient temperature of 24°C and 60% relative humidity (CON). These trials were performed in a balanced random order (cross-over design) at least 1 week apart.

On arrival, each subject was weighed unclothed. The participants donned swimming briefs covering the genitals and buttocks (7% of body surface area (BSA) (Heerfordt et al., 2017) and self-inserted a rectal probe, after which the strap used for recording heart rate was attached to the chest. The participant was then asked to lie in a semi-recumbent position for 20min at an ambient temperature of 24°C and 60% relative humidity. Baseline pre-immersion values of rectal (T_{re}) and skin (T_{sk}) temperatures were then measured. Within ~3 min after these resting measurements, the participant was seated at a table and performed the cognitive testing. Upon completion of the cognitive test battery, the CON, WI, or HWI procedure began. The participant was fully immersed within a period of 5s in a semi recumbent position up to the level of the manubrium in a 37°C (WI-37°C trial), 45°C (HWI-45°C trial) stirred water bath or underwent CON trial in an empty towel-covered bath under thermoneutral conditions. Within ~1 min after leaving the bath, the volunteer was towel dried and body temperatures were measured. After the end of the immersion procedure, cognitive testing was performed in the same order as before the procedure.

EXPERIMENTAL MEASUREMENTS

Anthropometric measurements

Body mass and body fat were measured using a body composition analyser (TBF-300, Tanita, Arlington Heights, IL, USA) and the body mass index was calculated. BSA was estimated according to the formula: BSA = 128.1 × weight$^{0.44}$ × height$^{0.60}$ (Tikuisis et al., 2001). Skinfold thickness was calculated as the average thickness of 10 skinfold sites (chin, subscapular, chest, side, suprailium, abdomen, triceps, thigh, knee, and calf) (McArdle et al., 1984) using a medical skinfold caliper (SH5020, Saehan, Masan, South Korea).

Body temperature and heart rate measurement

Rectal temperature (T_{re}) was measured before and immediately (within 1 min of leaving the bath) after CON, WI-37°C, and HWI-45°C trials. T_{re} was measured using a thermocouple (Rectal Probe, Ellab, Hvidovre, Denmark) inserted to a depth of 12cm past the anus (Brazaitis et al., 2019). The rectal thermistor sensor was placed by each participant.

Skin temperature (T_{sk}) was measured with thermistors (accuracy, ± 0.01°C, Skin/Surface Probe, DM852, Ellab) at three sites: midline of the anterior surface of the right scapula (back), anterior surface of the right thigh (thigh), and midline of the posterior surface of the right forearm (forearm). The mean Tsk was calculated using the equation $T_{sk} = 0.5_{back} + 0.36_{thigh} + 0.14_{forearm}$ (Burton, 1935).

Heart rate was measured before and throughout CON, WI-37°C, and HWI-45°C trials using a heart rate monitor (V800, Polar Electro OY, Kempele, Finland).

Cognitive performance

To assess cognitive performance, the Automated Neuropsychological Assessment Metric (ANAM4, Norman, OK, USA) was administered (Reeves et al., 2010). A programmed cognitive test battery was used to assess changes in simple reaction, 2-choice reaction and procedural reaction times after the different immersion procedures. All tasks were computer-controlled, and the information was presented on the screen of a laptop (Samsung R538). All tests were performed in a quiet and semi-darkened laboratory with a laptop screen 40cm in front of the participant. The participant was introduced to the test battery during the familiarisation before the experiments began. The duration of the cognitive test battery was 3.0 ± 0.5 min and included the following tasks, which were randomised between experimental trials.

Simple reaction time test

This task measures simple visuomotor mental flexibility (Mäkinen et al., 2006; Kadota and Gomi, 2010). The test presents a simple stimulus with a symbol of "*" on the screen. The participant is instructed to press a specified response key as quickly as possible each time the stimulus is present. The accuracy for this task was 100% for all participants (Figure 1).

2-choice reaction time test

This task measures processing speed (Tzambazis and Stough, 2000) and alternating attention with a motor speed component (Kubicki et al., 2012). This test presents the user with a 2-choice symbol "*" or "o" on the display. The user is instructed to respond as quickly as possible by pressing the designated button for each stimulus as soon as the stimulus appears. The accuracy and the response time was taken for analyses.

Procedural reaction time test

This test measures information processing speed, visuomotor reaction time, and attention (Churchill et al., 2016). A number (2, 3, 4, or 5) is presented on the display using a large dot matrix. The user is instructed to press 1 designated button for a "low" number (2 or 3) and another designated button for a "high" number (4 or 5). The accuracy and the response time was taken for analyses.

Statistical analysis

A dependent-sample *t* test was used to locate differences in time and condition. Significance was defined as $p<0.05$. Descriptive data are presented as mean ± standard deviation (SD). Statistical analyses were performed using IBM SPSS Statistics (v. 22; IBM Corp., Armonk, NY, United States).

RESULTS

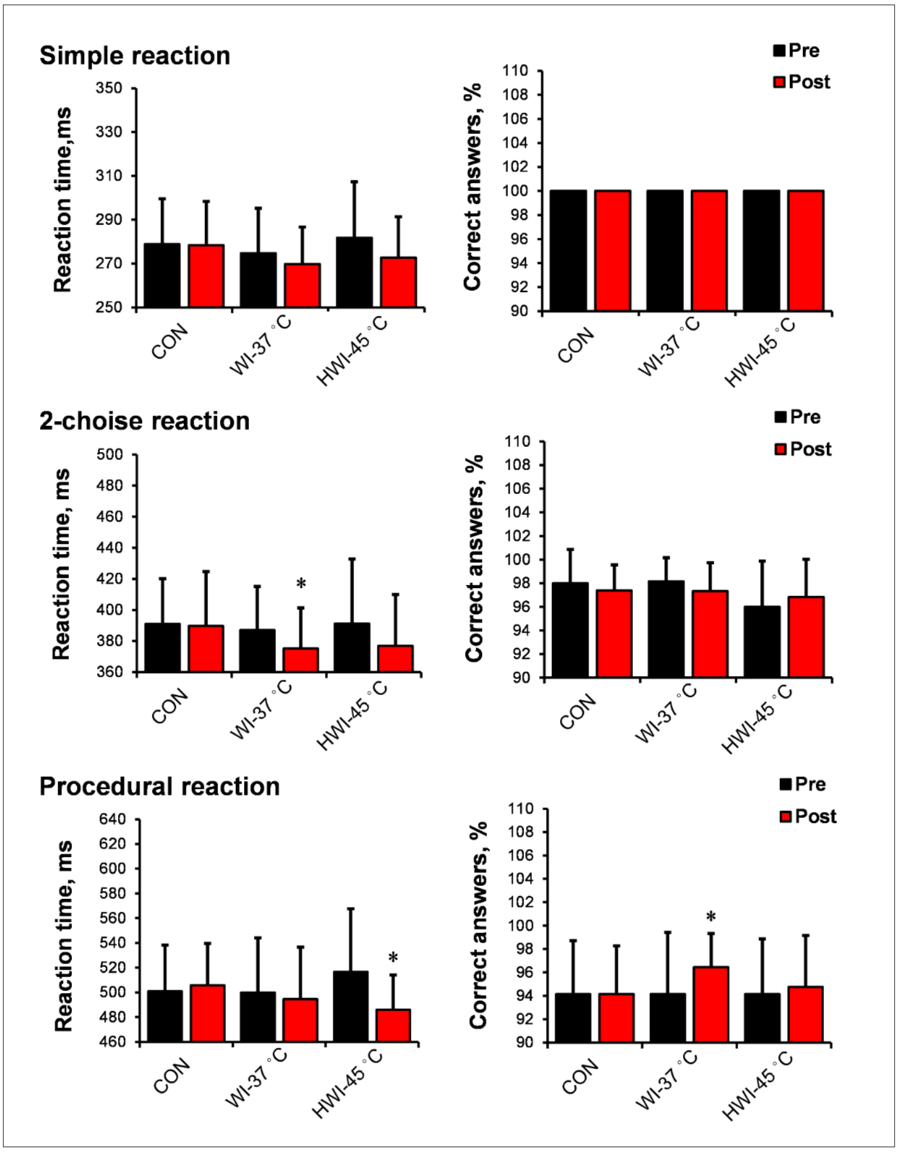
Body temperature and heart rate response

Baseline T_{re}, T_{sk} and heart rate were similar across all trials (trial effect, p>0.05). Both parameters remained unchanged throughout the experimental period in the CON condition (time effect, p>0.05). By contrast, body T_{re} increased (0.22 ± 0.06°C) only in HWI-45°C condition (time effect, p<0.05), and the body T_{sk} increase in both WI-37°C and HWI-45°C conditions (2.4 ± 0.4 and 7.3 ± 0.6°C), respectively. T_{sk} was significantly greater in HWI-45°C than in WI-37°C (condition effect, p<0.05). Like T_{re}, heart rate increased from before to after immersion (31.2 ± 3.6 bpm) only in HWI-45°C (time effect, p<0.05).

Simple, 2-choice and procedural reaction test

Baseline simple, 2-choice and procedural reaction time and percentage of correct answers did not differ significantly across all trials (trial effect, *p*>0.05) (Figure 1). We observed no change in simple reaction time from before to after transition to empty bath procedure across all trials (time effect, *p*>0.05). 2-choice reaction time was reduced (i.e. faster reaction) only after immersion to 37°C

Figure 1. **Changes in simple, 2-choice, and procedural reaction times, and percentage of correct answers before (pre) and after (post) the bath procedure in the control trial, and trails with 5-min whole-body immersion in warm (WI-37°C) and hot (HWI-45°C) water, respectively. Values are means ± SD. * P<0.05 compared to pre value**



water (time effect, $p<0.05$), and thus, this result was determined without the expense of correct answers. Interestingly, only whole-body immersion to 45°C was a sufficient trigger to reduce procedural reaction time (time effect, $p<0.05$) without the expense of correct answers (time effect, $p>0.05$). By contrast, WI-37°C reduced the percentage of incorrect answers (time effect, $p<0.05$) with no change in reaction time (time effect, $p>0.05$).

DISCUSSION

In the present study, we investigated for the first time the effects of acute short-duration whole-body immersion (for 5 min) in noxious hot water (45°C) on attention. As expected, we here show that thermophysiological strain was greater after HWI-45°C than after WI-37°C or CON condition. The unique findings of our study are that short-duration immersion in noxious hot water did not induce a greater cognitively operated attention deterioration at all three (difficulty) performed tasks. On the contrary, the subjects were able to show improvement in reaction time (faster response) while performing the procedural reaction task, which was the most difficult of the three to perform. Moreover, we show that not only HWI-45°C but and WI-37°C were sufficient to shorter reaction time in the 2-choice test and reduce the percentage of incorrect answers in procedural reaction test. Finally, the results of the simple reaction test were not affected by any of the temperature conditions.

Evidence indicates that the sudden application of external noxious hot (>42°C) stimuli to the body skin surface triggers high-temperature-sensitive receptors by causing a rapid volley of impulses in cutaneous nerve endings and by sensitising the preoptic area and insula to increase arousal and alertness as part of the thermoregulatory and sensation responses (Patapoutian et al., 2003; Tóth et al., 2014; Hoffstaetter et al., 2018). Such a stressful event is believed to affect cognitive function strongly. However, by contrast to our expectation, in the present study we found enhanced attention in response to HWI-45°C. This effect may be partly explained by arousal theory (Griffiths et al., 1971; Wilkinson et al., 1964). The latter theory postulates an inverted-U relationship between human performance and the arousal level of the performer. Many investigators have assumed the inverted-U relationship, and attempted to associate the level of arousal with the intensity of the environmental thermal load (Poulton et al., 1965). They suggested that as the body T_{re} rises, the arousal level of the performer increases, which in turn causes performance to improve. At some critical point of T_{re}, no further improvement is possible and performance decreases with increasing heat and arousal (Hancock et al., 2003). Interestingly, in addition to thermal-dose relationship, Provins encompassed the dimension of task complexity as one of the arousal determinants, and thus, more arousing tasks (e.g. dual tasks) present performance decrements at lower temperatures than less arousing tasks (e.g. simple mental tasks) (Provins et al., 1966).

Taken together, these studies suggest that, in our study, the increase in T_{re} were far from the moderate whole-body hyperthermia needed to affect central structure and deteriorate attention function. Moreover, experimental evidence indicates that long exposures rather than short duration exposure to heat are expected to cause cognitive performance decrement. In agreement with our results, previous reports have shown that short exposures of up to 18min have been associated with improved dual-task performance (Poulton et al., 1965).

Another factor which might be also considered to effect response time to the target is conduction velocity of nerves, which increases as the body temperature increases (Paulauskas et al., 2020). Indeed, physiologically, the conduction velocity of nerves decreases or increases at a speed rate of 1.1–2.4 m/s/°C (Henriksen 1956; Gasser et al., 1964; Abramson et al. 1966; Halar et al. 1983; Denys 1991). Considering that in our study there was no significant change in simple (task) reaction time in response to any of three temperature conditions, this means non-sufficient body temperature change to effect nervous impulse transition needed to response to task target.

In conclusion, the attention of young healthy men does not deteriorate in response to whole-body hot water immersion for a short duration. By contrast, we here show faster reaction time in the procedural reaction task, which was the most difficult of the three to perform.

Declaration of Interest

The authors report no conflicts of interest.

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