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Effects of heat strain on cognitive function among a sample of miners

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Abstract

Heat stress is associated with workplace injuries, likely through a combination of fatigue, reduced cognitive function, and thermal discomfort. The purpose of this study was to evaluate four cognitive tasks for sensitivity to heat stress. Eight participants performed treadmill exercise followed by assessments of serial reaction time (RT), Stroop effect, verbal delayed memory, and continuous performance working memory in an environmental chamber. A control (21.1 °C) trial, and “Hot 1” and “Hot 2” (both 37.8 °C) trials were run sequentially on two separate days to evaluate the four cognitive tasks. Heat strain (comparing Hot 1 and Hot 2 with the control trial) resulted in impairments in the serial RT test response and Stroop accuracy. Delayed memory was impacted only in the Hot 2 trial compared with the control trial. Given the demonstrated impact of heat on cognitive processes relevant to workers’ real-world functioning in the workplace, understanding how to assess and monitor vigilant attention in the workplace is essential.

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Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Keywords

Heat stress; Cognitive

1. Introduction

Heat stress can have an adverse impact on the health, safety, and performance of workers. The incidence and severity of work-related heat stress are likely to increase over time, with average and extreme temperatures increasing in many parts of the world (National Oceanic and Atmospheric Administration, NOAA, 2020). One negative effect of heat stress on the labor force is reduced work production. Dunne et al. (2013) estimated that over the past decades, heat stress reduced labor capacity to 90% during the hottest months; further reductions in labor capacity during peak months are expected by 2050. Additionally, risks to worker health and safety are predicted to increase as the effects of heat stress worsen (Levy and Roelofs, 2019).

In multiple studies across different occupations and industries, researchers have found associations between occupational injuries and heat exposure (Xiang et al., 2014; Tawatsupa et al., 2013; Fogleman et al., 2005; Knapik et al., 2002; Barreto et al., 1997; Ramsey et al., 1983). Further, researchers have observed increases in injuries leading to workers' compensation claims during hot weather. For example, Sheng et al. (2018) found that a 1 °C increase in ambient temperature was associated with a 1.4% increase in daily injury claims. Similarly, Varghese et al. (2019) demonstrated significantly higher workers' compensation claims during low and moderately severe heat waves. Although the underlying mechanism between heat exposure and injury is not precisely known, it likely involves a combination of fatigue, reduced cognitive and psychomotor function, and thermal discomfort (Varghese et al., 2018). One of the potential cognitive effects of heat exposure is declining attention, which is thought to affect task performance and result in unsafe work behaviors (Varghese et al., 2018). Declining worker attention could lead to slowed and inaccurate responses and have an immediate impact on worker safety. A better understanding of heat-related cognitive dysfunction is needed to decrease injury rates associated with heat exposure.

Although multiple studies have found links between cognitive performance and heat exposure, the findings are inconsistent. Many studies have reported decreases in cognitive function related to heat exposure, but other studies have reported either no effects or even improvements in cognitive performance with heat stress (MacLeod et al., 2018; Schlader et al., 2015; Lee et al., 2014a; Ely et al., 2013; Caldwell et al., 2012; Hancock et al., 2007; Hancock and Vasmatzidis, 2003).

Most heat stress studies were laboratory-based (Hancock and Vasmatzidis, 2003), but some studies evaluated workers on-site, with both types of studies demonstrating mixed results. Some workplace studies found that heat-exposed workers performed significantly worse on cognitive tests (Kumar et al., 1991; Lan et al., 2011; Mazloumi et al., 2014), whereas others did not find an effect of heat on cognitive function (Spector et al., 2018). Comparisons between studies are limited by several factors, including differences in tests used, cognitive domains assessed, conditions at the time of testing, and use of control measures. Furthermore, no systematic approach to assessing the cognitive effects of heat stress was used (Hancock and Vasmatzidis, 2003).

The correlations between cognitive dysfunction, heat stress, and work-related injuries support the need for systematic methods to identify heat-related cognitive changes among workers. Evaluating cognitive changes among workers could help to identify recommended limits for heat stress exposure in occupational settings (Hancock and Vasmatzidis, 2003). Tests that are feasible for use in the field are needed for future studies of work-related heat stress and in-person evaluations of workers. These tests should be brief, available on portable platforms, and require minimal training to administer. Field-ready tests could potentially detect performance impairments related to heat stress so adverse outcomes can be prevented. The purpose of this pilot study was to evaluate four cognitive tests, each testing specific abilities that could harm the safety of workers if these abilities were impacted by heat stress; to determine each test's effectiveness in identifying heat-related cognitive changes; and to determine each test's feasibility for use among workers in preparation for future field- and laboratory-based studies.

2. Materials and methods

2.1. Participants

Eight participants were recruited from a mine rescue team. These workers were chosen because they often train in hot, humid conditions. Similar to workers in other industries, mine rescue workers' heat acclimatization status can vary. To prepare for disasters requiring mine rescue, they take intermittent training in addition to their full-time responsibilities as miners. Although training activities expose these team members to heat stress, many of their day-to-day work tasks are not conducted in the heat and thus, team members are not always acclimatized to the heat.

All participants were required to be < 45 years of age and have no underlying chronic health issues. On the initial visit of the study, participants signed a written consent form and completed cardiovascular disease (CVD) risk stratification and an internally designed health questionnaire that was reviewed by an occupational health physician. The health questionnaire (NIOSH, 2016) was used to evaluate each participant's risk for heat illness and to exclude persons with chronic diseases or musculoskeletal conditions that could threaten participant safety. Persons with heart disease or chronic diseases that increased risk for heart disease were excluded to decrease the risk of an adverse cardiovascular incident during the treadmill activity. Similarly, persons with lower extremity musculoskeletal disorders were excluded to minimize the risk of exacerbation while walking on the treadmill. CVD risk stratification included measurement of automated resting blood pressure and heart rate (HEM-907XL, Omron, Kyoto, Japan), measurement of non-fasting lipids using a fingerstick blood test (Cholestech LDX, Alere Inc., Waltham, MA, USA), and for participants aged ≥40 years, entering the relevant data into the American College of Cardiology/American Heart Association CVD risk calculator (American College of Cardiology/American Heart Association, 2013). Persons with a 10-year CVD risk score of ≥7.5% or LDL >180 mg/dL were excluded. None of the participants who began the consent process were excluded through CVD risk stratification. After risk stratification, participants were oriented to the cognitive tests, and completed one practice administration of each test.

2.1.1. Study design—The study design and methods were approved by the Centers for Disease Control and Prevention (CDC) National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board. After the initial visit, participants were scheduled for two study days, each separated by at least 14 days (Fig. 1). Control, Hot 1 and Hot 2 trials were run sequentially on the first study day, and this protocol was repeated ≥14 days later on a second study day. Participants completed the full battery of tests on both study days. Participants were asked to avoid alcohol (Morley et al., 2012; Schlader et al., 2015) and products containing pseudoephedrine/phenylephrine, diphenhydramine, antihistamines, over-the-counter sleep medications, and herbal products that could affect physiologic functioning or heat tolerance (e.g., ma huang, yohimbine, ginseng, ephedra, khat, licorice root, bitter orange, and goldenseal) the day before testing (National Collaborating Centre for Environmental Health, 2010; NIH 2021).

Each morning at approximately 8 a.m., the participants swallowed ingestible temperature sensors (Equivital™, Equivital Ltd., Cambridge UK) and wore a chest bioharness. Participants then completed a brief health assessment to ensure no change in prior health status and no acute illness. Resting blood pressure and heart rate were measured. Baseline cognitive tests were completed in the office at room temperature, while participants were seated. They were asked to drink 16 ounces of water, and a urine specific gravity (USG; Atago Pocket Pal-10S, Atago USA, Inc., Bellevue WA) measurement was taken. If the USG was >1.010, they were asked to drink an additional eight ounces of water, and another USG was obtained.

Two hours after temperature capsule ingestion (Kolka et al., 1997; Ducharme et al., 2001; Byrne and Lim, 2006), participants began the first of three sequential exercise trials in an environmental chamber. The first trial was the control, in which the chamber was set at 21.1 °C and 40% relative humidity (RH). These temperature and humidity settings were based on EPA-recommended school settings for comfort indoors (EPA, 2009). The second and third trials were identical hot trials, in which the chamber was set at 37.8 °C and 80% RH. These settings were based on expert physiologist recommendations and were intended to generate elevated core body temperature. In all three sessions, participants walked on the treadmill for 20 min. The treadmill exercise included 6-min blocks, with a total of three 2-min intervals of increasing workload before returning to the initial interval at the beginning of the next 6-min block. For persons reporting that they did not exercise on a regular basis, a standard protocol was developed to ensure that a moderate range exercise (i.e., calculated metabolic equivalents [METs] = 4.7–5.78) as defined by the American College of Sports Medicine (ACSM, 2016) was not exceeded. Two options existed for these participants: a speed series with the treadmill incline set at 3.5% and speed increasing from 4.8 to 6.1 km per hour (kph) during the 6-min block, and an incline series, with the speed set at 4.8 kph and the incline increasing from 4.5 to 6.0%. Participants who exercised on a regular basis were allowed to exercise up to a MET of 7.85, with the treadmill set at an incline of 6% and the speed increasing from 5.6 to 6.9 kph during the 6-min blocks.

Because persons acclimated to exercise need higher exercise intensity to drive a similar heart rate response, different options for persons who did and did not regularly exercise were provided to achieve a sufficient heart rate threshold to drive elevations in core body temperature. Similarly, both speed and incline options were provided to ensure that persons whose heart rates respond better to one of the options had a high likelihood of a sufficient heart rate response. However, the calculated METs were similar for the speed and incline series.

Heart rate and core body temperature were monitored in real-time throughout each exercise session. Testing was stopped if participants requested to stop, reported symptoms related to heat exposure, or for persons who reported no regular exercise, if their heart rate exceeded the 76% age-adjusted maximal heart rate by 10% or greater for over 1 min. Persons who reported regular exercise were allowed to exercise to within 10% of 90% of age-adjusted maximal heart rate. The age-adjusted maximal heart rate was calculated as follows: 208 – (0.7 x age). The speed or incline was reduced by the investigator if heart rate approached the maximal heart rate that would require termination. If participants were asymptomatic but stopped exercise because of heart rate thresholds, they remained in the chamber to complete cognitive testing.

Each participant was provided water during each of the three exercise sessions and was encouraged to drink at least eight ounces during each treadmill session. The water was maintained at a tepid temperature to minimize the effect of cool water on the temperature reading of the ingested temperature capsule.

The cognitive tests included measures of serial reaction time (RT), Stroop effect, verbal delayed memory, and continuous performance working memory (N-back). The RT and N-back tests were administered by computer tablet, the Stroop effect task was presented on paper forms, and the memory task was administered verbally. The verbal memory task was completed first to minimize variability in time between presentation of to-be-remembered information and delayed recall, whereas the other three tests were administered in counter-balanced order following the memory task. At the initial visit after consent was obtained, all participants were familiarized with each of the cognitive tests. Additionally, during the 2 h after temperature capsule ingestion, while waiting to begin the trials, participants were administered each of the tests again for further familiarization. During the control session, cognitive tests were completed at the end of the 20-min treadmill exercise. During the heat-exposed second and third sessions (i.e., Hot 1 and Hot 2), cognitive tests were completed when core temperature reached 38 °C. If this threshold was reached prior to completing 20 min of treadmill exercise, the participant stopped walking and began the cognitive tests immediately. If core temperature did not reach the required threshold of 38 °C by the end of the 20-min treadmill exercise, the participant remained in the heated chamber (without continued exercise) until their temperature reached the threshold before beginning the cognitive tests. The threshold of 38 °C was chosen because the World Health Organization (WHO), American Conference of Governmental Industrial Hygienists (ACGIH), and the International Organization for Standardization (ISO) have developed standards, guidelines, or threshold limits designed to prevent core body temperatures among workers from exceeding 38 °C (World Health Organization, 1969; ACGIH, 2016; ISO, 2004). All cognitive tests were taken while seated within the chamber. Participants wore noise-reducing earmuffs.

After each exercise session, participants rested outside the chamber. Core temperature was required to decrease to at least 37.5 °C after the second session, prior to entering the chamber for the third session. Allowing core temperature to decrease permitted adequate rest time between sessions and additionally, ensured that core temperature was well under the 38 °C threshold recommended by national and international organizations such as WHO and ACGIH before beginning the final session. Each of the hot trials (e.g., second and third sessions) were identical.

Dehydration has been associated with impaired cognitive function, although studies are conflicting (Wittbrodt and Millard-Stafford, 2018; Goodman et al., 2019). Between each session, participants were encouraged to continue drinking water to prevent dehydration. USG was obtained between sessions, and if > 1.010, participants were asked to drink additional water to ensure that even if USG increased during sessions, final USG would be < 1.020 (Morley et al., 2012; Schlader et al., 2015). Weight was checked prior to the first session and at the end of the third session to assess evidence of dehydration. Participants were weighed in t-shirts and shorts.

2.2. Cognitive tests

2.2.1. 10-Min serial RT test—The 10-min serial RT test, based on the Psychomotor Vigilance Test (Inquisit Lab, Millisecond Software, LLC, Seattle, WA), was used to measure reaction time and sustained vigilance. At random intervals (i.e., inter-stimulus intervals ranging from approximately 2–10 s), a red dot appeared on the tablet screen, and participants pressed a response button as quickly as possible each time the dot appeared. Reaction time in milliseconds (ms) was recorded for each individual response (i.e., each time the red dot appeared) and averaged over responses throughout the 10-min test for an overall mean RT per session. Additionally, each response with an RT ≥500 ms was defined as a lapse. The total number of lapses during each 10-min test was calculated.

2.2.2. Stroop task—The Stroop task is among the most commonly administered measures of verbally mediated processing speed and executive functioning (Rabin et al., 2016) and generally consists of three tests: 1) naming color patches, 2) reading color words printed in black ink, and 3) naming the ink color of color words printed in incongruous colors (inhibition condition). In the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001) version of the Stroop task, called the Color Word Interference (CWI) subtest, a fourth condition requires examinees to switch between color naming and word reading of color words printed in incongruent colors. For example, participants name the ink color of color words until the color word is surrounded by a box, at which time they read the actual word instead of naming the color of the ink. For the current study, the inhibition (referred to as Stroop 1) and inhibition/switching (Stroop 2) tests from the CWI were used. D-KEFS CWI has demonstrated construct and convergent validity (Delis et al., 2004). For each Stroop test (i.e., Stroop 1 and 2), word stimuli were presented on paper forms, with one form containing the entire word collection. Alternate forms were used for each trial.

Performance was measured by number of words completed within 90 s and total number of errors (corrected and uncorrected).

2.2.3. Hopkins Verbal Learning Test-Revised—

The Hopkins Verbal Learning Test-Revised (HVLT-R; Benedict et al., 1998) was used as a measure of delayed memory. The HVLT-R has well-established psychometric properties, including demonstrated test-retest and inter-form reliability and construct and concurrent validity (Benedict et al., 1998; Shapiro et al., 1999). For administration of the HVLT-R, a list of 12 words were read aloud by an investigator four times prior to participants entering the chamber. After each learning iteration, participants recited as many words as they could remember. Following the treadmill exercise, participants were asked to recall as many words from the word list as they could remember. Alternate word lists were used at each trial (i.e., control, Hot 1, Hot 2) to reduce learning effects. The delayed recall total correct responses divided by the single highest word recall during the four learning iterations was used as the outcome measure.

2.2.4. N-back test—

The N-back test was used as a measure of continuous performance working memory (Kirchner, 1958) and has high test-retest reliability (Kulikowski and Potasz-Kulikowska, 2016; Sliwinski et al., 2018). A series of stimuli (e.g., individual letters) were presented on-screen at a fixed pace. The task required participants to decide whether each stimulus in a sequence matched the one that appeared a certain number of items ago. For example, in a 1-back task, the participant decided if each current letter was the same as the letter previously shown, whereas in a 2-back task, the participant decided if the current letter was the same as the item shown two items before. A 2-min 2-back test using letters was presented on a tablet through the Inquisit application (Millisecond Software, LLC, Seattle, WA), and participants pressed the response button each time the current letter was the same as the letter two items before. Each response was recorded as correct or incorrect, and odds of a correct response was the outcome measure.

2.3. Statistical analysis

Statistical analyses were performed using R (v4.0.3, R Foundation for Statistical Computing, Vienna Austria) for developing predictive models specific to each cognitive test. Statistical significance was set at $\alpha = 0.05$. We adjusted all models for the study day (i.e., first or second study day), session (i.e., control, Hot 1, or Hot 2), and age of the participant.

In the serial RT task, RTs were modeled with a log-logistic time to event models clustered by subject to account for repeated measures. Responses >2000 ms were censored at 2000 ms. Lapses (i.e., RTs ≥ 500 ms) were modeled with a random effects logistic mixed model to cluster observations within participants.

Two analyses were used for Stroop 1 and Stroop 2, with the first used to estimate response speed and the second to estimate accuracy of responses. A Poisson mixed model was used to estimate the total number of words completed within the time period (i.e., response speed). A logistic regression model with random intercept to cluster measurements within subjects was used to model the proportion of correct answers. Analyses were conducted with self-corrections counted as incorrect.

For HVLT-R, a logistic regression model was used to estimate the proportion of correctly recalled words after the delay in comparison with the maximum number of words recalled during the initial four readings. In addition to study day, session, and age, the model also adjusted for the number of minutes in the delay because some participants did not reach the temperature threshold directly after their 20-min exercise sessions.

The probability of a correct response for the N-back was modeled using a random intercept mixed logistic regression model to cluster measurements within subjects.

3. Results

Eight males with an average age of 32.8 years (range 20–40) participated in the study. Of these, three (38%) had body mass indices in the obese range (BMI ≥30). Participants lost an average of 0.4% of their body weight during study days, with only two participants losing >2% of body weight on one of the two study days. Average USG was 1.006 before exercise sessions and 1.009 after exercise sessions.

We assessed cognitive results from control, Hot 1, and Hot 2 trials on each of two study days for eight study participants, for a total of 16 session days and 48 sessions (i.e., 16 control, 16 Hot 1, and 16 Hot 2 trial results over two study days). Of 16 session days, 12 session days were completed in full, whereas 15 sessions included data through Hot 1, and all sessions completed the control trial. Cognitive tests in five total sessions lacked results because participants either left the chamber due to heat strain symptoms or equipment malfunction. Remaining data for these analyses originate from 16 control sessions, 15 Hot 1 sessions, and 12 Hot 2 sessions.

The average maximum core body temperatures and heart rates during Hot 1 and Hot 2 sessions were similar (Table 1). During both hot trials on both study days, the age-adjusted percent of maximal heart rate for participants who did not report regular exercise ranged from 80% to 87% (mean 83%). For participants who did report regular exercise, the range was 65%–95% (mean 83%). Other than one participant whose percent maximal heart rate was 65% and 68% during both hot trials on one study day, all other percent maximal heart rate values were similar (i.e., near the mean of 83%) for persons who regularly exercised. Mean number of minutes from beginning the treadmill exercise to reaching the threshold temperature of 38 °C was 37.9 min on study day 1 and 26.3 min on study day 2. Similarly, the average time to reach threshold temperature by hot trial was 30.8 min during Hot 1 and 34.4 min during Hot 2.

The cognitive tests showed varying impacts from heat exposure (Table 2). In the serial RT task, mean RTs were significantly slower in Hot 1 and Hot 2 compared with control, with Hot 1 being 8% slower than control ($p < 0.001$) and Hot 2 being 12% slower than control ($p < 0.001$). Mean RT in the control, Hot 1, and Hot 2 trials was 343.7 (SD 6.3), 366.3 (SD 6.3), and 379.0 (SD 6.6) ms, respectively. The odds of having a lapse during testing also significantly increased with heat exposure, with the odds of a lapse in Hot 1 and Hot 2 1.44 and 3.13 times that of control, respectively. The odds of a lapse during study day 2 was 2 times that of study day 1. The mean number of lapses in the control, Hot 1, and Hot 2 trials were 2.14 (SD 0.7), 2.7 (SD 0.7), and 5.5 (SD 0.8), respectively.

Both Stroop 1 and 2 demonstrated significantly faster responses on study day 2 compared with study day 1 (i.e., participants were able to respond to more color words on the list), with no difference in accuracy between the two study days (i.e., no differences in odds of correct response; Table 2). The mean numbers of words for Stroop 1 on days 1 and 2 were 95.7 (SD = 8.1) and 110.3 (SD = 8.0), respectively. The mean number of words for Stroop 2 on days 1 and 2 were 83.0 (SD = 5.6) and 92.6 (SD = 5.5), respectively. Stroop 1 had no significant difference in speed (i.e., number of words) between the hot trials and control, whereas accuracy was significantly lower in the hot trials compared with control (Table 2). The mean number of words for Stroop 1 in the control, Hot 1, and Hot 2 trials was 104.9 (SD = 8.3), 101.4 (SD = 8.3), and 102.7 (SD = 8.6), respectively. The mean number of errors for Stroop 1 in control, Hot 1, and Hot 2 trials was 1.4 (SD = 0.5), 2.1 (SD = 0.5), and 2.3 (SD = 0.5), respectively. Stroop 2 had no significant differences in either speed or accuracy when comparing the hot trials with control (Table 2).

No significant difference in delayed recall of the HVLT-R test was seen between study days 1 and 2 and between Hot 1 and control, whereas word recall in Hot 2 was significantly lower compared with control ($p = 0.02$; Table 2). On study days 1 and 2, respectively, 90% (SD = 0.09) and 89% (SD = 0.08) of words were retained during delayed recall. During control, Hot 1, and Hot 2 trials, respectively, 96% (SD = 0.09), 90% (SD = 0.09), and 82% (SD = 0.1) of words were retained.

N-back results were not significantly different comparing either Hot 1 or Hot 2 with control, and no significant differences in performance were seen between study days 1 and 2 (Table 2). Specifically, the odds ratios for getting a letter challenge correct in Hot 1 and Hot 2 compared with control were each 0.83 ($p = 0.17$ and 0.23 respectively). The proportion of correct responses in the control, Hot 1, and Hot 2 trials was 33.8 (SD = 1.0), 32.7 (SD = 1.0), and 34.1% (SD = 1.1), respectively. During study days 1 and 2, proportion of correct responses was 31.2 and 31.8%, respectively.

4. Discussion

In our study, we found that heat stress negatively affects cognitive performance. These findings may inform the known relationships between heat stress, workplace safety incidents, and worker productivity. However, our use of four different measures revealed that not all cognitive tasks were sensitive to heat stress, a finding that could partially explain why previous studies have found conflicting results. Some cognitive tasks may be more sensitive or resilient to the effects of heat stress. Heat stress impacted performance on the serial RT task, inhibition of automatic responses on Stroop 1, and delayed memory on HVLT-R. However, heat stress did not affect the continuous performance working memory task on N-back or inhibition with set-shifting task on Stroop 2. Serial RT task and inhibition task accuracy exhibited performance declines in both hot trials. In contrast, significant differences in delayed recall were only seen in the second hot trial. Significant differences between study days 1 and 2 were seen in the serial RT lapses and Stroop speed.

The serial RT task had the greatest effect size of all tests evaluated in our study. As this task measures response speeds and ability to sustain vigilant attention, our results indicate a significant worsening of vigilance during heat exposure. Several other studies have evaluated the impacts of heat on vigilant attention using a standard serial RT task that is widely used in the field of sleep research: the Psychomotor Vigilance Test (PVT; Lim and Dinges, 2008). However, study methods were too variable to discern notable patterns or consistency in findings. The task used in the present study did not include real-time feedback on RTs to participants and therefore does not meet the specifications to be considered a true PVT. This limitation could affect comparisons with results from other studies. However, the increases observed in mean RTs and lapses suggest that the task functioned similarly to a PVT.

Similar to our study, Qian et al. (2014, 2015) and Song et al. (2017) demonstrated slower reaction times with hyperthermia, even though these studies used passive rather than exercise-induced heat exposure. In contrast, other studies demonstrated that hyperthermia significantly improved reaction time (Lee et al., 2014b). Although Lee et al. (2014a, 2014b) conducted the PVT after exercise-induced hyperthermia, the testing conditions were different, with cooler ambient and higher core temperatures. Legault et al. (2017) found that workers with higher (but not elevated) core temperatures performed the PVT faster than those with lower temperatures. The possibility exists that reaction times improve with increased temperatures until a certain threshold of hyperthermia is reached, at which time performance begins to decrease. Yet, other studies demonstrated no difference in performance between hyperthermic and normothermic conditions (Ely et al., 2013; Parker et al., 2013). Morley et al. (2012) demonstrated mixed effects of heat exposure on PVT, with no changes in performance directly after exercise in the heat but increased mean RT of the 10 slowest RTs during the recovery period following the exercise.

Studies using vigilance tests other than the PVT also demonstrated variable findings. Faerevik and Reinertsen (2003) demonstrated no effects of heat on reaction time or missed reactions but did note significantly more incorrect responses in the heat condition. In contrast, Greenlee et al. (2014) demonstrated that the reaction time of the Continuous Performance Task improved immediately after simulated exercise under heat exposure, although reaction time slowed during recovery. Caldwell et al. (2018) demonstrated no change in reaction time under hyperthermic conditions.

Along with differences in heat stress conditions, the studies referenced above used different durations of RT tasks. We studied the effects of heat on a 10-min serial RT task, while other studies used a PVT or similar task ranging from 3 to 20 min. Different test lengths could lead to varying cognitive impairment findings, as vigilant attention has been shown to become progressively worse with increased time-on-task (i.e., vigilance decrement; Kribbs and Dinges, 1994). This performance instability is exacerbated with sleep deprivation (Doran et al., 2001; Honn et al., 2015). Results of repeated PVTs among sleep-deprived subjects demonstrated substantial variability, with increasing RT means and standard deviations (Doran et al., 2001). Performance instability during tasks requiring vigilant attention in the workplace might contribute to mistakes that could lead to injuries.

In addition to maintaining vigilant attention, workers also need to switch tasks and to inhibit automatic reactions (e.g., prevent oneself from pressing the wrong button on equipment). This is expressed in a worker's self-correction ability. Our study demonstrated that heat exposure affected the ability to inhibit automatic reactions from incongruent stimuli (Stroop 1) but did not affect performance when a set-shifting component was added (Stroop 2). We also found that heat affected speed and accuracy differently. In Stroop 1, speed was the same between hot and control trials, but accuracy decreased in the hot trials. These results suggest that heat exposure may affect a person's cognitive load, requiring them to choose between speed and accuracy. Unlike Stroop 1, Stroop 2 accuracy was the same between hot and control trials. Practice effects may be one possible reason for this occurrence, as participants always completed Stroop 1 prior to Stroop 2. As such, the effort required to inhibit the word reading response may have been reduced after the inhibition test (Lippa and Davis, 2010). Further, the inhibition (Stroop 1) test requires 100% color naming, whereas the inhibition/switching test (Stroop 2) requires that the participant simply read the word for 50% of the items. This could make the inhibition/switching test simpler despite the task switching component, as they are not inhibiting their automatic response.

Other studies have used Stroop tests (equivalent to Stroop 1 in our study) to investigate heat stress, with varying results. In two ecologic studies of heat stress, those living or working in heated environments performed significantly worse on the Stroop compared to those living or working in cooler environments (Laurent et al., 2018; Lan et al., 2011). Mazloumi et al. (2014) demonstrated significantly worse speed, reaction time, and accuracy among workers in a hot area compared with those in a cool area. Similar to our Stroop 1 results, accuracy but not speed was significantly reduced among persons exposed to higher heat loads (Chen et al., 2020; Tian et al., 2021). Chen et al. (2020) did not demonstrate these cognitive effects until persons had been exposed to heat for over 1 h, suggesting that cumulative heat loads affect cognitive performance. Tian et al. (2021) demonstrated reduced accuracy on Stroop only in high environmental temperatures coupled with high humidity (39 °C, 70% RH), which was similar to our environmental conditions of 37.8 °C and 80% RH. MacLeod et al. (2018) demonstrated no effect of heat on Stroop performance.

Studies evaluating heat-related performance on tests similar to Stroop also demonstrated differing results. Two studies using a filtering test found heat had no effect on performance (Caldwell et al., 2011, 2012), but substantial variability in performance was seen with heat exposure (Caldwell et al., 2012). The multiple variations of Stroop that exist make comparisons of studies difficult and could be one reason for differing results. Stroop also seems to be susceptible to a substantial learning effect, demonstrated in our study by significant improvements in speed from day 1 to day 2. A practice-related reduction in size of interference effect has also been reported in previous studies (Beglinger et al., 2005; Chen et al., 2013; Davidson et al., 2003; Edwards et al., 1996). Practice effects could mask the impact of heat exposure on performance, decreasing the usefulness of this test for studies in which participants are required to perform cognitive tests multiple times.

In addition to vigilant attention, task switching, and inhibition of automatic responses, manual labor workers also need active memory capacity to complete their tasks successfully. Our results using a word list memory task demonstrated significant effects of heat on verbal delayed recall, but only during the second hot trial. Consistent with our results, Gaoua et al. (2011) demonstrated that visual memory using a pattern recognition paradigm was significantly affected by heat, with the proportion of correct answers significantly lower in the hot trial than in the control trial. Masuda et al. (2020) demonstrated that villagers performing harvesting work in deforested conditions with higher ambient temperatures had significantly worse scores on an episodic memory test, where a series of 10 words was recalled at two points during a survey. However, other studies have demonstrated no difference in performance on memory tests between heat-exposed and unexposed persons. For example, Schlader et al. (2015) demonstrated no differences in visual pattern recognition memory among heat-exposed subjects. McMorris et al. (2006) demonstrated no differences in verbal and visual spatial recall when comparing heat exposure to baseline among subjects. Lan et al. (2011) demonstrated no effect of heat on visual memory.

The vast number of memory paradigms used in these studies makes comparisons among studies difficult. Our findings of decreased verbal recall during the second hot trial could reflect cumulative effects of heat. Morley et al. (2012) demonstrated no difference in memory between hot and baseline conditions, although significant impairments in memory were noted 1 h after exercising in the heat, possibly implicating late effects of heat. Our study was limited by variability in the delay following the fourth word list in the hot trials. In some participants, this delay correlated to a 20-min delay, while a longer delay was seen in participants whose temperatures rose more slowly. The delay between the fourth word list iteration and the HVLT-R delayed recall ranged from 20 to 66 min.

Like studies assessing verbal, visual, and delayed memory, studies evaluating the impact of heat stress on working memory have used multiple types of tests. Using the N-back, a continuous performance task measuring aspects of working memory, we did not find a significant difference in the odds of getting a letter challenge correct in the hot trials. This finding could be related to sample size, but other studies have demonstrated adverse effects of heat on working memory using backwards digit span performance (Hocking et al., 2001; Kumar et al., 1991). Tian et al. (2021) evaluated the effects of heat exposure on N-back. Similar to our N-back (2-back) results, they did not demonstrate a difference in accuracy in 2-back between environmental conditions, although they did find that reaction time was significantly faster in the highest heat and humidity condition compared with control (Tian et al., 2021).

Several investigators have hypothesized reasons for inconsistencies in study results. Absolute core temperature might have less effect on cognitive function than dynamic or relative changes in body temperature (Hancock, 1986; Hancock and Vasmatzidis, 2003; Gaoua, 2010). Although our participants began cognitive tests when their temperature reached 38 °C, their body temperatures were dynamic at the time of testing. Dynamic changes in temperature at the time of testing have not generally been assessed in studies, and thus, variability in results could be related in part to whether body temperatures of participants changed or were stable during the testing process.

Differences in gender distribution among study participants could also affect results of previous studies. Females might be able to tolerate heat-related negative effects on memory better than males (Hancock and Vasmatzidis, 2003). Varied physiologic responses to heat stress between men and women are also reported (Gaoua, 2010). Although women were recruited for our study, all participants were male.

Many previous studies reported changes in body weight, and variations in dehydration level could have affected results. Dehydration has a harmful effect on cognitive changes (Gaoua, 2010), but this may depend on the severity of dehydration, and the extent to which mild dehydration affects cognitive performance is unknown (Secher and Ritz, 2012). In general, our participants did not demonstrate evidence of dehydration, although two participants lost >2% body weight on one of the study days.

Few studies, including ours, have evaluated acclimatization status. However, Gaoua (2010) argued that “habitual acclimatization” is likely not an important confounder in studies of heat and cognition. Duration of heat exposure is different in the various studies, and evidence suggests that short exposures of up to 18 or 30 min can improve certain cognitive functions (Gaoua, 2010; Hancock and Vasmatzidis, 2003). Furthermore, heat likely affects various cognitive tasks differently, depending on task complexity (Gaoua, 2010; Hancock and Vasmatzidis, 2003). On average, our participants spent >30 min in the chamber prior to reaching the threshold required for the cognitive tests, but this varied by participant.

Finally, the type of heat exposure may affect study results. Evidence exists that a short duration of low or moderate exercise can improve certain cognitive functions, and thus, studies using exercise may blunt the adverse effects of heat (Gaoua, 2010). On the other hand, studies have also demonstrated that prolonged or intense exercise can adversely affect cognitive performance (Gaoua, 2010). Our study used moderate exercise to increase core temperature and therefore may have blunted the effect of heat exposure on cognitive function.

The results and implications of the current study should be considered in the context of several limitations. Sample size may have limited the ability to distinguish differences in performance. However, our method of modeling outcomes using measurements on a continuous scale allowed us more power to demonstrate differences in results. Participants were members of a mine rescue team with training requirements and might be more capable than others to perform arduous work in elevated temperatures. Although female participants were recruited, all participants were male, which could limit generalizability to women. Additionally, participants with a limited age range were included; however, our study included participants in their early 40s, whereas some laboratory-based studies only included persons in their 20s. The time between the start of exercise and the start of cognitive testing differed between participants, depending on how quickly their core temperature rose. Some participants reached the threshold core temperature more quickly than others, resulting in a shorter heat exposure time. Although exercise can affect cognitive performance apart from its effects on body temperature, we used exercise to drive core temperature elevations. Many workers at risk for heat stress perform tasks requiring physical exertion; therefore, using exercise to drive core body temperature is relevant to understanding these workers’ responses. We tested four cognitive tests to evaluate different cognitive functions. Including more tests might have had a larger impact on body temperature changes during testing, because temperatures continued to rise during testing. Despite limiting the number of tests, core body temperature was still dynamic during cognitive testing and could have affected results differentially depending on the direction of temperature change. Cognitive tests not evaluated in this study might be even more sensitive to heat stress than those we tested. Finally, differences in cognitive results between hot and control conditions could have resulted from thermal discomfort related to changes in ambient temperature or humidity, rather than from elevated core body temperature.

Despite these limitations, this study provides valuable information on heat-related cognitive function that has implications for future research. The serial RT task is feasible for use in both field and laboratory-based studies and is impacted by heat. Because it can be administered electronically, requires little training, and is brief, the serial RT task is also feasible for use in workplaces. The N-back test is feasible but did not demonstrate sensitivity to heat stress, although sample size might have limited our ability to detect heat-related impacts. Stroop test demonstrates heat-related decrements in performance but is highly susceptible to practice effects, making it less useful for future studies and for workplace applicability. HVLT-R is not feasible for field studies or workplaces, because the requirement for multiple learning readings and recall after several minutes may be challenging to achieve in the field and disruptive to workflow.

In addition to gaining a better understanding of test feasibility for future studies, we demonstrated unexpected findings that have implications for workplaces and should be investigated in future research. Unlike many studies, we performed two hot trials on the same day. Although we lacked the sample size for trend analyses from control to Hot 1 to Hot 2, elevated lapses in the Hot 2 trials suggest the possibility of a cumulative effect of heat on vigilant attention. This effect was seen even after a break between the Hot 1 and Hot 2 trials, where core temperatures cooled to at least 37.5 °C. Further investigation is needed to evaluate the discrepancies in performance between study days in the serial RT lapses, worse performance in both hot trials of the serial RT task and Stroop 1 accuracy, and in Hot 2 of HVLT-R. This finding could be related to variability in performance or to the cumulative effects of heat. Additionally, we do not have information on recent heat exposure outside the lab that could have affected performance.

The cumulative effect of heat on cognitive performance needs to be characterized further. Many workplaces involve prolonged and repeated exposure to heat over the course of several days or longer. Our study provides important information regarding the impact of repeated ex posures on workers. Repeated exposure to heat stress of short duration and its associated cognitive performance needs further evaluation as well because some workers have short, intermittent elevations of core body temperature (Yeoman et al., 2019). The impact of a break between heat exposures in the same day or between separate heat-exposed days could be further investigated to determine how to mitigate the effects of heat stress on cognitive performance. Understanding how to assess and monitor the cumulative effects of heat is also an important aspect of heat stress research moving forward. Given the potential impact of lapses on real-world functioning in the workplace, understanding how to assess and monitor vigilant attention in the workplace is essential.

Finally, a better understanding of the operational relevance of these cognitive tests to workplaces is essential. Correlations between cognitive domains evaluated by various tests with specific types of workplace tasks, and the real-world consequences of decrements in these cognitive domains is vital. For example, PVT performance is predictive of specific aspects of simulated driving performance (Jackson et al., 2013) and simulated train driving (Dorrian et al., 2007). The tests selected evaluated delayed memory, executive functioning, vigilance, and working memory. All four functions are vital for efficient and safe work in any environment. For example, intact memory is required to safely carry out tasks or updated safety instructions dictated by supervisors earlier in the shift. Executive functioning, including the ability to inhibit information, multitask, and shift from one activity to another, is important for adequate planning of activities, thinking before acting, and safe execution of task demands. Working memory is needed to stay on task and integrate new information as needed. Finally, lapses in attention may result in reduced ability to act quickly or safely in various situations. Although studies have been performed in workplaces to identify whether workers in real-world situations experience heat-related cognitive declines, whether these tests can be operationalized for use in workplaces to identify performance decrements is unknown. Cognitive tests that are valid, reliable, feasible, and provide actionable data for workplaces should be implemented and assessed for effectiveness. This study contributes to this need by providing information on tests that are sensitive to heat stress and feasible for field use.

5. Conclusions

Heat stress had differential impacts on cognitive tests, with the greatest impact on the serial RT task and the least impact on a continuous performance working memory task (N-back). In our study, heat stress appeared to impact vigilance, inhibition of automatic responses, and verbal memory more than aspects of working memory, although sample size could have limited our ability to demonstrate an effect. These cognitive domains are relevant to safety-critical work tasks where workers may be exposed to heat stress. The serial RT task demonstrated the highest sensitivity and feasibility of all tests evaluated in our study. Future studies could expand on these findings by accounting for additional factors relevant to workplaces, including the effects of cumulative and variable durations of heat on workers.

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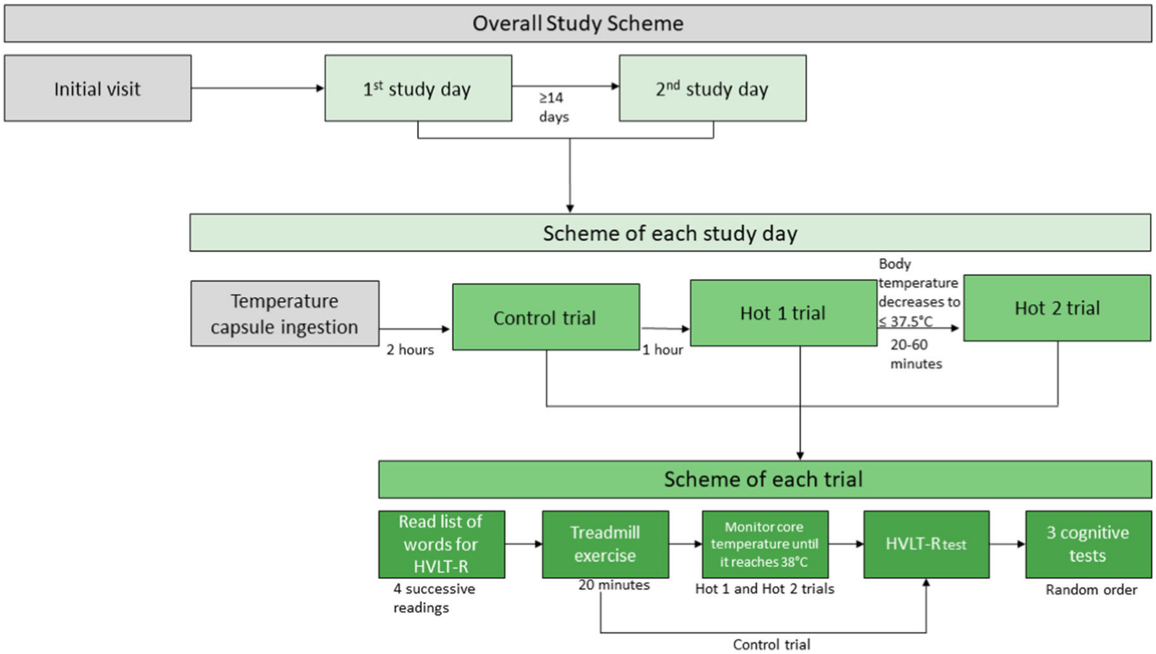

Fig. 1.
Study scheme.

Table 1

Average maximum core body temperatures (°C) and heart rates (beats per minute) during control, Hot 1, and Hot 2 trials.

	Control	Hot 1	Hot 2
Maximum core body temperature	37.3	38.2	38.2
Maximum heart rate	122	154	152

Table 2

β estimates of model variables for N-back, Serial Reaction Time (RT) and lapses, Stroop 1 and 2, and Hopkins Verbal Learning Test-Revised (HVLT-R) tests

Cognitive test (dependent variable)	Independent variable	β estimate[a]	Std error	P value	e^{β}	Interpretation[b]
Model 1						
Serial RT	Day 2	**0.030**	0.023	0.19	1.03	Reaction time was 3% slower on day 2 compared with day 1.
	Hot 1	**0.077**	0.013	<0.001	**1.08**	Reaction time was 8% slower during Hot 1 compared with control.
	Hot 2	**0.115**	0.022	<0.001	**1.12**	Reaction time was 12% slower during Hot 2 compared with control.
	Age	−0.005	0.004	0.16	0.99	For every one-year increase in age, reaction time increases by 1%.
Model 2						
Serial RT lapse	Day 2	**0.691**	0.148	<0.001	**2.0**	Odds of lapse on study day 2 was twice that of study day 1.
	Hot 1	**0.368**	0.182	0.04	**1.44**	Odds of lapse in Hot 1 was 1.44 times that of control.
	Hot 2	**1.144**	0.166	<0.001	**3.13**	Odds of lapse in Hot 2 was 3.13 times that of control.
	Age	**−0.064**	0.029	0.03	**0.94**	For every one-year increase in age, odds of a lapse decrease by 6%.
Model 3						
Stroop 1 speed	Day 2	**0.136**	0.031	<0.001	**1.15**	Stroop 1 speed was 15% faster on study day 2 compared with day 1 (i.e., participants provided responses to 15% more color words).
	Hot 1	−0.032	0.035	0.37	0.97	Stroop 1 speed in Hot 1 was 0.97 times that of control.
	Hot 2	−0.005	0.037	0.89	1.0	Stroop 1 speed in Hot 2 was equivalent to that of control.
	Age	**−0.021**	0.007	0.004	**0.98**	For every one-year increase in age, speed decreased by 2%.
Model 4						
Stroop 1 accuracy	Day 2	0.564	0.294	0.06	1.76	The odds of a correct answer during Stroop 1 was 76% higher on day 2 compared with day 1 (not significant).
	Hot 1	**−0.878**	0.383	0.02	**0.42**	The odds of a correct Stroop 1 answer during Hot 1 was 42% that of control.
	Hot 2	**−0.942**	0.393	0.02	**0.39**	The odds of a correct Stroop 1 answer during Hot 2 was 39% that of control.
	Age	−0.030	0.040	0.46	0.97	For every one-year increase in age, the odds of a correct answer decreased by 3%.
Model 5						
Stroop 2 speed	Day 2	**0.107**	0.033	0.001	**1.11**	Stroop 2 speed was 11% faster on study day 2 compared with day 1.
	Hot 1	0.029	0.038	0.45	1.03	Stroop 2 speed was 3% faster in Hot 1 compared with control.
	Hot 2	0.012	0.041	0.77	1.01	Stroop 2 speed was 1% faster in Hot 2 compared with control.
	Age	−0.014	0.007	0.07	0.99	For every one-year increase in age, speed decreased by 1%.
Model 6						

Cognitive test (dependent variable)	Independent variable	β estimate[a]	Std error	P value	e^{β}	Interpretation[b]
Stroop 2 accuracy	Day 2	−0.169	0.184	0.36	0.84	Stroop 2 accuracy (correct responses) on day 2 was 84% that of day 1.
	Hot 1	−0.255	0.207	0.22	0.77	Stroop 2 accuracy (correct responses) in Hot 1 was 77% that of control.
	Hot 2	0.030	0.236	0.9	1.03	Stroop 2 accuracy in Hot 2 was 3% higher than in control.
	Age	−0.034	0.024	0.16	0.97	For every one-year increase in age, accuracy decreased by 3%
Model 7						
HVLT-R correct responses	Day 2	0.461	0.284	0.1	1.59	Odds of remembering any of the previous words on study day 2 was 1.59 times that of study day 1.
	Hot 1	−0.272	0.425	0.52	0.76	Odds of remembering any of the previous words in Hot 1 was 0.76 times that of control.
	Hot 2	**−0.838**	0.353	0.02	**0.43**	Odds of remembering any of the previous words in Hot 2 was 0.43 times that of control.
	Minutes after 4th trial	−0.014	0.017	0.42	0.99	For every additional minute delay, odds of remembering any of the previous words decreased by 1%.
	Age	0.058	0.058	0.32	1.06	For every one-year increase in age, odds of remembering any of the previous words was 1.06 times higher than one year younger age.
Model 8						
N-back accuracy	Day 2	0.111	0.119	0.36	1.12	Odds of getting a letter challenge correct was 12% higher on study day 2 compared with study day 1 (not significant).
	Hot 1	−0.188	0.138	0.17	0.83	Odds of getting a letter challenge correct in Hot 1 was 0.83 times that of control (not significant).
	Hot 2	−0.182	0.153	0.23	0.83	Odds of getting a letter challenge correct in Hot 2 was 0.83 times that of control (not significant).
	Age	0.034	0.025	0.19	1.03	Odds of getting a letter challenge correct was 1.03 times higher with each additional year in age.

[a] Statistically significant values in **bold**.

[b] All interpretations are assuming adjustments for study day, session, and age; HVLT-R interpretations additionally assume adjustment for number of minutes in delay.