The independent and interactive effects of thermal stress and mental fatigue on manual dexterity

Alessandro Valenza[1,2]; Harry Charlier[1], Antonino Bianco[2], Davide Filingeri[1]

[1]*THERMOSENSELAB, Environmental Ergonomics Research Centre, Loughborough University, Loughborough, UK*

[2] *Sport and exercise Sciences Research Unit, SPPF Department, University of Palermo, Palermo, Italy*

Type of submission: Research article

Running title: Interaction of thermal stress and mental fatigue on manual performance

Key words: Mental Fatigue, Hot Temperature, Cold Temperature, Hand, Physical Functional Performance

Word count: 5793

Number of references: 44

Corresponding author:

Davide Filingeri PhD

THERMOSENSELAB

Environmental Ergonomics Research Centre, Loughborough Design School

Loughborough University

Loughborough LE11 3TU UK

Phone: +44 01509 228169

E-mail: d.filingeri3@lboro.ac.uk

Abstract

Many occupations and sports require high levels of manual dexterity under thermal stress and mental fatigue. Yet, multi-stressor studies remain scarce. We quantified the interactive effects of thermal stress and mental fatigue on manual dexterity. Seven males (21.1±1.3y) underwent 6 separate 60-min trials characterised by a combination of 3 air temperatures (HOT: 37°C; NEUTRAL: 21°C; COLD: 7°C) and 2 mental fatigue states (MF: mental fatigue induced by a 35-min cognitive battery; No-MF: no mental fatigue). Participants performed complex (O'Connor test) and simple (Hand-Tool test) manual tasks pre- and post-trials to determine stressors-induced performance changes. We monitored participants' rectal temperature and hand skin temperature (T_{hand}) continuously and assessed reaction time (Hand-Click test) and subjective mental fatigue (5-point scale). Thermal stress ($p<0.0001$), but not mental fatigue ($p=0.290$), modulated T_{hand} (HEAT: +3.3°C [95%CI +0.2, +6.5]; COLD: -7.5°C [-10.7, -4.4]). Mental fatigue ($p=0.021$), but not thermal stress ($p=0.646$), slowed reaction time (~10%) and increased subjective fatigue. Thermal stress and mental fatigue had an interactive effect on the complex manual task ($p=0.040$), with COLD-No-MF decreasing performance by -22% [-39, -5], while NEUTRAL-MF, COLD-MF, and HEAT-MF by -36% [-53, -19], -34% [-52, -17], and -36% [-53, -19], respectively. Only mental fatigue decreased performance in the simple manual task (-30% [-43, -16] across all thermal conditions; $p=0.002$). Cold stress-induced impairments in complex manipulation increase with mental fatigue; yet combined stressors' effects are no greater than that of mental fatigue alone, which also impairs simple manipulation. Mental fatigue poses a greater challenge to manual dexterity than thermal stress.

Introduction

Many occupations such as those in the military and healthcare sectors, as well as competitive sports, require high levels of manual dexterity to ensure optimal performance. However, these occupations and sports are often performed under conditions of thermal stress and mental fatigue, which pose a challenge for manual performance. A military doctor treating a gunshot wound during a cold-weather operation, an ICU nurse intubating a patient after a long shift and while wearing personal protective equipment, and a shooting athlete reloading a rifle during a hot summer Olympics' final, are all examples of real-life scenarios where optimal manual performance is essential, yet it may be impaired by the combined presence of thermal and cognitive stressors.

Manual dexterity is described as the ability to make coordinated hand and finger movements aimed at manipulating objects (21). This motor ability relies on neurophysiological (e.g. reflex motor control of grip force) as well as neurocognitive mechanisms (e.g. visuo-motor coordination, information processing and reaction time), and ranges from simpler to more complex actions (e.g. from simply unscrewing a bolt using the thumb and index finger to pinch-gripping a needle and placing it in a small hole) (21).

It is well established that thermal stress, and particularly cold stress, has a detrimental effect on manual dexterity (9). For example, manual dexterity worsens when local hand and finger temperatures decrease to ~20°C as a result of cold air exposure (20), with this effect becoming more severe at hand skin temperatures of 15°C and below (9). Furthermore, localised heating of the hand increases tapping speed; yet it also delays simple reaction time (25). Local changes in hand and finger temperatures play a greater role in worsening manual performance than changes in core temperature, with manipulative performance being hardly influenced by decreases in core temperatures when the hand is kept warm (8; 12). Changes in manual performance due to hand and fingers cooling are due to loss of cutaneous sensitivity (35), secondary to conduction slowing in cold cutaneous nerve afferents (10; 41). Conduction velocity in cutaneous nerve fibers decreases linearly when skin temperature drops from 36 to 23°C (10); a more pronounced slowing occurs at temperatures below 20°C (41), with conduction blocks developing at skin temperatures ~8°C (35). Furthermore, cooling (but not heating) of synovial fluid, reduces joint mobility, which can in turn contribute to thermal-stress induced decrements in manual performance (22).

Beside thermal stress, cognitive stressors such as mental fatigue (i.e. a psychobiological state induced by prolonged periods of demanding cognitive activity) (11; 23) can also be detrimental to manual performance (3; 13) by increasing perceived exertion (32) and hindering cognitive and perceptual skills (14), including reaction time (25).

While the independent effects of thermal (i.e. heat and cold stress) and cognitive stressors (i.e. mental fatigue) on manual performance have been studied in isolation, there is a paucity of data on their combined effects on the dexterous execution of both simple and more complex manual tasks. This opens to the question of which stressor, i.e. thermal stress or mental fatigue, poses a greater challenge to manual dexterity, and how their effects combine under a multi-stressor scenario. There is some evidence that heat stress and mental fatigue can interact synergistically in reducing cycling endurance capacity (36); yet, multi-stressors studies remain scarce, particularly in the context of manual performance. Quantifying the independent and interactive effects of multi-stressor scenarios on performance is fundamentally important to better understand human integrative physiological responses (27). Furthermore, this basic knowledge can support the development of applied interventions aimed at mitigating the impact of the more detrimental stressor, to preserve performance more effectively.

The interactions between stressors depend on the mechanisms by which each stressor exerts its effects (5; 28). Stressors with largely independent mechanisms of action often induce additive effects, while stressors that are mechanistically similar may induce synergistic or antagonist effects (27). Both thermal stress and mental fatigue induce deterioration of reaction time and hand motor coordination by either slowing peripheral conduction velocity or engaging central cognitive resources. Accordingly, it would be reasonable to hypothesize that those stressors may induce a synergistic deterioration of manual performance when combined.

The aim of this study was to quantify the independent and interactive effects of thermal stress and mental fatigue on manual performance. Our objectives were to assess manual dexterity during simple and complex tasks following 60-min exposures to six combinations of three environmental temperatures (i.e. 7, 21 and 37°C) and two mental fatigue states (i.e. with and without mental fatigue) in healthy young adults. We hypothesized that thermal stress and mental fatigue would interact synergistically in impairing manual dexterity, i.e. their combined impact would be greater than the sum of their individual impacts.

Methods

Ethical approval

The testing procedure and the conditions were explained to each participant and they all gave written informed consent for participation. The study was approved by the Loughborough University Ethics Sub-Committee for Human Participants, and testing procedures were in accordance with the tenets of the Declaration of Helsinki. All testing took place in Loughborough (UK) between June and September 2017.

Participants

Given the experimental demands of the present study (i.e. each participant would partake in six separate 60-min trials in hot, cold, and mentally fatigued conditions), and in line with similar research (see e.g. 28; 36), we used a convenience sampling approach to recruit eight non-smoking, recreationally active males (i.e. more than/or 3 exercise sessions per week) with no neurological, cardiovascular nor sensory-related disorders (e.g. numbness over the hands), and with normal or corrected-to-normal vision, were recruited from the student population of Loughborough University to take part in this study.

Due to technical reasons, only 7 participants (age 20.6±1.3y; body fat 12.7±2.1%; height 180.3±4.1cm) completed all experimental trials. In the 24h prior to each trial, participants were instructed to refrain from: 1) performing mental and physical training; 2) consuming caffeine, alcohol or any other stimulant. All participants performed their trials at the same time of the day. As we appreciated the limitations of a convenience sampling approach, we performed a sensitivity analysis to determine the required effect size and F critical for a statistically significant interaction between thermal stress and mental fatigue for the complex manual task (i.e. ANOVA repeated measure, within-between interaction), given our sample size of 7, an α of 0.05, a β of 0.95, a number of groups of 6, and a number of measurements of 12. We determined those values to be 1.09 (effect size f) and 2.49 (F critical) and we therefore used these parameters as a threshold for interpreting our findings. The power analysis was performed in GPower 3.1.9.2.

Experimental design

We used a single-blind, repeated measure design, where participants were made aware of the purpose of the study, but not of its hypotheses nor the characteristics of each experimental trial (e.g. ambient temperature and induction of mental fatigue), to limit any expectation bias. All participants took part in six different 60-min trials on separate days, which were characterised by a different combination of three ambient temperatures (HEAT: 37.0±0.4°C; NEUTRAL: 21.0±0.4°C; COLD: 7.0±0.4°C; relative humidity maintained at 40.0±1.5% RH for all temperatures) and two mental fatigue states (MF: mental fatigue; No MF: no mental fatigue) (Fig. 1). At the beginning (i.e. baseline) and at the end (i.e. post-test) of each trial participants performed a complex manual task, i.e. O'Connor finger dexterity test (O'Connor dexterity test, 2017), and a simpler manual task, i.e. modified Hand-Tool Dexterity test (Hand-Tool Dexterity test, 2017). We introduced both simpler and more complex manual dexterity tasks to provide a more comprehensive assessment of the potential interactive effects of our chosen stressors, as well as for their relevance to occupational settings (e.g. a soldier controlling a drone or reloading a gun). The mode of execution of both tests administered falls within a general assessment of manual dexterity, which depending on the task may require more complex vs. simpler motor actions.

During all trials, participants rested in a seated position in a climatic chamber, while wearing a standardised clothing ensemble consisting of T-shirt, running shorts, socks and running shoes. We monitored participants' whole-body thermal state [i.e. rectal temperature (T_{rec}), hand skin temperature (T_{hand}), and upper body mean skin temperature ($T_{upper\ body}$)] and cognitive state (i.e. reaction time and subjective mental fatigue), in order to quantify the impact of each stressor on participants' physiological and cognitive responses. All trials were performed in a counter-balance order to avoid any order effect.

By comparing participants' change in manual performance between pre- and post-test in each trial with the pre-to-post change in performance in the NEUTRAL-No MF trial (i.e. namely the control condition), this design allowed for the quantification of the independent effect of each individual stressor (i.e. HEAT-No MF; COLD-No MF; NEUTRAL-MF), as well as of their interaction (i.e. HEAT-MF; COLD-MF), on both simple and complex manual tasks.

It should be noted that magnitude of heat stress (i.e. 60 min of passive exposure in moderate heat & humidity) was known to likely be insufficient to impair psychomotor function and hence manual dexterity; yet the question of more relevance during the HEAT trials was whether addition of mental fatigue would elicit impairments in dexterity.

Thermal stress

To induce hot and cold thermal stress, we passively exposed participants to a hot, a thermo-neutral, and a cold climate, characterised by an ambient temperature of 37, 21 and 7°C, respectively, with a constant relative humidity of 40%. We chose these ambient temperatures for several reasons. First and foremost, we wanted to ensure that the heat and cold exposures selected for the 60-min trials would be sufficient to induce large changes in hand skin temperature (e.g. reducing hand temperature to ~20°C), which was confirmed during pilot studies. Second, we wanted to replicate average ambient temperatures likely to be experienced in an occupational setting relevant for the purpose of this study such as a military operation in Afghanistan. We confirmed that the average temperature during the coldest part of the year in Helmand province in Afghanistan is ~7°C (~40% RH), whereas the average temperature during the hottest part of the year in the same province is ~37°C (~40% RH) (World Weather Online.com).

Mental fatigue

In order to generate prolonged periods of demanding cognitive activity (Desmond et al. 2001; Job et al. 2001) that would be sufficient to induce a state of mental fatigue at the end of the mental fatigue trials, participants underwent a 35-min cognitive test battery, consisting of 5 separate tasks, each lasting 7 min. The first three tasks were arithmetic calculations (based on the Key stage 2 of the UK national curriculum (17), followed by The Stroop Colour and Word Test (37), and the McKinsey problem solving test (34). All tests were written tests, performed using a sheet of paper and a pencil provided to participants. To avoid a learning effect between trials, while maintaining the same level of cognitive demands, each participant performed three different versions of the same five tasks (e.g. different papers from Key stage 2) during each of the three mental fatigue trials they took part in. The tests were performed under time pressure, and verbal encouragement was given to complete them within the time allocated. The combination of time pressure and cognitive demand provided by these tests was deemed appropriate to induce a state of mental fatigue, which was later confirmed by both objective (i.e. reaction time) and subjective measures (i.e. self-reports of mental fatigue via a Likert scale). During the no-mental fatigue trials, participants watched non-stimulating videos.

Experimental protocol

Participants arrived at the laboratory on testing days, they changed into shorts and short sleeve t-shirt and underwent preliminary measurements and preparation. They then underwent a full familiarization with testing procedures, including the manipulative tasks (i.e. several mock trials were allowed until participants confirmed confidence in the task), and the assessments of mental fatigue (i.e. reaction time and Likert scale).

Following the familiarisation, participants self-inserted a rectal probe 13 cm passed the anal sphincter (BlueTemp temperature probe, UK) to record T_{rec} as an index of core temperature. A skin thermistor (Grant, UK) was taped to the centre of the hairy portion of the dominant hand with hypoallergenic medical tape (3M, UK) to record local T_{hand}. Similarly, six additional skin thermistors were taped to the centre of the forehead, the chest, the abdomen, the scapula, the tricep and forearm, to record local skin temperatures for the calculation of a simple mean of upper body skin temperature ($T_{upper\ body}$). T_{rec}, T_{hand}, and $T_{upper\ body}$ were recorded at 2Hz via a dedicated data acquisition system (USB- Temp, MCCdaq, USA) and custom-written software (DASYLab, MCCdaq, USA), and then averaged every 5 min for the duration of the 60-min trials. At this point, participants moved into the climatic chamber, which had been previously regulated to the air temperature and humidity required for the specific 60-min trial. Participants took 5 min to enter the chamber and assume a seated position on a small desk, where testing equipment was placed by accompanying the investigator. The following 55 min consisted of: a. baseline fatigue assessment and manipulation tasks (10 min); b. cognitive test battery or watching non-stimulating videos (35 min); c. post-test fatigue assessment and manipulation tasks (10 min).

Once seated in the chamber, participants first performed 3 consecutive reaction time tests, consisting of having to tap a box on a computer screen with their dominant index finger as fast as they could when this turned from red to green (click test; Humanbenchmark.com, 2017). Reaction time was recorded in milliseconds and the average of 3 attempts was calculated. Second, participants had to report on a 5-point Likert scale [1: Not mentally fatigued; 2: Slight mental fatigue; 3: Mentally drained; 4: Mentally fatigued; 5: Mentally exhausted; note: this was modified from the 12-point mental fatigue scale (24; 18)] their current mental fatigue state. Third, participants performed the pre-test manual tasks. The O'Connor dexterity test consisted in having to place as many pins as possible in each hole of the O'Connor board in 3 min (note: participants were instructed to place three pins per hole). Upon completion of the O'Connor dexterity test, participants performed a modified version of the Hand-Tool Dexterity test. This test consisted of having to unscrews and screw as many horizontal hex nuts as possible in 3 min. Nuts were screwed on 23 horizontal bolts mounted on a wooden board. The number of pins and nuts were used as performance indicators for complex and simple manual tasks, respectively. At this point, and depending on the trial, participants underwent either the cognitive test battery or watched non-stimulating videos. Upon completion of this period, participants underwent again the objective and subjective assessment of mental fatigue, as well as the two manipulative tasks. Once those tasks were completed, participants exited the climatic chamber and were de-instrumented.

Statistical analysis

To assess the independent and interactive effects of thermal stress and mental fatigue on physiological and perceptual responses, and on manual performance, we first calculated the difference (i.e. Δ) between baseline and post-test assessments for each parameter and for each individual participant. While units of measures were maintained for physiological and perceptual parameters in baseline vs. post-trial differences (e.g. changes in T_{hand} were expressed as Δ°C), participants' manual performance was calculated as a percentage difference between baseline and post-test in each trial.

First, we analysed differences in baseline (i.e. pre-test) T_{rec}, T_{hand}, $T_{upper\ body}$, reaction time, subjective fatigue, fine and gross manipulative performance, by means of 1-way repeated measures ANOVAs (i.e. 6 levels, one for each experimental trial). Second, we analysed ΔT_{rec}, ΔT_{hand}, $\Delta T_{upper\ body}$, Δreaction time, Δsubjective fatigue, Δperformance in fine and gross manipulation (%), for the independent and interactive effect of thermal stress (3 levels: NEUTRAL vs. HEAT vs. COLD) and mental fatigue (2 levels: MF vs. No-MF), by means of 2-way repeated measure ANOVAs.

Post-hoc analyses were conducted with Tukey's multiple comparison tests. Regarding the manual tasks, we compared participants' performance in each experimental trial including either thermal stress, mental fatigue or both, with the performance in the NEUTRAL-No MF (i.e. control) trial.

Data are reported as means, standard deviation (SD), and 95% Confidence Intervals (CI). Observed power was computed using alpha=0.05. Statistical analysis was performed using GraphPad Prism (version 8.0; GraphPad Software, La Jolla, CA, USA).

Results

Body temperatures

Baseline (i.e. pre-test) T_{rec}, T_{hand}, $T_{upper\ body}$ did not differ amongst the six trials (Tab.1).

First, we found that neither thermal stress ($F_{(2,12)}$=1.051; p=0.380; explained variance 4.5%), nor mental fatigue ($F_{(1,6)}$=1.386; p=0.284; explained variance 4.1%) had a significant effect on ΔT_{rec} (Fig. 2A).

Second, we found that thermal stress ($F_{(2,12)}$=44.96; p<0.0001; explained variance 75.6%), but not mental fatigue ($F_{(1,6)}$=1.344; p=0.290; explained variance 0.3%), had a significant effect on ΔT_{hand}. No interactions occurred between thermal stress and mental fatigue ($F_{(2,12)}$=0.20; p=0.820; explained variance 0.2%). When collapsed over mental fatigue trials and compared to the NEUTRAL trial, ΔT_{hand} was -7.5°C ([95%CI: -10.7, -4.4]; p<0.0001) in the COLD, while it was +3.3°C ([95%CI: +0.2, +6.5]; p<0.0001) in the HEAT (Fig. 2B). When expressed in absolute terms, post-test T_{hand} corresponded to 22.7±2.5°C during COLD trials, and 34.7±1.1°C during HEAT trials.

Third, we found that thermal stress ($F_{(2,12)}$=116.6; p<0.0001; explained variance 85.1%), but not mental fatigue ($F_{(1,6)}$=0.281; p=0.615; explained variance 0.1%), had a significant effect on $\Delta T_{upper\ body}$. No interactions occurred between thermal stress and mental fatigue ($F_{(2, 12)}$=0.08; p=0.917; explained variance 0.1%). When collapsed over mental fatigue trials and compared to the NEUTRAL trial, $\Delta T_{upper\ body}$ was -4.4°C ([95%CI: -5.6, -3.2]; p<0.0001) in the COLD, while it was +2.2°C ([95%CI: +1.0, +3.4]; p<0.0001) in the HEAT (Fig. 2C). Table 2 reports post-trial data for T_{rec}, T_{hand}, and $T_{upper\ body}$.

All in all, these results indicated that our thermal stress conditions were effective in inducing large changes in local skin temperature of the hand and in upper body skin temperature, independently of the presence of mental fatigue.

Objective and subjective measures of mental fatigue

Baseline (i.e. pre-test) reaction time and subjective fatigue did not differ amongst the six trials (Tab.1).

First, we found that mental fatigue ($F_{(1,6)}$=9.44; p=0.021; explained variance 21.4%), but not thermal stress ($F_{(2,12)}$=0.45; p=0.646; explained variance 2.6%), had a significant effect on Δreaction time (Fig. 3A). No interactions occurred between thermal stress and mental fatigue ($F_{(2, 12)}$=1.38; p=0.288; explained variance 4.1%). When collapsed over thermal stress trials, the difference in Δreaction time between No-MF and MF trials was +33 ms ([95%CI: +7, +59]; p<0.0001). Given that baseline reaction times were on average 352 ms (see Tab. 1), this difference corresponded to ~10% increase in reaction time because of the cognitive test battery administered during MF trials.

Second, we found that mental fatigue ($F_{(1,6)}$=1405; p<0.0001; explained variance 86.9%), but not thermal stress ($F_{(2,12)}$=0.84; p=0.452; explained variance 0.8%), had a significant effect on Δsubjective fatigue (Fig. 3B). No interactions occurred between thermal stress and mental fatigue ($F_{(2, 12)}$=1; p=0.396; explained variance 0.8%). When collapsed over thermal stress trials, the difference in Δsubjective fatigue between No-MF and MF trials was +2.5 scale points ([95%CI: +2.3, +2.7]; p<0.0001). Given that all participants reported a mental fatigue of "1 – Not Mentally fatigued" at the beginning of all trails (see Tab. 1), this difference indicated that participant reported being between "3 – Mentally drained" and "4 – Mentally fatigued" at the end of MF trials. Table 2 reports post-trial data for reaction time and subjective fatigue.

All in all, these results indicated that our mental fatigue conditions were effective in inducing a state of mental fatigue, which was confirmed by both objective (i.e. rection time) and subjective measures (i.e. self-reports), and which was independent of thermal stress.

Manual performance

Baseline performance in the complex and simple tasks did not differ amongst the six trials (Tab.1).

First, we found that mental fatigue ($F_{(1,6)}$=54.4; p=0.0003; explained variance 48.7%), but not thermal stress ($F_{(2,12)}$=2.88; p=0.094; explained variance 6.6%), had a significant effect on Δcomplex manual performance. Also, we found a significant interaction between thermal stress and mental fatigue ($F_{(2, 12)}$=4.24; p=0.040; explained variance 8.9%). When compared to NEUTRAL-No MF, manual performance in the complex task decreased by: -22% ([95%CI -39, -5]; p=0.012) in the COLD-No MF; by -16% ([95%CI -33, +1]; p=0.075) in the HEAT-No MF; by -36% ([95%CI -53, -19]; p=0.0002) in the NEUTRAL-MF; by -34% ([95%CI -52, -17]; p=0.0003) in the COLD-MF; and by -36% ([95%CI -53, -19]; p=0.0002) in the HEAT-MF (Fig. 4). These results indicated that mental fatigue alone induced greater detriments on dexterity in the complex task (i.e. 36% performance drop) than cold stress alone (i.e. 22% performance drop), and that when interacting with either cold or heat stress, mental fatigue decreased manual performance by an extent equal (i.e. ~35% combined performance drop) to what observed when fatigue acted alone.

Second, we found that mental fatigue ($F_{(1,6)}$=28.9; p=0.002; explained variance 36.1%), but not thermal stress ($F_{(2,12)}$=0.81; p=0.468; explained variance 3.9%), had a significant effect on Δsimple manual performance. No interactions occurred between thermal stress and mental fatigue ($F_{(2, 12)}$=0.78; p=0.476; explained variance 2.2%). When collapsed over thermal stress trials, the difference in Δsimple manual performance between No-MF and MF trials was -30% ([95%CI: -43, -16]; p=0.002). Table 2 reports post-trial data for the complex and simple tasks.

All in all, these results indicated that mental fatigue was the main inducer of the observed detriments in dexterity during the simple manual task (i.e. 30% performance drop), and that these detriments were independent of thermal stress.

Discussion

The aim of this study was to determine the independent and interactive effects of thermal stress and mental fatigue on manual dexterity. In assessing changes in manual performance during complex and simple tasks following on single and combined exposures to heat, cold, and mental fatigue, we hypothesized that thermal stress and mental fatigue would interact synergistically in reducing manual dexterity in healthy young adults.

With regards to the complex manual task, and contrary to our hypothesis, we found that, while thermal stress and mental fatigue interacted in reducing manual dexterity (i.e. ~35% performance decrement), their mode of interaction was not synergistic. In fact, stressors interaction followed a pattern whereby mental fatigue increased the individual impact of cold (i.e. 22% performance decrement) and heat (i.e. 15% performance decrement), yet by an extent no greater than that induced by mental fatigue alone (i.e. 36% performance decrement). With regards to the simple manual task, we found that mental fatigue was the main inducer of the observed detriments in dexterity (i.e. 30% performance drop), with these detriments being independent of thermal stress.

Independent effects of thermal stress

When considering the effects of thermal stress, our findings are in line with previous single-stressor studies. Our observed ~22% performance decrement in dexterity during the complex task resulting from hand skin temperature dropping to an absolute value ~23°C (Δ -7.5°C), is in line with previous results that have demonstrated an increase in hand numbness and a decrease in finger dexterity at finger skin temperature between 22 and 14°C (9; 38). It is important to note that we measured hand skin temperature at the centre of the back of the hand. Given the large capacity for fast vaso-constriction (and -dilation) of the glabrous portion of the fingers (39), one would expect that our recorded drops (and rises) in hand skin temperature provide an underestimation of the actual extent of finger skin cooling (and heating) occurring during our experiments. It is well-known that whole-body exposures to cold increase proximal-to-distal differences in skin temperature, and that drops in local skin temperature are more pronounced as one moves from to central body parts to fingers and toes (e.g. as confirmed in our study when comparing ΔT_{hand} vs. $\Delta T_{sk\text{-}upper\ body}$) (39). Hence, it appears likely that fingers' skin temperature may have dropped well below our recorded hand temperature of ~23°C and within the 22 to 14°C range previously shown to be associated with decreased hand dexterity (9; 38). Mechanistically, changes in manual performance due to hand and fingers cooling arise from loss of cutaneous sensitivity (35), secondary to conduction slowing in cold cutaneous nerve afferents (10; 41). Given that conduction velocity in cutaneous nerve fibers decreases linearly when skin temperature drops from 36 to 23°C (10), it could be hypothesised that our observed decrements in fine manipulation were likely due to loss of cutaneous sensitivity. However, we did not measure peripheral conduction velocities in the current study, and so this hypothesis remains speculative. Beside cold-induced conduction slowing, cold-induced changes in joint mobility may have also played a role in decreasing manual dexterity during the complex task in the current study. Cold causes joints' synovial fluid to become viscous, which in turn reduces movements speed and efficiency by increasing hand stiffness (6; 21; 22), all of which could have contributed to our observed cold-induced decrements in dexterity.

Finally, we did not observe any clear effect of thermal stress on dexterity during the simpler manual task. This is not entirely surprising when considering that the cutaneous sensory feedback that was likely impaired by thermal (and particularly cold) stress in the current study is generally more important for finer and more complex sensorimotor actions, such as those required when participants had to pinch-grip, move and accurately place each pin in their respective small hole in the O'Connor test board (15b, 21, 36b). In fact, increases in local tissue temperature can improve simpler, gross motor function (particularly during whole body exercise) and these effects underlies the classic benefits of pre-exercise warm up on subsequent motor performance (15).

Independent effects of mental fatigue

Regarding mental fatigue, it appears clear from our findings that this stressor had a prominent role in reducing manual performance. Specifically, mental fatigue explained ~49% and ~36% of observed variance during complex and simple manual tasks whereas thermal stress explained only 6% and 4% of the variance, respectively.

Albeit lasting only 35 min, our cognitive test battery appeared effective in inducing both a subjective state of mental fatigue, as well as an objective ~10% reduction in reaction time during a task requiring visuo-motor coordination of the hand analogous to what required by the manipulative tasks we administered (see Fig.3). The increase in both objective and subjective measures of mental fatigue indicated that our cognitive test battery elicited a significant level of cognitive load and perceived strain over the course of the MF trials.

Current theories on the effects of mental fatigue on physical performance suggest that this psychobiological state may limit exercise tolerance via higher perceived exertion (32). Furthermore, and in the context of short duration tasks presenting a certain level of cognitive demand such as manual dexterity tasks, mental fatigue may hinder hand function (3; 13) due to its detrimental impact on cognitive and perceptual skills (14), including reaction time (26). Mental fatigue has been previously demonstrated to negatively influence attention, action monitoring and cognitive control (2). Accordingly, we believe that our observed effects of mental fatigue on manual performance are likely due to the induction of a significant cognitive load, which may have been detrimental to neuropsychological parameters such as attention, action monitoring, and reaction time, all of which are important for efficient manual handling.

Although we did not record rates of perceived exertion, it could also be speculated that, similarly to what is reported for submaximal whole-body exercise such as cycling (32), a state of mental fatigue could have increased the perceived effort required by our manual tasks, in turn leading to greater motor fatigue and worse overall performance given the same task. It is important to note that mental fatigue seems to be similarly detrimental to both local and whole-body exercise (40). For example, Bray et al. showed that cognitive effort induced by a short-duration protocol negatively affected voluntary submaximal and maximal contractions during a handgrip test (3; 4). These authors reported greater proportional EMG amplitude scores in the hand flexor muscles during the handgrip tasks in the participants who performed the cognitive tasks. Bray et al.'s observations indicated that cognitive strain contributed to peripheral fatigue (e.g. accumulation of metabolites) by inhibiting descending neural activation of muscle motor units required to support the submaximal contraction (3; 4). Given that grip strength plays an important role in efficient manual handling, it cannot be excluded that similar mental fatigue-induced changes in descending neural input to hand and fingers muscles may have contributed to our observed decrements in dexterity under mental fatigue states.

Combined effects of thermal stress and mental fatigue

Thermal stress and mental fatigue combine in many occupational and sporting settings (6), and the potential for additive or synergistic interactions between these stressors may result in magnifying hazards to individuals exposed to real world, multi stressors scenarios (27). Within the constraints of our experiment (i.e. 60-min thermal stress exposure and 35-min cognitive load), our findings indicated that, even when combined with thermal stress, mental fatigue caused the greatest challenge to manual tasks. Importantly, and contrary to our initial hypothesis, we found that, while thermal stress and mental fatigue interacted in reducing dexterity during the complex task (i.e. ~35% performance decrement), their mode of interaction was not synergistic. In fact, stressors interaction followed a pattern whereby mental fatigue increased the individual impact of cold (i.e. ~22% performance decrement) and heat (i.e. ~15% performance decrement), yet by an extent no greater than that induced by mental fatigue alone (i.e. ~36% performance decrement). This observation indicated a mode of interaction between thermal stress and mental fatigue which followed the recently proposed "most severe strain takes precedence" principle (27), whereby the more severe strain "mental fatigue" takes precedence over the less severe strain "thermal stress". According to this multi-stressor principle, the mode of interaction between stressors is influenced by the impact magnitude of each individual stressor (e.g. thermal stress and mental fatigue) (29). That is, the greater the effect of one stressor (e.g. mental fatigue), the greater the probability that the detrimental effects of this stressor will take precedence over the effects of the second stressor (e.g. thermal stress). This model fits well with our observation that the interactive effects of thermal stress and mental fatigue were neither additive nor synergistic, but that in fact their interactive-impact magnitude was equivalent to the individual impact of the "most severe stressor" mental fatigue.

A state of mental fatigue in our participants is likely to have contributed to a less efficient information's processing, secondary to a reduced allocation of attentional resources to task-relevant cognitive processes (26). Mental fatigue may affect all stages of information processing that receive modulatory top-down input, from stimulus processing to response execution, and this notion is supported by studies that examined the effects of mental fatigue on preparatory processes in different cognitive tasks (1; 31). It could be therefore argued that in our study, mental fatigue may have negatively affected the efficiency of stimulus information processing relevant for initiating hand motor responses (26). The (likely) "central effect" of mental fatigue appeared to be more severe than the (likely) "peripheral effects" of thermal (cold) stress on hand sensorimotor function, and this differential impact could explain why mental fatigue took precedence over thermal stress in limiting the manipulative performance of our participants.

Mental fatigue has been recently reported to interact synergistically with heat stress during cycling performance in the heat (36). Hence our findings may at first appear to contrast with those of Otani et al. (36). However, it should be noted that in the study of Otani et al. (36) both mental fatigue and heat stress induced independent severe strains, particularly as the heat stress exposure resulted in a significant rise in core temperature prior to the cycling tests in the heat. The severe mental and heat strain induced by the protocol of Otani et al. (36) could have therefore produced the hyper-additive effects they observed. Our trials in the heat did not induce any changes in core temperature, but in fact it only raised skin temperature. Furthermore, it is likely that we did not observe a synergistic effect between heat and mental fatigue because of the different performance task we adopted, and the differential effects that heat has on local vs. whole-body motor tasks and exercise. In contrast with the effects of a high core temperature on endurance whole body performance, local increases in tissue and muscle temperatures can indeed be beneficial to perform short-duration dynamic work such as the dexterity tasks we administered (21). Accordingly, we believe that our findings and those of Otani et al. (36) can be interpreted as two examples of how variations in the impact magnitude of a stressor may modulate its role in a multi-stressor interaction (27).

Limitations

We recognise some limitations to this study. First, our sample size is rather modest, although it appeared sufficient to demonstrate the effects of our chosen stressors, likely due to their large effect sizes (i.e. stressors induced performance decrements in the range of 20 to 30%). Second, we did not implement performance tests that would clearly delineate central from peripheral effects of our stressors (i.e. simple- vs. choice-reaction time tasks using the same peripheral motor demands). Third, our experimental model did not involve a scenario where core temperature is shifted along with skin temperature. While evidence indicates that local changes in hand and finger temperatures play a greater role in worsening manual performance than changes in core temperature, we appreciate that increases in core temperature due to a combination of activity-induced metabolic heat and exposure to hot environments may have implications for manual dexterity and may be relevant to some occupational settings. Building on our findings, future studies should therefore consider mechanistic approaches to isolate peripheral from central effects in the interaction of thermal stress and mental fatigue, and how those may be modulated by changes in core temperature.

Perspectives and significance

From a fundamental standpoint, our study provides further support to the fact that human integrative responses to multi-stressor scenarios follow a "worst-stressor-takes-precedence" principle. From an applied point of view, our study supports the development of strategies that primarily target the mitigation of mental fatigue to sustain manual performance in those real world occupational (e.g. military, healthcare) and sport scenarios, which sees workers and athletes being exposed to a combination of mental fatigue (e.g. induced by cognitive stress or long shift work) and thermal stress (e.g. induced by exposure to extreme climates of by wearing personal protective equipment).

Conclusions

We conclude that, within the constraints of our experiment (i.e. a combination of 60-min passive exposures to air temperatures of 7 or 37°C with 35-min of cognitive load), mental fatigue posed the greatest challenge to manual dexterity in healthy young adults, even when combined with heat and cold stress. Our findings highlight the important role that mental fatigue can play in decreasing physical performance, both in isolation as well as when interacting with other environmental stressors known to deteriorate manual dexterity such as cold stress.

Acknowledgements

The authors thank Prof. George Havenith for the use of the climatic chambers at the Environmental Ergonomics Research Centre (Loughborough University, UK).

References

1. **Boksem MA, Meijman TF, Lorist MM.** Mental fatigue, motivation and action monitoring. *Biological Psychology* 72: 123–132, 2006.
2. **Boksem MA, Tops M.** Mental fatigue: Costs and benefits. *Brain Research Review* 59: 125-139, 2008.
3. **Bray SR, Graham JD, Martin Ginis KA, Hicks AL.** Cognitive task performance causes impaired maximum force production in human hand flexor muscles. *Biol Psychol* 89(1): 195-200, 2012.
4. **Bray SR, Martin Ginis KA, Hicks AL, Woodgate J.** Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology* 45: 337-343, 2008.
5. **Broadbent D.** Differences and interactions between stresses. *Q J Exp Psychol* 15: 205-211, 1963.
6. **Cheung SS, Lee JKW, Oksa J.** Thermal stress, human performance, and physical employment standards. *Appl. Physiol. Nutr. Metab.* 41: 148-164, 2016.
7. **Cheung SS, Montie DL, White MD, Behm D.** Changes in manual dexterity following short-term hand and forearm immersion in 10 °C water. *Aviat. Space Environ. Med.* 74(9): 990-993, 2003.
8. **Daanen HAM, Heus R.** The effect of body temperature on CIVD. *Concept Report IZF*, 1993.
9. **Daanen HAM, Wammes LJA, Vrijkotte TGM.** Windchill and dexterity. *Report IZF* A-7, 1993.

10. **De Jong RH, Hershey WN, Wagman IH.** Nerve conduction velocity during hypothermia in man. *Anaesthesiology* 27(6): 805-810, 1966.
11. **Desmond PA, Hancock PA.** Active and passive fatigue states. *Stress, Workload and Fatigue* 455-465, 2001.
12. **Ducharme MB, Brajkovic D, Frim J.** The effect of direct and indirect hand heating on finger blood flow and dexterity during cold exposure. *J Thermal Biol* 24(5-6): 391-396, 1999.
13. **Duncan MJ, Fowler N, George O, Joyce S, Hankey J.** Mental fatigue negatively influences manual dexterity and anticipation timing but not repeated high-intensity exercise performance in trained adults. *Res Sports Med* 23(1): 1-13, 2015.
14. **Faber L, Maurits NM, Lorist MM.** Mental fatigue affects visual selective attention. *PLos One* 7(10): e48073, 2012.
15. **Fradkin AJ, Zazryn TR, Smoliga JM.** Effects of warming-up on physical performance: a systematic review with meta-analysis. *Journal of Strength and Conditioning Research* 24(1): 140-148, 2010.

15b. **Nadia Gaoua, Sebastien Racinais, Justin Grantham & Farid El Massioui** (2011) Alterations in cognitive performance during passive hyperthermia are task dependent, International Journal of Hyperthermia, 27:1, 1-9, DOI: 10.3109/02656736.2010.516305

16. **Giesbrecht GG, Bristow GK.** Decrement in manual arm performance during whole body cooling. *Aviat Space Environ Med* 63: 1077-1081, 1992.
17. **Gov.UK.** Key stage 2 mathematics. Available at: https://www.gov.uk/government/publications/key-stage-2-tests-2019-mathematics-test-materials
18. **Grant S, Aitchison T, Henderson E, et al.** A comparison of the reproducibility and the sensitivity to change of visual analogue scales, Borg scales, and Likert scales in normal subjects during submaximal exercise. *Chest* 116: 1208-1217, 1999.
19. **Hagger MS, Wood C, Stiff C, Chatzisarantis NLD.** Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin* 136: 495-525, 2010.
20. **Hellström B.** Local effects of acclimatization to cold in man. Universitetsforlaget, Oslo. 1965.
21. **Heus R, Daanen HA, Havenith G.** Physiological criteria for functioning of hands in the cold: a review. *Appl Ergon* 26: 5-13, 1995.
22. **Hunter J, Kerr EH, Whillans MG.** The relation between joint stiffness upon exposure to cold and the characteristics of synovial fluid. Can J Med Science 30: 367-377, 1952.

23. **Job RFS, Dalziel J.** Defining fatigue as a condition of the organism and distinguishing it from habituation, adaptation and boredom. *Stress, Workload and Fatigue* 466-475, 2001.

24. **Joshi A, Kale S, Chandel S, Pal DK.** Likert scale: explored and explained. *British Journal of Applied Science &* Tecnology 7(4): 396-403, 2015.

25. **Kauranen K, Vanharanta H.** Effects of hot and cold packs on motor performance of normal hands. *Physiotherapy* 83(7): 340-344, 1997.

26. **Langner R, Steinborn MB, Chatterjee A, Sturm W, Willmes K.** Mental fatigue and temporal preparation in simple reaction time performance. *Acta Psychologica* 133: 64-72, 2010.

27. **Lloyd A, Havenith G.** Interactions in human performance: an individual and combined stressors approach. *Temperature* 3:1-4, 2016.

28. **Lloyd A, Hodder S, Havenith G.** The interactive effect of cooling and hypoxia on forearm fatigue development. *Eur J Appl Physiol* 115: 2007-2018, 2015.

29. **Lloyd A, Raccuglia M, Hodder S, Havenith G.** Interaction between environmental temperature and hypoxia on central and peripheral fatigue during high-intensity dynamic knee extension. J *Appl Physiol* 120: 567-579, 2016.

30. **Lockhart JM, Kiess HO, Clegg TJ.** Effect of rate and level of lowered finger surface temperature on manual performance. *J Appl Physiol* 40(1): 106-113, 1975.

31. **Lorist MM.** Impact of top-down control during mental fatigue. *Brain Research* 1232: 113-123, 2008.

32. **Marcora SM, Staiano W, Manning V.** Mental fatigue impairs physical performance in humans. *J Appl Physiol* 106(3): 857-64, 2009.

33. **McCormick F, Kadzielski J, Landrigan CP, et al.** Surgeon fatigue: a prospective analysis of the incidence, risk, and intervals of predicted fatigue-related impairment in residents. *Arch Surg* 147(5):430-435, 2012.

34. **McKinsey&Company.** McKinsey Problem Solving Test. Available at: https://www.mckinsey.com/~/media/mckinsey/careers%20redesign/interviewing/main/problem%20solving%20test%20pdfs/practice-test-a.ashx

35. **Morton R, Provins KA.** Figure numbness after acute local exposure to cold. *J Appl Physiol* 15(l): 149-154, 1960.

36. **Otani H, Kaya M, Tamaki A, Watson P.** Separate and combined effects of exposure to heat stress and mental fatigue on endurance exercise capacity in the heat. *Eur J Appl Physiol* 117: 119-129, 2017.

36b. **Jacob F. Piil, Jesper Lundbye-Jensen, Steven J. Trangmar & Lars Nybo** (2017)

Performance in complex motor tasks deteriorates in hyperthermic humans, Temperature, 4:4, 420-428, DOI: 10.1080/23328940.2017.1368877

37. Scarpina F, Tagini S. The Stroop Color and Word Test. *Front Psychol* 8: 557, 2017.

38. **Schieffer RE, Kok R, Lewis MI, Meese GB.** Finger skin temperature and manual dexterity; some inter-group differences. *Appl Ergonomics* 15(2): 135-141, 1984.

39. **Taylor NA, Machado-Moreira CA, van den Heuvel AMJ, Caldwell JN.** Hands and feet: physiological insulators, radiators and evaporators. *Eur J Appl Physiol* 114(10): 2037-2060, 2014.

40. **Van Cutsem J, Marcora SM, De Pauw K, Bailey S, Meeusen R, Roelands B.** The effects of mental fatigue on physical performance: a systematic review. *Sports Medicine* 47: 1569-1588, 2017.

41. **Vanggaard L.** Physiological reactions to wet cold. *Aviat Space Environ Med* 46(2): 33-36, 1975.

Table and figure captions

Table 1. Baseline (i.e. pre-test) T_{rec}, T_{hand}, $T_{sk\text{-}upper\ body}$, reaction time and subjective fatigue, and fine and gross manipulative performance (i.e. number of pins correctly placed and number of bolts screwed and unscrewed in 3 min), for the 7 participants, for of each of the 6 experimental trials. Data are reported as means and standard deviations. p-values for the independent effect of trial (1-way ANOVA) are also reported.

Table 2. Post-test T_{rec}, T_{hand}, $T_{sk\text{-}upper\ body}$, reaction time and subjective fatigue, and fine and gross manipulative performance (i.e. number of pins correctly placed and number of bolts screwed and unscrewed in 3 min), for the 7 participants, for of each of the 6 experimental trials. Data are reported as means and standard deviations.

Figure 1. Experimental design outlining the six separate trials undertaken by each participant. By comparing participants' change in manipulative performance between pre- and post-test in each trial with the pre-to-post change in performance in the NEUTRAL-No MF trial (i.e. namely the control condition), this design allowed for the quantification of the independent effect of each individual stressor (i.e. HEAT-No MF; COLD-No MF; NEUTRAL-MF), as well as of their interaction (i.e. HEAT-MF; COLD-MF), on both fine and gross manipulation.

Figure 2. Mean (N=7) difference and 95% CI for the ΔT_{rec} (A), ΔT_{hand} (B), and $\Delta T_{upper\ body}$ (C). Data were collapsed over mental fatigue trials and compared to the NEUTRAL trial to visualise the independent effect of HEAT and COLD stress on body temperatures. * corresponds to $p<0.05$ for 2-way ANOVA post-hoc analyses.

Figure 3. Mean (N=7) difference and 95% CI for the reaction time (A) and subjective fatigue (B). Data were collapsed over thermal stress trials to visualise the independent effect of mental fatigue on objective and subjective measures. * corresponds to $p<0.05$ for 2-way ANOVA main effect.

Figure 4. Mean difference (N=7) and 95% in manual performance for the complex task. Data for the 5 experimental conditions (i.e. COLD-MF, HEAT-MF, NEUTRAL-MF, COLD-No MF, HEAT-No MF) were compared to the NEUTRAL-No MF trial (i.e. namely the control

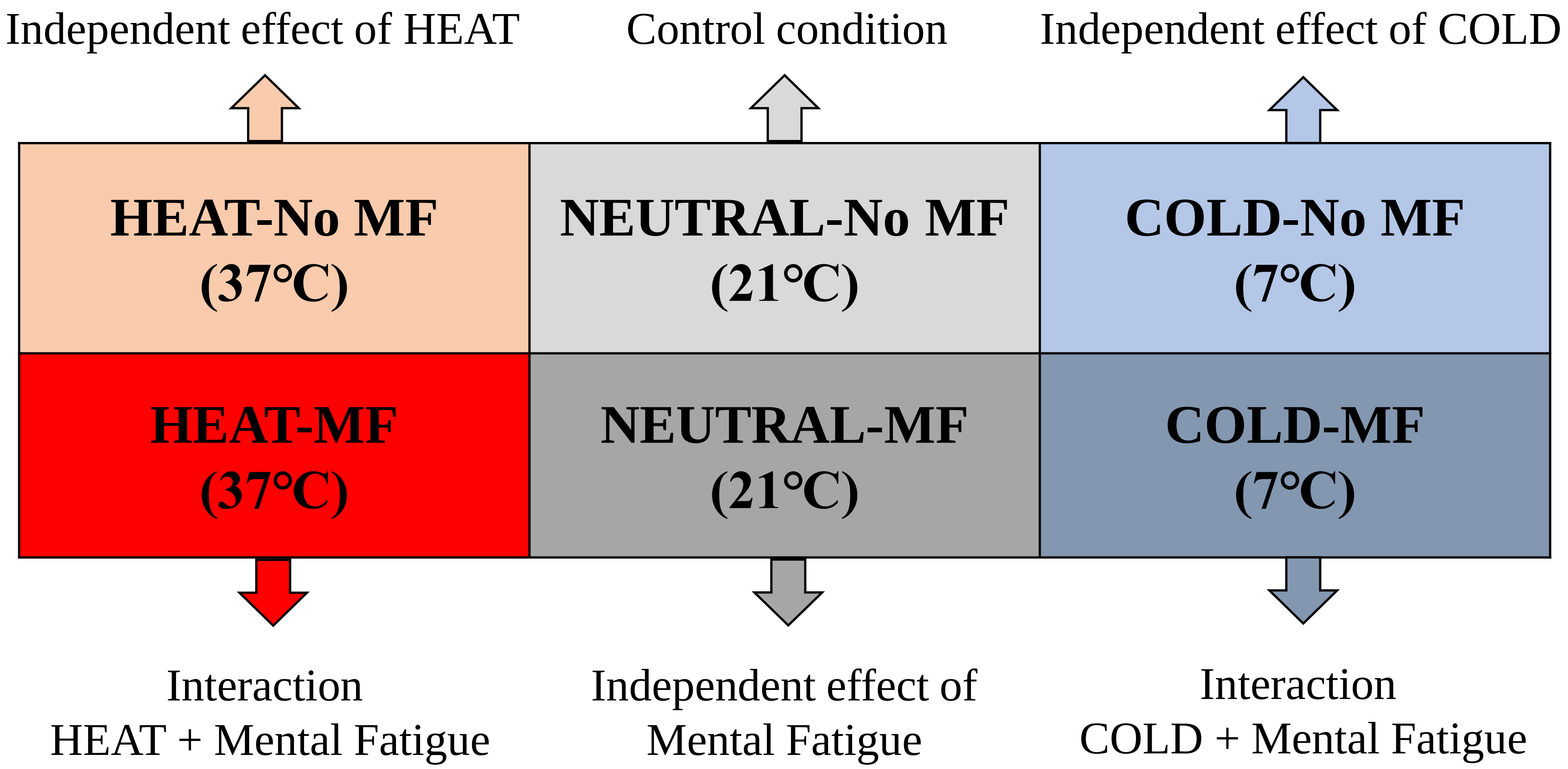
condition) to visualise the independent and interactive effects of HEAT and COLD, and of MENTAL FATIGUE, on manual performance. * corresponds to $p<0.05$ for 2-way ANOVA post-hoc analyses.

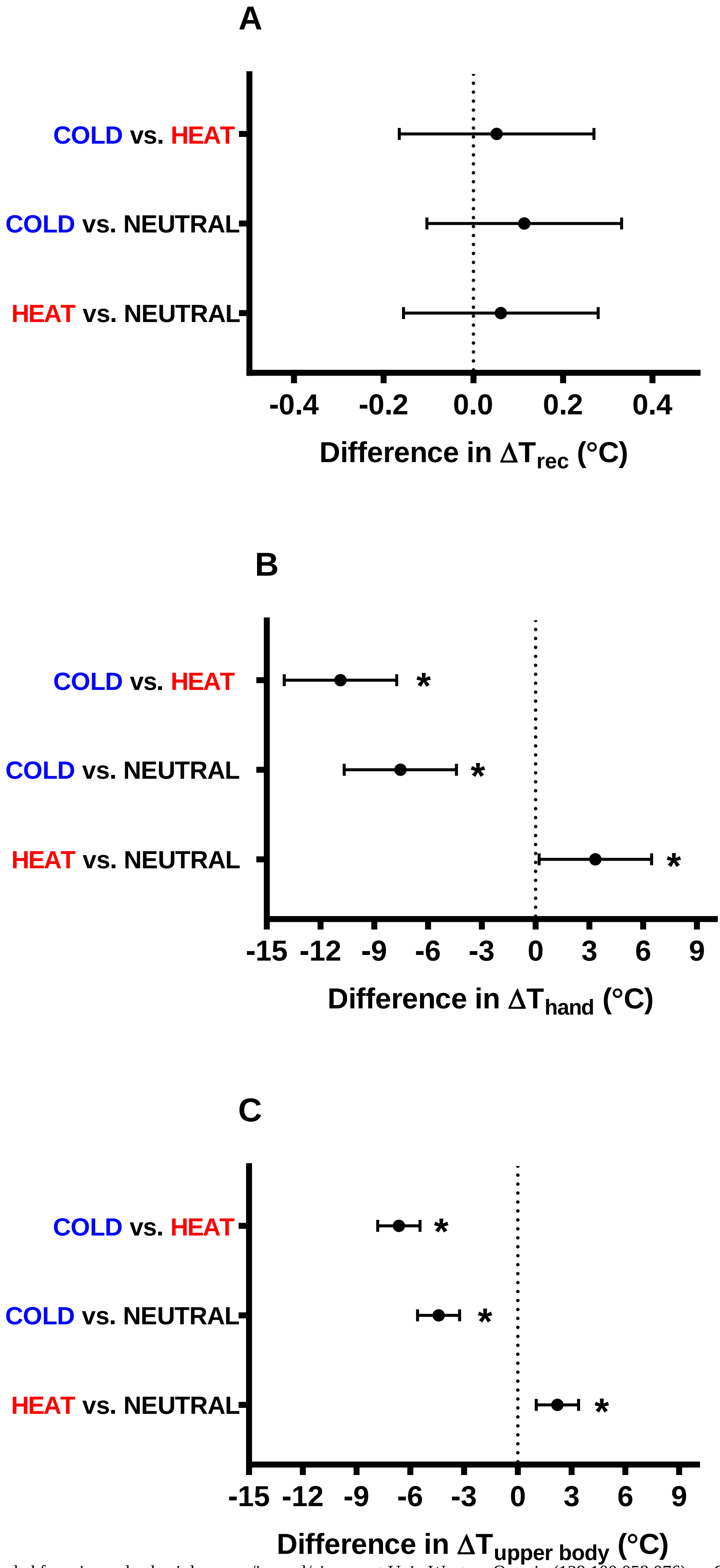
	NEUTRAL-No MF		NEUTRAL-MF		COLD-No MF		COLD-MF		HEAT-No MF		HEAT-MF		
T_{rec} (°C)	37.32	±0.21	37.11	±0.17	37.24	±0.18	37.29	±0.32	37.19	±0.27	37.26	±0.26	(p=0.560)
T_{hand} (°C)	31.34	±2.65	30.15	±1.72	29.67	±2.87	29.45	±2.07	30.52	±2.81	30.29	±3.01	(p=0.584)

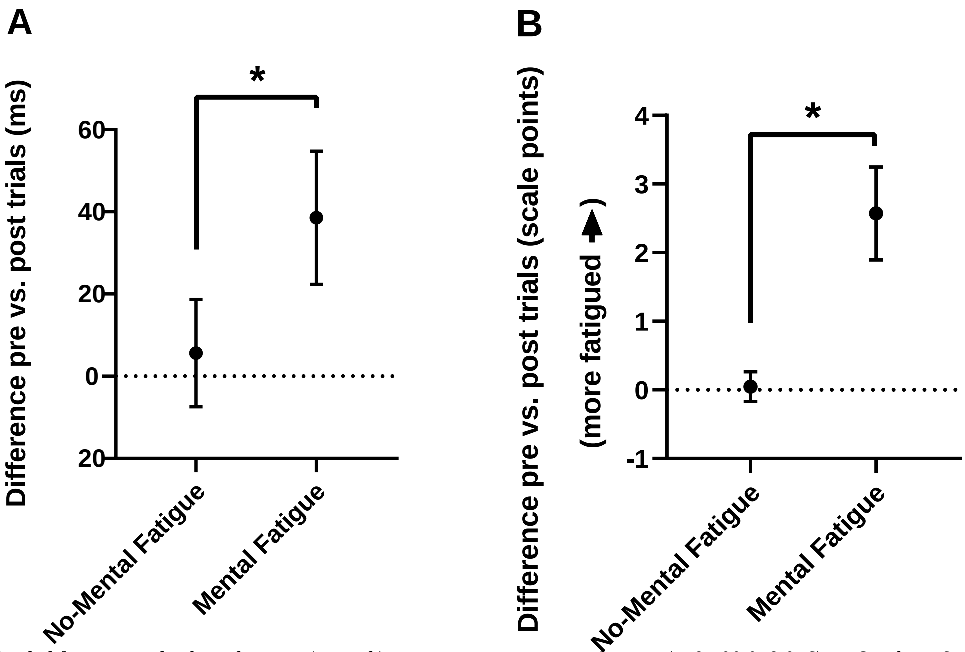
$T_{upper\ body}$ (°C)	31.81	±0.80	31.26	±0.81	31.62	±0.99	31.53	±0.27	31.75	±1.25	32.02	±1.46	(p=0.580)
Reaction time (ms)	352	±38	357	±40	347	±32	348	±52	353	±52	357	±27	(p=0.886)
Subjective fatigue (1-5)	1.0	±0.0	1.0	±0.0	1.0	±0.0	1.0	±0.0	1.0	±0.0	1.0	±0.0	(p=1.000)
Fine manual task (N pins)	43.3	±6.2	49.4	±4.6	48.4	±8.8	48.9	±5.1	43.4	±6.7	49.3	±7.7	(p=0.200)
Gross manual task (N bolts)	42.3	±9.8	49	±9.6	42.3	±10.4	49.7	±4.3	45.7	±8.0	51	±4.0	(p=0.199)

	NEUTRAL-No MF		NEUTRAL-MF		COLD-No MF		COLD-MF		HEAT-No MF		HEAT-MF	
T_{rec} (°C)	37.12	±0.22	36.96	±0.16	37.15	±0.22	37.25	±0.36	37	±0.18	37.23	±0.26
T_{hand} (°C)	32.08	±1.72	30.78	±0.99	23.48	±3.19	21.93	±1.50	34.76	±1.42	34.65	±0.92

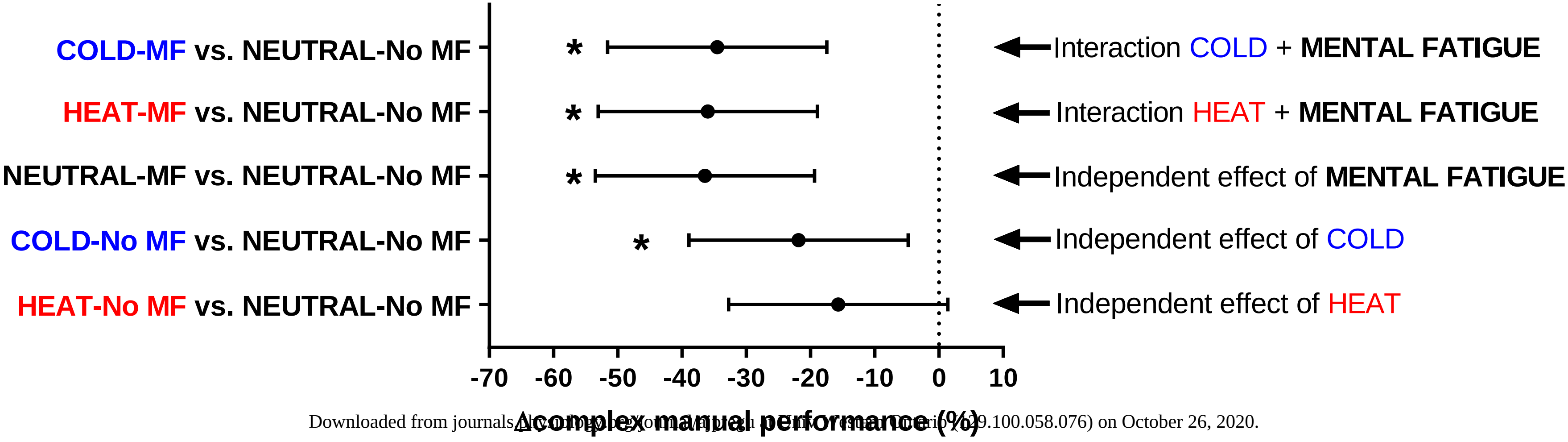
$T_{upper\ body}$ (°C)	32.29	±0.75	31.7	±0.60	27.71	±2.49	27.52	±1.48	34.65	±0.43	34.46	±0.81
Reaction time (ms)	359	±37	377	±34	350	±38	400	±48	360	±66	400	±42
Subjective fatigue (1-5)	1.1	±0.4	3.6	±0.8	1.0	±0.0	3.8	±0.7	1.0	±0.0	3.4	±0.5
Fine manual task (N pins)	48.1	±4.4	37.6	±2.6	44.1	±10.1	38.1	±7.5	41.9	±5.1	37.6	±5.1
Gross manual task (N bolts)	46.7	±5.6	39.6	±4.0	41.1	±7.8	40.1	±8.6	53.3	±6.3	42.6	±7.6


Independent effect of HEAT
Control condition
Independent effect of COLD
HEAT-No MF (37°C)
NEUTRAL-No MF (21°C)
COLD-No MF (7°C)
HEAT-MF (37°C)
NEUTRAL-MF (21°C)
COLD-MF (7°C)
Interaction HEAT + Mental Fatigue
Independent effect of Mental Fatigue
Interaction COLD + Mental Fatigue


A
COLD vs. HEAT
COLD vs. NEUTRAL
HEAT vs. NEUTRAL
-0.4
-0.2
0.0
0.2
0.4
Difference in ΔTrec (°C)
B
COLD vs. HEAT
COLD vs. NEUTRAL
HEAT vs. NEUTRAL
*
-15
-12
-9
-6
-3
0
3
6
9
Difference in ΔThand (°C)
C
COLD vs. HEAT
COLD vs. NEUTRAL
HEAT vs. NEUTRAL
*
-15
-12
-9
-6
-3
0
3
6
9
Difference in ΔTupper body (°C)



A
B
*
*
Difference pre vs. post trials (ms)
60
40
20
0
20
No-Mental Fatigue
Mental Fatigue
Difference pre vs. post trials (scale points)
(more fatigued)
4
3
2
1
0
-1
No-Mental Fatigue
Mental Fatigue



COLD-MF vs. NEUTRAL-No MF
HEAT-MF vs. NEUTRAL-No MF
NEUTRAL-MF vs. NEUTRAL-No MF
COLD-No MF vs. NEUTRAL-No MF
HEAT-No MF vs. NEUTRAL-No MF
*
*
*
*
Interaction COLD + MENTAL FATIGUE
Interaction HEAT + MENTAL FATIGUE
Independent effect of MENTAL FATIGUE
Independent effect of COLD
Independent effect of HEAT
-70
-60
-50
-40
-30
-20
-10
0
10
Δcomplex manual performance (%)