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No large effects on cognitive performance in high versus low solar green-flag WBGT conditions

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ABSTRACT

Excessive solar radiation negatively affects cognitive performance. Occupational guidelines typically combine environmental components into one value, such as wet-bulb globe temperature (WBGT). Here, we evaluated cognitive performance in two similar 28.6 °C WBGT-effective (WBGT_{eff}) that were designed differently; using high or low levels of solar radiation. Eight soldiers were exposed to a virtual-reality environment in a climate chamber set to high (900 Wm⁻²) or low solar radiation conditions (300 Wm⁻²). Soldiers walked 3 x 30 min at 5 kmh⁻¹. Cognitive performance was evaluated using a virtual-reality scenario and a computerised test battery. There was no statistically significant effect of condition on the cognitive tasks ($p > 0.05$). Associations were found between mean body temperature (T_b) and visual detection ($P \leq 0.01$). Differences in solar radiation with similar WBGT_{eff} (28.6 °C) do not cause large systematic differences in cognitive performance. Certain aspects of cognitive performance (i.e. response inhibition) seem to be partly associated with T_b rather than solar radiation.

Practitioner summary: Cognitive performance was evaluated in two similar WBGT conditions that were designed differently; using high or low levels of solar radiation. Differences in solar radiation with similar WBGT do not cause systematic differences in cognitive performance. Certain aspects of cognition were partly associated with mean body temperature rather than solar radiation.

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1. Introduction

As global urbanisation keeps increasing, the likelihood for future military operations to occur in urban regions grows simultaneously. Urban regions are characterised by relatively warm urban heat islands (Rizwan, Dennis, and Chunho 2008; Pyrgou, Santamouris, and Livada 2019; Oke 2010). Consequently, military operations in urban regions will be physically more demanding for soldiers. Urban regions also yield more complexity compared to rural regions and, in general, soldiers are exposed to an increasing amount of information by provided technological support. The complexity of urban regions and the increasing information potentially causes a shift towards more cognitively dominated performance for soldiers on foot (Billing et al. 2021).

Cognitive performance is known to be negatively affected by heat stress (Gaoua 2010; Kingma et al. 2020; Doohan 2022). Previous research demonstrated that following a severe body core temperature (T_c) elevation ($\sim 2^\circ\text{C}$), cognitive performance was deteriorated (Sun et al. 2012; Gaoua et al. 2011; Hocking et al. 2001; Lee et al. 2014; Liu et al. 2013; Racinais, Gaoua, and Grantham 2008; Simmons et al. 2008). T_c elevations up to $\sim 1^\circ\text{C}$ hamper cognitive performance less (Clarke et al. 2017; Gaoua et al. 2011; Hocking et al. 2001; Lee et al. 2014; Liu et al. 2013; McMorris et al. 2006; Racinais, Gaoua, and Grantham 2008; Schlader et al. 2013, 2015; Schmit et al. 2017; Sun et al. 2012; Hancock 1986; Kingma et al. 2020). Cognitive task performance could also be perturbed by skin temperature (T_{sk}), thermal comfort and thermal sensation without a T_c increase (Gaoua 2010; Gaoua

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et al. 2012; Ioannou et al. 2021; Gibbons et al. 2021). Recently, evidence suggested that high levels of solar radiation ($\sim 800\text{--}1000\text{ W m}^{-2}$) directed towards the head on itself deteriorated motor-cognitive performance (Piil et al. 2020). Further, a framework that highlights that severe hyperthermia or moderate hyperthermia in combination with solar radiation has a notable effect on cognitive performance (Piil et al. 2021). Previous research already suggested that different climate types could elicit the same WBGT but differ in terms of heat load (Lotens and Middendorp 1986). The authors emphasise the heat load difference in radiant and non-radiant climate types. The potential mechanism behind temperature-related cognitive performance deterioration has to do with vasodilation, which occurs during heat stress to maintain T_{c} . Due to vasodilation more blood is distributed towards the periphery and less towards the brain, which may explain the aforementioned cognitive performance reductions (Martin et al. 2019; Gaoua et al. 2012; Brothers et al. 2009; Wilson et al. 2006; Hancock and Vasmatzidis 2003). By direct sun exposure T_{sk} increases, augmenting the aforementioned process. Likewise, direct sun exposure could cause discomfort, drawing away attention from the task.

The deployability of military personnel is determined based on occupational guidelines. Occupational guidelines to assess environmental heat stress typically do not distinguish between the intensity of solar radiation. Instead, occupational guidelines typically use a single value that represents the overall thermal environment (i.e. air temperature, mean radiant temperature, relative humidity and wind), such as the wet bulb globe temperature (WBGT) (ISO 7243 2017). Based on ranges of WBGT-values, NATO proposed work-rest-ratios and fluid recommendation guidelines depending on the type of activity performed (Spitz et al. 2012). For example, having a WBGT of $31.1\text{--}32.2^{\circ}\text{C}$ whilst deploying a moderate work intensity (metabolic rate of $\sim 425\text{ W}$), individuals should adhere to a 30/30 min work-rest-ratio whilst ingesting 0.75 L h^{-1} of fluid (Spitz et al. 2012).

As future military operations will occur more and more in urban regions where solar radiation is a large contributor of heat stress (Rizwan, Dennis, and Chunho 2008; Pyrgou, Santamouris, and Livada 2019; Oke 2010; Billing et al. 2021), it is important to elaborate on the potential separate effects of solar radiation. This is even more relevant as current operational guidelines do not assume a separate effect of solar radiation on (cognitive) performance (ISO 7243 2017).

In the present study, we evaluated cognitive task performance in two 28.6°C WBGT-effective conditions ($\text{WBGT}_{\text{eff}} = \text{WBGT} + \text{Clothing Adjustment Value} = 25.8 + 2.8$) that were designed differently; using high or low solar radiation levels. Whilst in practice similar WBGT-values impose the same practical recommendations, reductions in cognitive performance could differ by solar radiation levels. The 28.6°C WBGT_{eff} falls in the green flag WBGT category of NATO HFM187 (Spitz et al. 2012), and is generally considered as the first (and lowest) level of heat stress, but does already imply work-rest restrictions for moderate to high activity levels. It is not known if the green-flag WBGT condition would elicit a cognitive performance decline per se. Here, we aim to test whether there would already be differences in cognitive performance that are operationally relevant for a military operation; and that may potentially require an adjustment of the guidelines to separately recommend work-rest cycles for physical activity versus cognitive activities. Since cognitive performance is known to be sensitive to solar radiation, and WBGT is an aggregate thermal stress index, we hypothesised that potential cognitive performance deterioration is larger in a high compared to a low solar radiation condition whilst WBGT_{eff} is similar (Piil et al. 2021; Ioannou et al. 2021; Gibbons et al. 2021; Piil et al. 2020).

2. Material and methods

2.1. Participants

Experimental procedures were approved by the local Ethics Committee of TNO (2020-127). The study was conducted in accordance with the guidelines of the revised *Declaration of Helsinki* (2013). Written informed consent and a basic health check by a medical physician were obtained from all participants before participation in the study. Eight male soldiers on active duty (age: 25 ± 4 years; body mass: $76.5 \pm 11.8\text{ kg}$) participated in this study. Contrary to an a priori sample size analysis to detect a difference between two or more (in)dependent means, this study was set up to detect only large effect sizes. The rationale behind this logic is that if the difference cannot be clearly detected in any small group of participants, it may not be important in an operational setting (i.e. military squad size). Given $\alpha = 0.05$, power = 0.8 and $n = 8$, we were able to detect a difference between two dependent means once the effect size exceeded 0.98 (which is considered a large effect size). To ensure hydration, participants were instructed to refrain from alcohol and drugs 24 h before the experiment and to

consume 500 mL of water 0–2 h before starting the experiment. Participants self-reported that they did not take any prescription medication, had no history of heat-related illnesses or cardiovascular complications and did not have any known issues with thermoregulation.

2.2. Design

Participants reported to the laboratory on two occasions to repeat the exact same procedures in two different environmental conditions (i.e. within-subject design). Environmental conditions were set to either high or low solar radiation but with a similar WBGT of 25.8 °C. The effective WBGT (i.e. $WBGT_{eff}$) represents an estimate of the heat stress provided by adding a clothing adjustment value (CAV) ($WBGT_{eff} = WBGT + CAV$). In the present study, we added +2.8 °C to account for the worn clothing configuration (Spitz et al. 2012). The consequent $WBGT_{eff}$ of 28.6 °C is considered green-flag (i.e. WBGT range: 27.7–29.4 °C (Spitz et al. 2012)). The green flag condition is not considered as hot, but does already imply a work-rest cycle of 50 min/10 min per hour for moderate activity levels, that in a cooler environment would be possible to carry out during a full hour. Two large lamps (each 25 × 1 cm at a height of 2 m, halogen, 220–250 V, 1000 W, 9 J, Philips, Eindhoven) were used to set the high solar radiation condition (Table 1). The required solar radiation was determined using Climate CHIP (<https://www.climatechip.org/excel-wbgt-calculator>). An overview of the WBGT-values from head to feet is shown in Appendix B. By adjusting the relative

humidity the water vapour pressure was kept similar (1.57 kPa) between conditions, allowing for an equal capacity to evaporate. The order of conditions was balanced among participants.

2.3. Protocol

During each occasion, participants walked on a self-propelled treadmill (Bari Mill 55, Woodway, Waukesha, Wisconsin, USA) in a climate chamber (Weiss Technik, Tiel, The Netherlands). Participants intermittently walked three times 30 min at 5 kmh⁻¹ whilst wearing a summer battle dress trousers (Woodland camouflage pattern, 65% polyester, 35% cotton), t-shirt (green, 100% polyester), combat shirt (beige core, 65% polyester, 35% cotton, multi-cam camouflage pattern sleeves, 50% nylon, 50% cotton), helmet and carrying a ~15 kg backpack (adding up to ~1.2–1.3 clo). Between the 30-min blocks there were 10 min of rest (Figure 1).

Participants were exposed to a virtual-reality urban region using the 'mobile immersive cognitive environment' (MICE; Figure 2) (Beurden and Roijendijk 2019). By walking on the self-propelled treadmill, participants could move through the virtual-reality environment. Participants had to navigate through the streets of an urban scene in West-Central Asia using the mission navigation belt (<https://elitacwearables.com/projects/mission-navigation-belt/>) (Figure 3). This belt, worn around the waist, was programmed to vibrate on the left or right side prior (~10 s) to each crossing at which participants had to change direction. While walking and navigating, participants had to perform three cognitive tasks simultaneously. The first task comprised of participants having to visually detect friends or foes (i.e. 50 per 30 min, wearing a slightly different camouflage pattern) that stood in alleys between buildings in the virtual-reality environment. When seeing a foe, participants had to push a button that was attached to the right handgrip of the treadmill whilst they had to ignore friends. In the second task, participants had to detect high (440 Hz for 500 ms) or low frequency signals (311 Hz for 500 ms)

Table 1. Characteristics of the high and low solar radiation conditions.

Parameter	High	Low
WBGT (°C)	25.8	25.8
Solar radiation (Wm ⁻²)	900	<300
Air temperature (°C)	23	32
Relative humidity (%)	50	33
Wind speed (ms ⁻¹)	0.6	0.6
Mean radiant temperature (°C)	43.8	37.6
Water vapour pressure (kPa)	1.57	1.57

WBGT: Wet-bulb globe temperature.



Figure 1. Schematic overview of the study protocol: alternating 30 min of walking and 10 min of rest. Participants wore a ~15 kg backpack throughout. Cognitive evaluation took place during both the 30-min walking blocks and 10-min breaks.

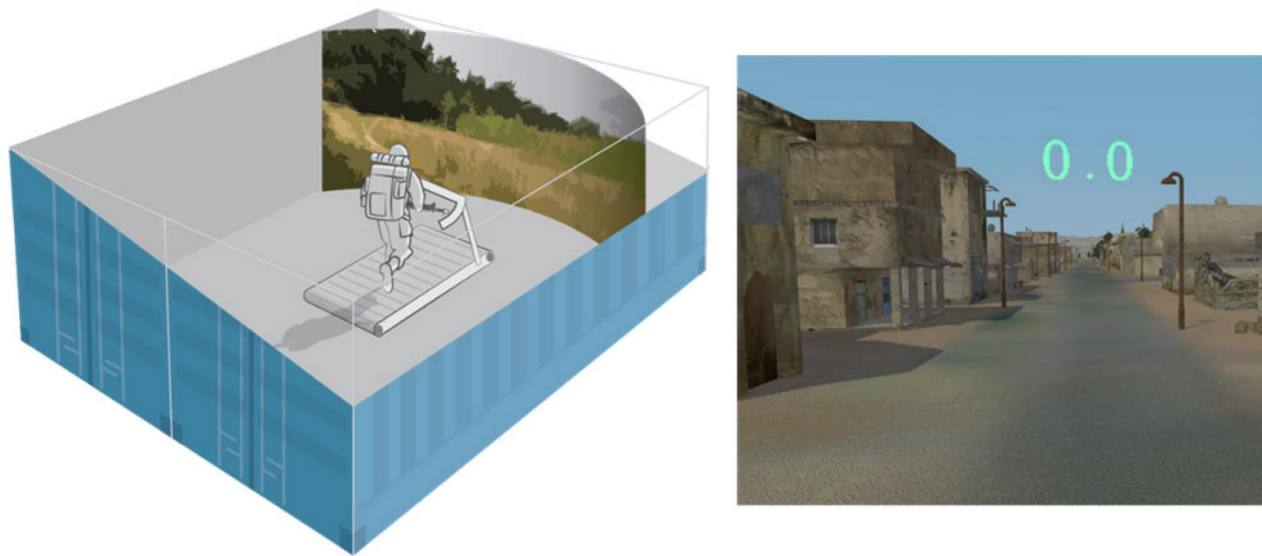


Figure 2. Mobile immersive cognitive environment (MICE, left) and example of the virtual-reality urban region (right).



Figure 3. Mission navigation belt (left), friend and foe in the virtual-reality urban region (middle), Groton maze learning test (GMLT) tile grid (right). Of note, navigation and the friend and foe task were performed during walking whilst the GMLT was carried out during breaks.

during walking. By hearing the high tone, participants had to push a button that was attached to their left index finger whilst they had to ignore the low tone signal. The third task was a memory task in which participants had to detect and imprint a total of ten billboards that they encountered during each 30-min block in the on buildings next to the route. In the 10-min rest periods, participants had to recall the billboards in the order of appearance by selecting ten billboards from a set of 30 billboards and placing them in the correct order. The pictures on the billboards were selected from the Nencki Affective Picture System (Marchewka et al. 2014). Six sets of 10 pictures were selected in this experiment. These were all selected from the categories 'happiness' and 'happiness, surprise'. The selected pictures were then

categorised in ten groups of six pictures with similar arousal ratings. Immediately after that, participants conducted the Groton maze learning test (GMLT) (Snyder et al. 2005). In this test, the aim is to find a hidden pathway concealed within a 10×10 tile grid presented on a computer screen (Figure 3). Each trial starts in the top left corner and has 28 moves and 11 turns to approach the bottom right corner. Participants find the route by clicking step-by-step on the adjacent tiles. After each step feedback was provided on whether the step was correct or incorrect. When the step was incorrect, participants continued the task from the last correctly identified tile. When the step was correct, participants received instructions to continue. Participants completed five consecutive trials followed by a 2 min break and a delayed trial.

2.4. Measurements

To confirm hydration, urine specific gravity (USG) was measured with a handheld refractometer (PAL-S, Atago, Bellevue, USA; $USG \leq 1.020$). Heart rate (HR) was monitored continuously using a chest strap and watch (OH1 and M430, Polar, Kemele, Finland). As an indication of T_{cr} , gastrointestinal temperature was measured using a telemetric capsule (BodyCap, e-Celsius, Hérouville-Saint-Clair, France) that was ingested an hour before starting the experiment. T_{sk} sensors (i-Button DS1922L, Maxim Integrated, USA) were attached to four skin locations according to ISO 9886 (ISO 9886 2004) using sticking adhesive (Fixomull stretch, BSN Medical, Almere) and a weighed mean T_{sk} was calculated (ISO 9886 2004). Mean body temperature (T_b) was calculated using Eq. 1. Cognitive workload was rated on a 5-point scale with continuous values (1 – very high, 2 – high, 3 – average, 4 – low, 5 – very low) (Brennan 1992). To ensure hydration throughout the protocol, participants drank ~ 65 mL of water every five minutes (i.e. adding up to ~ 0.78 Lh $^{-1}$ which corresponds to the recommended 0.75 Lh $^{-1}$ (Spitz et al. 2012)). The water temperature was adjusted to the observed T_c ($\pm 0.5^\circ\text{C}$) (Hardy, Du Bois, and Soderstrom 1938).

$$T_b(^{\circ}\text{C}) = 0.8 T_c + 0.2 \text{ mean } T_{sk} \quad (1)$$

Multiple functions of cognitive performance were evaluated. An overview of the tasks, corresponding cognitive function that was addressed, and the actual cognitive performance measures taken is listed in Table 2. No measures were taken for the tactile navigation task as participants all succeeded to

successfully navigate through the scenario. For the visual and auditory detection tasks four measures were taken: accuracy, hit rate, false alarm rate and response time. Accuracy was also obtained from the short-term memory task. Lastly, for the spatial working memory task the number of errors and the mean correct moves per second (CMS) were registered and reported. CMS is also known as maze efficiency index (Table 2).

2.5. Statistics

All data were synced and formatted using Matlab (The Mathworks, Natick). HR, T_{cr} , mean T_{sk} and T_b data were converted into 30-min and 10-min block averages. Statistical analyses were performed using IBM SPSS Statistics 28.0. Physiological, perceptual and cognitive outcomes were assessed using a mixed effect model with condition and block as fixed effects and participant as random effect (i.e. both intercept and slope). The selected covariance structure was variance components. To find out if there were relations ($p < 0.05$) between physiological and cognitive outcome parameters, one could opt for linear regression analysis. However, in the military it is essential to know what parameters are risk factors (or not) for cognitive performance. Since to our knowledge there is no specific value or percentage of cognitive performance reduction known that should be avoided in a military setting, the group average on each variable was taken as threshold value. To analyse the potential relation between the physiological and cognitive parameters, binary logistical regressions on accumulated data of both solar conditions were conducted. Cognitive

Table 2. Cognitive performance measures.

Task	Cognitive function	Measure	Explanation	Unit
Navigation	Tactile navigation	None	None	None
Visual detection (friend or foe)	Attention and inhibition	Accuracy	Number of correct foe responses divided by total number of visible soldiers * 100	%
		Hit rate	Number of detected foes divided by total number of visible foes * 100	%
		False alarm rate	Number of detected friends divided by total number of visible soldiers * 100	%
		Response time	Average time from popping up of foes to pressing the button	Sec
Auditory response (high or low tone)	Attention and inhibition	Accuracy	Number of correct high tone response divided by total number of tones * 100	%
		Hit rate	Number of detected high tones divided by total number of high tones * 100	%
		False alarm rate	Number of detected low tones divided by total number of low tones * 100	%
		Response time	Average time from tone to pressing the button	Sec
Memory (billboards)	Short-term memory	Correct	Number of correct billboards	%
GMLT (maze)	Spatial working memory	Errors	Number of errors (i.e. wrong moves)	#
		CMS	Number of correct moves divided by the total duration in seconds	#sec $^{-1}$

GMLT: Groton maze learning test; CMS: correct moves per second; Sec: seconds.

performance was considered as the dependent variable and was coded dichotomously ('0' denotes result < group average and '1' denotes result > average). T_c , mean T_{sk} and T_b were factors in the analysis. Non-significant variables were removed from the model in a backwards stepwise manner. Lastly, total thermal load was established by calculating the area under the curve for T_b (Equation 2). In this equation, T_{b-i} is T_b at time point i ($^{\circ}\text{C}$) and dt is the duration of the thermal stimulus (min).

$$\text{Total thermal load for } T_b (^{\circ}\text{C min}) = \int (T_{b-i}) dt \quad (2)$$

3. Results

3.1. Physiological

For all physiological variables, there was a main effect of block ($p < 0.001$, Figure 4), indicating that there were changes over time. For HR, there was no significant main effect of condition ($p = 0.274$), neither an interaction effect of condition $\times$ block ($p = 0.828$). Such findings indicate that HR overall did not significantly differ between the high and low solar radiation condition. Neither was the increase in HR over blocks larger in one of the conditions (Figure 4). Moreover, there

was a significant main effect of condition on T_c ($p = 0.018$), indicating that T_c was higher in the low solar radiation condition. The condition $\times$ block interaction on T_c was statistically significant as well ($p = 0.039$), indicating that the raise in T_c was larger in the low compared to the high solar radiation condition (Figure 4). Furthermore, there was a significant main effect of condition on mean T_{sk} ($p < 0.001$). This indicates that mean T_{sk} was continuously higher in the high solar radiation condition (Figure 4). No interaction effects were found for mean T_{sk} by condition $\times$ block ($p = 0.811$). For T_b there was no statistically significant effect of condition per se ($p = 0.510$) but the interaction of condition $\times$ block of T_b was significant ($p = 0.033$). Such findings indicate that overall T_b was not higher or lower in one condition but the raise in T_b was larger in the low solar low condition (Figure 5). The total thermal load for T_b in the high solar radiation condition was 3708°Cmin and 3707°Cmin in the low solar condition ($p > 0.05$).

2.2. Cognition

In general, cognitive performance was high on all tasks (visual detection, auditory response, memory and GMLT), with absence of significant condition and condition $\times$ block effects on any of the cognitive

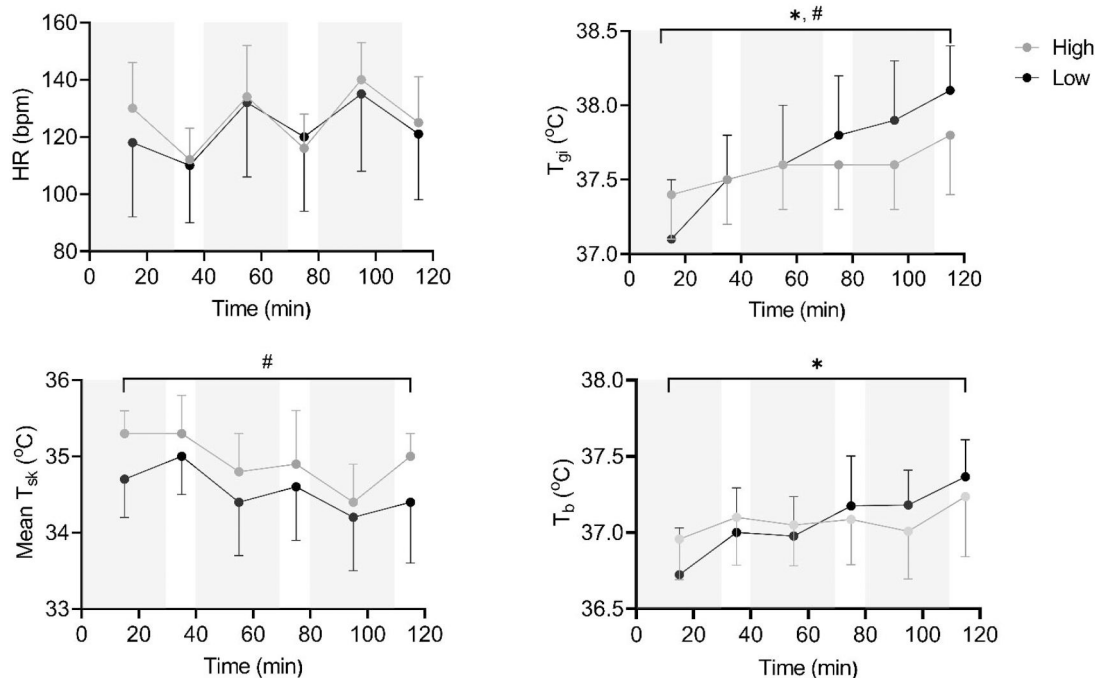


Figure 4. Heart rate (HR), core temperature (T_c) and mean skin temperature (mean T_{sk}) over time. Grey dots show the high solar radiation condition. Black dots show the low solar radiation condition. Light grey rectangles represent the three 30-min walking blocks. * represent a significant ($p < 0.05$) interaction effect of condition $\times$ block. # represent a significant main effect of condition ($n = 8$).

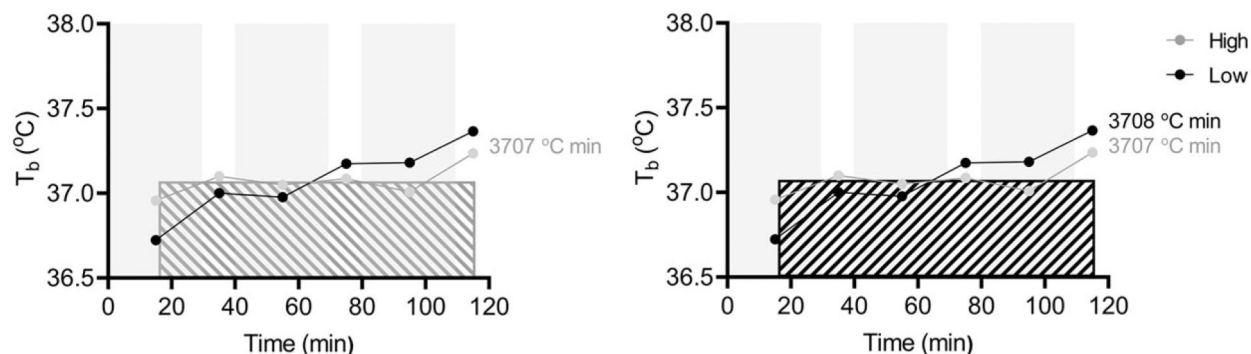


Figure 5. Total thermal load (or area under the curve) for mean body temperature (T_b). Grey dots and the grey filling pattern show the high solar radiation condition. Black dots and the black filling pattern show the low solar radiation condition. Light grey rectangles represent the three 30-min walking blocks ($n = 8$).

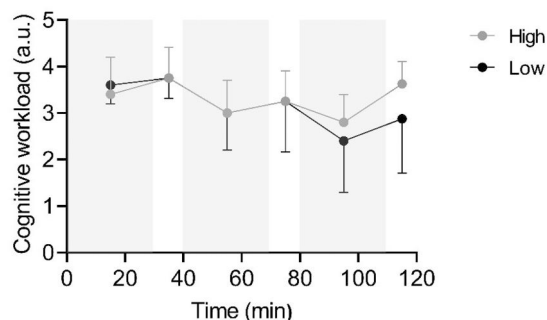


Figure 6. Cognitive workload over time. Grey dots show the high solar radiation condition. Black dots represent the low solar radiation condition. Light grey rectangles represent the three 30-min walking blocks ($n = 8$).

performance outcomes ($p > 0.05$). For an overview of all cognitive performance measures in both solar radiation conditions see [Appendix A](#). Further, there were no condition or interaction effects found for experienced cognitive workload. This indicates that the cognitive workload was not perceived differently due to the solar condition and that the decrease in cognitive workload score over time was not larger in one of the solar radiation conditions ([Figure 6](#)).

2.3. Associations

As there was no separate effect of condition on T_b , the two data points per participants (i.e. T_b and cognitive result in both conditions) are included in the following graphs. Two significant relations were observed between physiological and cognitive outcome parameters. Firstly, there was a significant positive relation between T_b and scoring above average on accuracy of the visual detection task ($p = 0.019$, [Figure 7](#)). The odds (i.e. probability to occur divided by the probability to not occur) were 6.3, indicating that for a T_b raise from 37°C to 37.5°C there was a

6.3 times higher chance of accuracy being less accurate. The probability (i.e. fraction of times expecting to see it in many trials) of this performance decline to occur at $T_b = 37.5^\circ\text{C}$ was 82%. The opposite goes for T_b and scoring above average on false alarm rate of the visual detection task, where a significant negative relation was observed ($p = 0.003$, [Figure 7](#)). The odds were 10.5, indicating that for a T_b raise from 37°C to 37.5°C there was a 10.5 times higher chance of false alarms being 1 (i.e. more false alarms). The probability of this performance decline to occur at $T_b = 37.5^\circ\text{C}$ was 79%.

3. Discussion

The aim of the present study was to evaluate cognitive performance in two green-flag (28.6°C) WBGT_{eff} conditions that were designed differently; using high or low solar radiation levels (900 Wm^{-2} and 300 Wm^{-2} respectively). We found that differences in solar radiation with similar WBGT may not cause large systematic differences in cognitive performance; but there were significant associations to performance decline dependent on the level of individual heat strain. This finding supports the theory that cognitive performance deterioration is dependent on the total heat load, which was similar in both solar conditions (i.e. 3707°Cmin in high and 3708°Cmin in low). Because T_{re} was higher in the low solar radiation condition and mean T_{sk} was higher in the high solar radiation condition, it seems that the body has distributed heat differently between conditions. Only certain aspects of cognitive performance (i.e. attention and inhibition) seem to be partly associated with T_b rather than solar radiation during relative low (green flag) heat stress levels.

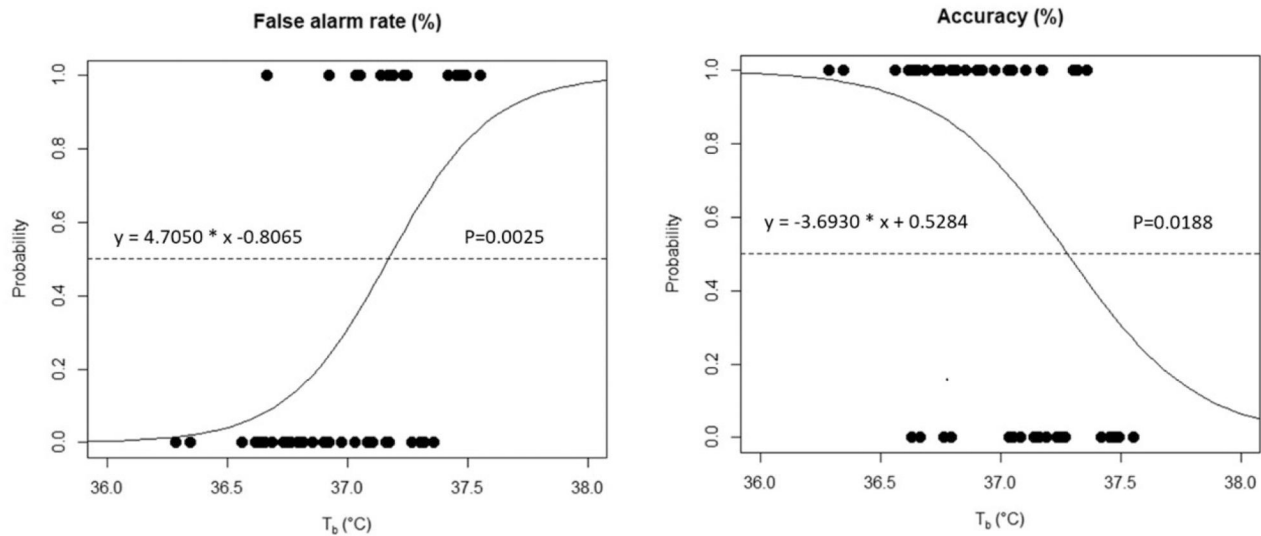


Figure 7. Sigmoid curves that show the significant relations between mean body temperature (T_b) and scoring below (0) or above average (1) on false alarm rate (%) and accuracy (%) of the visual detection task. 0 denotes a score below average (i.e. disadvantageous in terms of accuracy but beneficial in terms of false alarms). 1 denotes a score below average. The corresponding regression equation and p -values are shown in the graphs.

4.1. Physiological

First and foremost, it is essential to elaborate on the physiological responses that occurred in the present study. Where HR was unaffected by the conditions, T_c increased more with low solar radiation. The larger raise in T_c is probably due to the higher environmental temperature in that condition (32°C and 23°C). The relatively high environmental temperature causes a relatively small air-to-skin temperature ratio, restricting conductive and convective heat loss. The higher T_c and larger T_c raise in the low solar radiation (but higher environmental temperature) condition could be caused by the restricted conductive heat loss potential. The direct effect of solar radiation on human skin was observed in the present study as a continuously higher mean T_{sk} in the high compared to the low solar radiation condition. When combining T_c and mean T_{sk} in one single parameter, T_b , we found that the T_b increase in the low solar radiation condition was higher compared to the high solar radiation condition. However, baseline T_b was slightly higher in the high solar radiation condition and increased less. This resulted in a similar total heat load (Figure 5).

4.2. Cognition

There were no statistical effects of condition on any of the cognitive outcome measures (Appendix A). An explanation for this finding could be that the total thermal load for T_b was similar between conditions

and T_b is known to negatively affect cognitive performance (Martin et al. 2019; Gaoua et al. 2012; Brothers et al. 2009; Wilson et al. 2006; Hancock and Vasmatazidis 2003). Scores on cognitive outcomes measures were in general relatively high. This could imply that the participants were able to cope well with the situation, preventing a considerable cognitive performance reduction. Another possibility could be that the T_c raise was insufficient to actually deteriorate cognitive performance. Previous research reported considerable cognitive performance reduction when T_c increased by 2°C (Sun et al. 2012; Gaoua et al. 2011; Hocking et al. 2001; Lee et al. 2014; Liu et al. 2013; Racinais, Gaoua, and Grantham 2008; Simmons et al. 2008). The effect was less in situation with a 1°C T_c increase. In the present study, the reported T_c increase was up to 1°C. In relation to this, another study found that there was no effect of solar radiation on cognition in neutral conditions (20°C WBGT) (Ioannou et al. 2021). The physiological responses of their 20°C WBGT condition (high solar: $T_c \sim 37.6^\circ\text{C}$ and $T_{sk} \sim 34.5^\circ\text{C}$; low solar: $T_c \sim 37.6^\circ\text{C}$ and $T_{sk} \sim 34.3^\circ\text{C}$) were relatively similar to the present study (high solar: $T_c \sim 37.6^\circ\text{C}$ and $T_{sk} \sim 35.0^\circ\text{C}$; low solar: $T_c \sim 37.6^\circ\text{C}$ and $T_{sk} \sim 34.6^\circ\text{C}$). It might therefore be that in such environmental conditions the thermal stimulus was not sufficient to elicit a cognitive performance reduction on group level per se. The aforementioned study did find a cognitive performance reduction in a hot condition (30°C WBGT) (Ioannou et al. 2021). Corresponding physiological responses in the high solar ($T_c \sim 38.3^\circ\text{C}$,

T_{sk} 38.5 °C) and low solar radiation condition (T_c ~38.1 °C, T_{sk} 36.8 °C) considerably exceeded the present study. Whilst T_c did not differ much between their high and low solar radiation condition, the ~3 °C higher T_{sk} stands out and might have caused (part of their) cognitive performance reduction. It could also be that the worn helmet reduced radiative exposure of the head. In a recent study (Piil et al. 2020) where a direct effect of sun exposure was found, indeed participants did not wear any type of hat. On the other hand, the military helmet is highly insulative and limits the ability to dissipate heat. Likewise, as the clothing ensemble covered almost the entire body surface (i.e. except from the hands, part of the neck and face) this could have been protective against the impact of solar radiation on cognitive performance. Further, based on logistic regressions we found that T_b is a risk factor for the attention and inhibition aspects of cognitive performance (i.e. as elucidated by the visual detection task). This finding is in agreement with previous research (Hancock 1986; Doohan 2022; Schmit et al. 2017; Hancock and Vasmatazidis 2003). It could be that the visual detection task was mostly affected due to distraction as this task was carried out during the scenario. Other tasks such as the GMLT were carried out during breaks. However, for instance the auditory response task was also performed during walking and was unaffected. Therefore, it remains unclear why only this aspect of cognitive performance were affected.

Interestingly, the cognitive workload scores did not differ due to solar radiation. The cognitive scores varied between ~3 ('average') and ~4 ('low') in both conditions. During the last experimental blocks, scores of experienced cognitive workload seemed higher (i.e. less experienced cognitive workload) in the high solar radiation condition. However, this difference was not statistically significant. Previous research suggested a hypothetical relation between (cognitive) task demands, workload and effort (Veltman and Jansen 2003). Their model shows that an inverted-U relation can be observed between task demands and performance in a task situation depending on the workload. At the moderate or high levels of workload, performance can still be unchanged but the extra effort that was put in could have been significantly increased. In relation to the present study, cognitive performance was not affected by high or low solar radiation at a certain workload. According to the model presented, it could however also be that the effort that was put in the task to sustain the optimal performance differed between conditions.

4.3. Practical implication

Based on the findings in the present study, there does not seem to be reason to adjust WBGT guidelines for the military regarding cognitive performance in a green-flag WBGT_{eff} (28.6 °C) condition. Even though body heat was likely distributed differently (i.e. towards the core or the periphery), the total thermal load may have the most impact on cognitive performance. Future research should confirm such suggestions and, more importantly, should focus on the effects of solar radiation with higher corresponding WBGT-values (i.e. orange, red, and black flag).

4.4. Limitations

A limitation to the present study could be that we evaluated cognitive performance in a virtual-reality rather than a real life setting. The most common way to evaluate cognitive performance is using computer based tasks. Due to the nature of military employment it is not ecologically valid to evaluate cognitive performance on a computer. By using the virtual-reality environment and selecting cognitive tests that are relevant for military field work, we have tried to reach a real life setting in a controllable way. It could be that real-life situations would lead to different results. On the other hand, using the virtual-reality environment computer based tasks were brought closer to reality. This could be considered a strength as well. In addition to the virtual-reality setting rather than a real life setting for cognitive evaluation, the environmental conditions were also a representation from reality (i.e. climate chamber rather than outside in the field). It could be that there are separate effects of wind and ultraviolet radiation, for example, which have not been considered here. In brief, it is recommended that the translation of such findings to reality will be verified. Another limitation could be that the complexity of the cognitive tasks was not high enough to show differences in cognitive performance. The relatively high cognitive scores would support this theory. However, there is no measurement that confirms such ideas. Lastly, it would have been interesting to evaluate the effect of solar radiation on cognition in women too. As the distribution of heat across the body varies as a function of gender, the physiological and cognitive outcomes may be different in women. On the other hand, we suggested that total thermal load rather than heat distribution determines cognitive performance. If true, the gender differences in this experiment may be negligible. Future research should clarify this. Lastly, whilst the number of participants in

this study ($n=8$) is a relevant amount for the military (i.e. in agreement with military squad size), for research purposes it would be good to include more participants in future research.

4.5. Conclusions

Differences in solar radiation (900 Wm^{-2} and 300 Wm^{-2}) with similar green-flag effective WBGT (28.6°C) do not cause large systematic differences in cognitive performance. Certain aspects of cognitive performance (i.e. response inhibition and spatial working memory) seem to be partly associated with mean body temperature rather than solar radiation.

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Appendix A

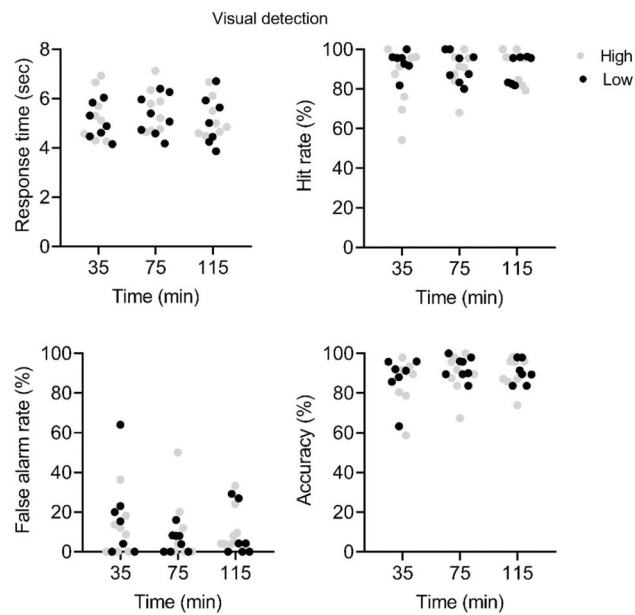


Figure A1. Response time, hit rate, false alarm rate and accuracy on the visual detection task. Grey dots show the high solar radiation condition. Black dots show the low solar radiation condition ($n = 8$).

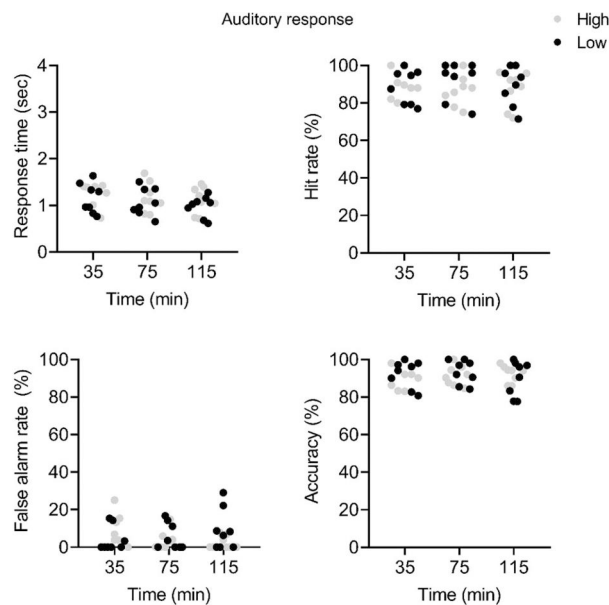


Figure A2. Response time, hit rate, false alarm rate and accuracy on the auditory response task. Grey dots show the high solar radiation condition. Black dots show the low solar radiation condition ($n = 8$).

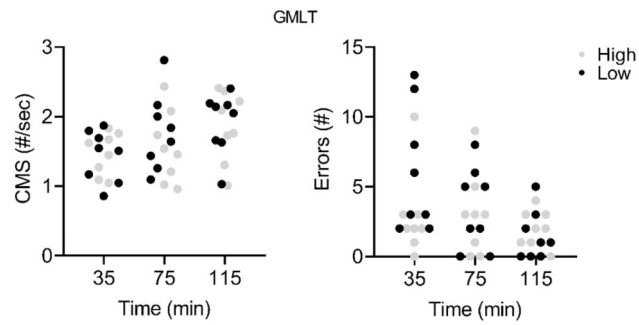


Figure A3. Mean correct moves per second (CMS) and number of errors on the Groton maze learning test (GMLT). Grey dots show the high solar radiation condition. Black dots show the low solar radiation condition ($n = 8$).

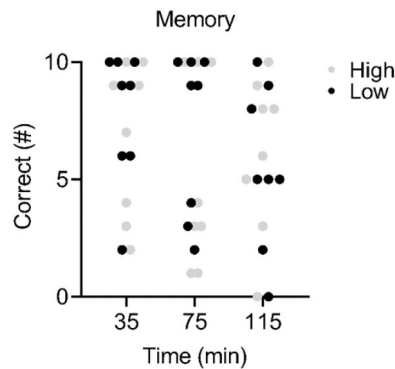


Figure A4. Number of correct pictures on the memory task. Grey dots show the high solar radiation condition. Black dots show the low solar radiation condition ($n = 8$).

Appendix B

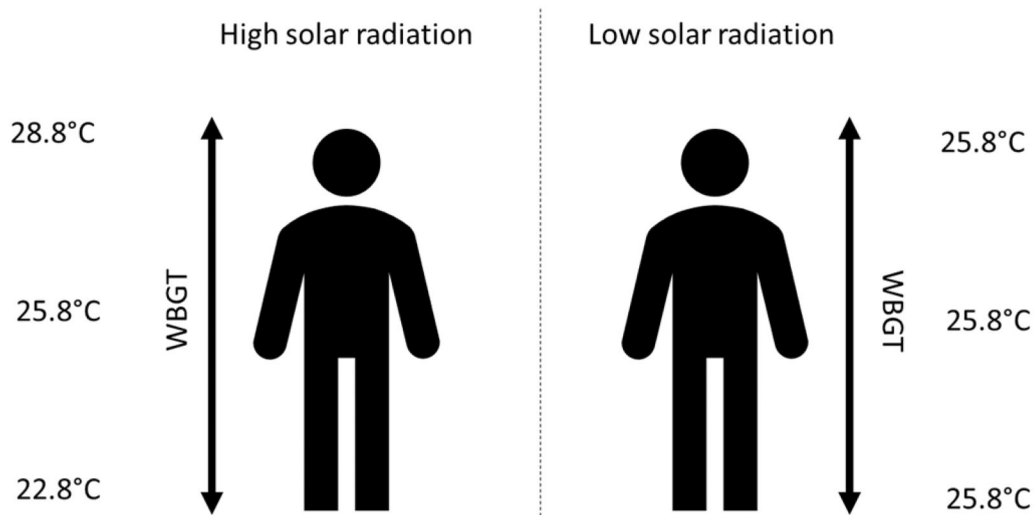


Figure B1. Wet-bulb globe temperature (WBGT) at different body levels (i.e. head, waist, feet) in the high and low solar radiation conditions.