Sensory displeasure reduces complex cognitive performance in the heat

N. Gaoua, a,*, J. Grantham, a, S. Racinais, a, F. El Massioui, b

a Research and Education Centre, ASPETAR — Qatar Orthopaedic and Sports Medicine Hospital, Doha, Qatar
b Laboratoire Cognition Humaine et Artificielle (CHart), UFR de Psychologie, Université Paris 8, France

ARTICLE INFO

Article history:
Available online 12 January 2012

Keywords:
Attention
Planning task
Brief exposure
Heat
Affects

ABSTRACT

The aim of this study was to verify that in a hot environment, the subjective state could affect cognitive performance before any increase in core temperature. Eighteen volunteers performed a planning (OTS) and a reaction time task in hot and control environments. Before starting the cognitive assessment, subjects completed the Positive and Negative Affect Schedule (PANAS) and provided subjective measures of thermal comfort and thermal sensation. Our results showed that while simple tasks were not affected, complex cognitive task performance was significantly reduced in the HOT. Furthermore, although subjects responded faster during the complex task (OTS) they took longer to find the correct solution. Within the 15 min of heat exposure, skin temperature (Tskin) significantly increased by ~3 °C. However, core temperature remained unchanged and there were cortical excitability alterations that could have influenced cognitive performance. Therefore, the increase in Tskin appears to be a sufficient physiological response to alter the subjective state of individuals and impair effective decision-making that could have important consequences in occupational settings.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Increasing evidence demonstrates that prolonged passive heat exposure of sufficient intensity and duration induces hyperthermia and is associated with adverse effects upon cognitive function (Gaoua, Grantham, Girard, El Massioui, & Racinais, 2011; Gaoua, Racinais, Grantham, & El Massioui, 2011). Hyperthermia also affects a number of neuromuscular indices, such as, voluntary force production and voluntary activation (Racinais, Gaoua, & Grantham, 2008). Given the contribution that these variables have upon human performance, physiological studies have identified cortical, spinal and peripheral triggers for these decrements in relation to increases in core temperature (Tcore) (Racinais et al., 2008).

Despite the methodological discrepancies between studies in the intensity and duration of heat exposure, previous reviews have concluded that cognitive function is essentially unaffected unless thermal stress is sufficient to change Tcore away from homeostatic or steady state conditions (Hancock & Vasmatzidis, 2003). An early study revealed that as Tcore increased to 38.5 °C, vigilance task performance improved but complex task (mental addition) performance was reduced (Wilkinson, Fox, Goldsmith, Hampton, & Lewis, 1964). While passively increasing Tcore up to 38.7 °C augmented the speed of response, it did not affect accuracy during a reasoning task (Allnut & Allan, 1973). Another passive heating protocol that induced an increase in Tcore to 38.97 °C failed to significantly affect either short or long-term memory (Holland, Sayers, Keatinge, Davis, & Peswani, 1985). These contrasting results suggest that the physiological literature remains equivocal as to whether it is the absolute change in Tcore or surpassing a critical body temperature that is associated with impaired cognitive function.

More recently, it was suggested that cognitive function is more sensitive to environmental temperature changes per se than to the associated physiological response (Hancock & Vasmatzidis, 2003). An early study demonstrated there is an inverted U-shaped relationship between performance and the level of thermal stress (Pepler, 1958). It was subsequently proposed that performance efficiency does not necessarily become impaired at a higher absolute Tcore but rather when Tcore is in a dynamic state (Hancock & Vasmatzidis, 2003). This conclusion was confirmed when a negative correlation was found between both simple and choice reaction time performance and the rate of change in Tcore (Ramzjou & Kjellberg, 1992).

It becomes apparent that cognitive function is not solely responsive to changes in Tcore and the associated physiological perturbations. In fact, short heat exposures of less than 30 min have induced complex task performance decrements, which are unlikely to have originated from variations in Tcore (Ramsey & Kwon, 1992).
In addition, improvements in reaction time were improved immediately upon exposure to a hot environment (Grether, 1973) possibly due to an increase in nerve conduction velocity (De Jesus, Hausmanowa-Petrusewicz, & Barchi, 1973), which decreases the latency in the transmission of the motor action potential (Racinais et al., 2008).

Several observations from our laboratory suggest an influence of skin temperature ($T_{\text{skin}}$) upon cognitive function. First, we demonstrated that selective cooling head skin during whole-body hyperthermia could preserve some complex cognitive functions (Gaoua, Racinais et al., 2011). Second, while investigating the effects of prolonged heat exposure, we observed a decrement in complex task performance immediately upon heat exposure when only $T_{\text{skin}}$ was significantly increased (Gaoua, Grantham et al., 2011). However, in the second instance we cannot ignore the possible adverse impact of the subject’s apprehension to spending the subsequent 5 h in environmentally stressful conditions.

Therefore, we hypothesize that in the absence of $T_{\text{core}}$ variations the subjective state of individuals could represent the main factor affecting cognitive performance in hot environments. We will use the alliesthesial effect (Cabanac, 1971), as it relates to heat exposure, as an explicative model. In addition, different cognitive tasks appear to have varied performance thresholds and response patterns during heat exposure (Hancock & Vasmatzidis, 2003) with tasks requiring less attention being less sensitive than more demanding tasks (Gaoua, Grantham et al., 2011; Gaoua, Racinais et al., 2011; Hancock & Vasmatzidis, 2003; Ramsey & Kwon, 1992). To reduce the influence of a rise in $T_{\text{core}}$ 18 volunteers participated in experimental trials in hot and neutral environments to investigate simple and complex cognitive performance immediately upon exposure to a hot environment. To minimize the possible adverse effect of apprehension associated with prolonged heat exposure, subjects were informed that the duration of the experiment would be less than 30 min.

2. Methods

2.1. Subjects

Eighteen volunteers (11 males and 7 females, 33 ± 1.36 y, 75 ± 3.58 kg and 175 ± 2.12 cm for age, weight and height, respectively) participated to the study. Subjects were asked to avoid all vigorous activity for the 24 h preceding the test. This study was approved by the Institutional Ethics Committee and designed in accordance with the 1964 Helsinki Declaration.

2.2. General procedure

One week before commencing the experimental trials subjects completed a familiarization session. Using a counter-balanced design subjects then completed two experimental trials in hot (HOT) and control (CON) conditions, separated by at least four days of recovery. Both experimental trials were conducted at the same time of the day in an environmental chamber (Tescor, Warminster, PA, USA), with constant noise and light. During both trials subjects wore shorts and t-shirt and completed tests for subjective measures, cognitive performance and transcranial magnetic stimulation (TMS). In order to avoid the confounding effects of dehydration, water was provided ad libitum throughout both experimental trials to maintain body weight within 1% of the pre-test value.

Familiarization trial. One week before starting the trials, the subjects were familiarized with the experimental procedures for the subjective scales, the cognitive testing and TMS. The software used for the cognitive testing battery (see below) provided a familiarization procedure for each test before completing the full test procedure of both cognitive tests.

Experimental trials. Subjects entered the room and rested for 5 min in a seated position. Before starting the cognitive assessment the subjects completed the Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988) and measures of thermal comfort (Tc) and thermal sensation (Ts) obtained from subjective visual scales. Subjects then reported their perceived $T_{\text{core}}$ before their actual $T_{\text{core}}$ and $T_{\text{skin}}$ were recorded. Following this the subjects completed both cognitive tests (described below) before the TMS was applied on the cortex in the hemisphere, which innervated the dominant arm. The room was set at 24 °C and 30% RH and 50 °C and 30% RH in CON and HOT trials, respectively.

2.3. Temperature recording

$T_{\text{core}}$ and chest $T_{\text{skin}}$ were monitored using the VitalSense® system (resolution 0.01 °C, Mini Mitter, Respironics, Herrsching, Germany). A wireless Jonah™ ingestible thermometer pill was swallowed at least 5 h before each trial to measure $T_{\text{core}}$ (Gaoua, Grantham et al., 2011; Gaoua, Racinais et al., 2011). Chest $T_{\text{skin}}$ was monitored with Mini Mitter XTP wireless adhesive dermal temperature patch. Both $T_{\text{core}}$ and $T_{\text{skin}}$ sensors sent data by telemetry to and recorded by the same data logger every 60 s.

2.4. Subjective measures

Measures for Tc and Ts were recorded on scales ranging from very cold to very hot (green to red scale) and from very comfortable to very uncomfortable (white to black graduation), respectively (Fig. 2). Corresponding scores ranging from 0 to 20 were on the reverse side of both scales and only visible to the researcher. Higher scores represented feeling hotter and less comfortable for Ts and Tc, respectively.

The PANAS is a 20-item self-report psychometric scale developed to measure the largely independent constructs of positive (PA) and negative (NA) affects as both states and traits (Watson et al., 1988). PA and NA have been shown to relate to other personality states and traits, such as anxiety (Stone, 1981). NA and PA reflect dispositional dimensions, with high-NA epitomized by subjective distress and unpleasurable engagement, and low NA by the absence of these feelings. By contrast, PA represents the extent to which an individual experiences pleasurable engagement with the environment. Emotions such as enthusiasm and alertness are indicative of high PA, whilst lethargy and sadness characterize low PA (Watson & Clark, 1984).

2.5. Cognitive testing

An attention task (RTI: Reaction Time) and a planning task (OTS: One-Touch Stockings of Cambridge) were performed in a seated position during both experimental trials using CANTAB software (CANTABeclipse, Cambridge Cognition, Cambridge, UK) and hardware (13.3” tactile screen and touch pad). The order of the cognitive tests was counter-balanced between subjects to reduce any order effect, but kept constant within subject.

RTI. This task is designed to measure the subject’s speed of response to a visual target where the stimulus is either predictable (SRT; simple reaction time) or unpredictable (5-CRT: 5-choice reaction time). Each section is divided into practice and test phases. In the first phase the subjects had to hold the press pad button down, then release it and touch the screen when a yellow spot appears in the centre of the screen, neither touching too soon nor too late. In the second phase, the yellow spot can appear in any one of five locations. In each practice session subjects were required to
make at least 9 out of 10 correct responses before progressing to the test phase. If the subject failed to reach this criterion they were given a second trial after which the task proceeds to the test block irrespective of how well the subject has performed. The outcome measures were the simple reaction time, the 5 choice reaction time and the simple accuracy score and the five choice accuracy score.

OTS is a planning task where subjects were shown two displays containing three coloured balls. The displays were presented in such a way that they could be perceived as stacks of coloured balls held in stockings suspended from a beam (Fig. 1). Along the bottom of the screen there was a row of numbered boxes. Subjects were initially shown how to move the balls in the lower display to copy the pattern in the upper display. The experimenter completed one demonstration problem, where the solution required one move, followed by the subjects completing three further practice problems, one each of two, three and four moves before starting the test. For the test itself, subjects were shown other problems, and had to mentally calculate the minimum number of moves required to solve the problems, and then to touch the corresponding box at the bottom of the screen to indicate their response. The outcome measures were the number of problems solved on the first choice (accuracy), the latency to first choice and the latency to the correct choice (latency) for two different levels of complexity that required four (OTS-4, simple) and six moves (OTS-6, complex). Each measure was obtained by averaging the score over four trials.

2.6. Transcranial magnetic stimulation (TMS)

TMS was delivered on the motor cortex to estimate cortical excitability. A circular coil (13.5 cm outside diameter) was positioned over the left vertex with direction of the current mostly activating the left motor cortex. All subjects were right handed and wearing a 3 kg weight in the right arm. Stimulations were elicited at an intensity of 100% of the magnetic stimulator (Magstim 200, MagstimCo, Dyfed, UK). The average of 6 motor evoked potentials (MEP) recorded from the biceps femoris via surface EMG (Biopac System Inc, Santa Barbara, CA) was considered for analysis.

2.7. Statistical analysis

Statistical analyses were performed using Predictive Analytics Software PASW (Version 18.0). A paired-samples t-test was conducted to compare measures in HOT and CON conditions. A p-value < 0.05 was considered statistically significant.

3. Results

3.1. Temperature

There was a significant difference (−2.82 °C, t (17) = −7.23, p < 0.001) in the Tskin in HOT (M = 36.07, SD = 1.50) and CON (M = 33.26, SD = 0.35) conditions (Fig. 3). There was no significant difference in Tcore between HOT and CON (t (16) = 0.57, p = 0.57).

3.2. Subjective measures

Subjects perceived themselves to be significantly hotter when they were in HOT (t (16) = −5.7, p < 0.001, Fig. 4A, +3 °C) but not in CON (Fig. 4A, −0.2 °C, NS). Subjects felt hotter (Ts, t (17) = −10.36, p < 0.001) and less comfortable (Tc, t (17) = −4.78, p < 0.001) in the HOT condition than in CON (Fig. 4A). The responses on the PANAS questionnaire indicated that subjects had more NA in HOT (Fig. 4B, t (17) = −4.01, p = 0.001). However, there was no difference in the PA between conditions (t (17) = 0.08, p = 0.93).

3.3. Cognitive functions

There was no significant difference between conditions in reaction times and accuracy measures for both complexity levels (CRT and 5-CRT) of the RTI test (Table 1, t (17) ≤ 1.84, p > 0.08). There was no significant difference in OTS-4 between conditions for both accuracy and latency (Table 2, t (17) ≤ 1.15, p > 0.26). Performance was significantly better in CON than in HOT for the OTS-6 (Table 2, t (17) = 2.53, p = 0.022). However, subjects answered faster in HOT than in CON (t (17) = 2.34, p = 0.032) but took more time to find the correct response (Table 2, t (16) = −3.02, p = 0.008).

3.4. Transcranial magnetic stimulation

There was no significant difference in the amplitude of MEP between conditions (t (13) = −1.01, p = 0.333).

4. Discussion

The aim of this study was to investigate simple and complex cognitive performance immediately upon exposure to a hot environment, in the absence of Tcore variations. Our results showed that complex cognitive task performance was altered in HOT independently of variation in Tcore or cortical excitability alterations.
This confirms previous studies that have suggested that $T_{\text{skin}}$ is more responsive to the environmental stimuli than to an increase in $T_{\text{core}}$ (Hancock & Vasmatzidis, 2003). In the HOT condition, OTS-6 was reduced presumably in response to the sudden change in environmental conditions. Within 15 min of entering the environment the cognitive trial was completed. During this period $T_{\text{skin}}$ increased by $\sim 3$ °C (Fig. 3), however, there was no change in $T_{\text{core}}$ or motor cortical excitability (MEP) that could have influenced OTS-6 performance (Gaoua, Grantham et al., 2011). These findings suggest that a trigger other than $T_{\text{core}}$ was related to the increase in $T_{\text{skin}}$ and responsible for the impaired complex cognitive performance.

The alliesthesial effect (Cabanac, 1971) suggests that complex cognitive performance in HOT may have been influenced by the feelings of displeasure induced by the rapid increase in $T_{\text{skin}}$. The self-reported PANAS scale revealed that subjects experienced more negative feelings in HOT, which coincided with them also reporting they felt hotter and less comfortable. Thermal stimuli can induce either feelings of pleasure or displeasure depending on the existing thermal conditions. Therefore, pleasurable thermal stimuli return the body to, while unpleasurable thermal stimuli take the body away from its homeostatic state (Cabanac, 1987). Environmental temperature variations imposed on different skin regions influence the thermal perception of heat stress due to the alliesthesial effects of sweat rate and convection, independently of $T_{\text{core}}$ (Mower, 1976).

This was seen when increasing the environmental temperature from 22 to 30 °C reduced thermal comfort and mental performance (Lan, Wargocki, Wyon, & Lian, 2011). It has been suggested that a $T_{\text{skin}}$ of 32–33 °C corresponds to the homeostatic state (Lan et al., 2011), while the average $T_{\text{skin}}$ recorded in the HOT trial was 36 °C. In the current study there was also no change in $T_{\text{core}}$ in either environmental condition, therefore, it could then be concluded that the sudden change in $T_{\text{skin}}$ and the unpleasant response induced by a raise of $\sim 25$ °C in environmental temperature in the HOT trial could have had similar detrimental alliesthesial effects on complex cognitive performance.

Decrement in cognitive performance have been attributed to the impossibility to achieve complete physiological compensation to hot environments and the transition from a dynamic stability to a dynamic instability (Hancock & Warm, 1989). Given the short duration of heat exposure in the current study participants were able to compensate for the environmental temperature and did not develop hyperthermia. However, there was still instability led by the compensatory process that facilitated the maintenance of homeostasis. Therefore, our data complete this previous model by revealing that it is not the impossibility to compensate that leads to a decrement in cognitive capacities but the compensatory processes themselves.

Our laboratory (Gaoua, 2010) recently proposed the Global Workspace theory (Baars, 1993) as a possible explanation for the

| Table 1 |

<table>
<thead>
<tr>
<th>Reaction Time (RTI)</th>
<th>CON (M, SD)</th>
<th>HOT (M, SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple</td>
<td>261.22 (±34.2)</td>
<td>258.11 (±29.9)</td>
</tr>
<tr>
<td>Complex</td>
<td>294.56 (±39.18)</td>
<td>289.88 (±37.87)</td>
</tr>
<tr>
<td>Accuracy (nb)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple</td>
<td>14.61 (±0.61)</td>
<td>14.67 (±0.6)</td>
</tr>
<tr>
<td>Complex</td>
<td>14.61 (±0.61)</td>
<td>14.11 (±1.02)</td>
</tr>
</tbody>
</table>
decrement in cognitive performance in hot environments. The Global Workspace theory suggests that there are a vast number of subconscious processes, such as maintaining body temperature or mapping the body in space, occurring in parallel to successfully executing routine tasks. In contrast to the vastness of the unconscious, there is a narrow and limited conscious capacity that acts as a gateway and co-ordinator of unconscious processes (Baars, 1993). There is accumulating evidence to suggest that information from a stimulus is distributed to many neuronal populations dispersed throughout the brain (John, 2000). The Global Workspace theory suggests that consciousness enables multiple neuronal networks to cooperate and compete in solving problems, such as retrieving specific items from short-term memory (Baars, 1993). According to this theory, humans have a limited cognitive capacity due to different external stimuli constantly competing for the limited conscious access to the vast global workspace in order to obtain a successful outcome. Therefore, in the current study the alliesthesial response to the rapid increase in $T_{\text{skin}}$ in HOT can be considered as further ‘cognitive load’ that placed additional attentional demands upon a limited conscious workspace and reduced the resources available for the concurrent, cognitive tasks. Performance of cognitive tasks deteriorates when the total cognitive resources are insufficient for both the task and the thermal stress (interfering load) imposed on the subject (Hocking, Silberstein, Lau, Stough, & Roberts, 2001). The cognitive energetic approach (Hockey, 1997) gives additional support to these conclusions. This approach stipulates that behaviours are modified by reference to internal standards and set points (i.e. homeostasis) to maintain the same performance. This regulatory activity generates costs to the emotional and physiological systems that may be interpreted as an expenditure of mental resources. Performance is then maintained only by the increase of energetic costs up to a point where a passive coping mode is adopted by reducing the levels of accuracy and speed of the task itself (Hockey, 1997).

We recently demonstrated using two different complexity levels of the OTS that complex tasks are more vulnerable to the effect of increases in $T_{\text{skin}}$ and/or $T_{\text{core}}$ (Gaoua, Grantham et al., 2011). In the current experiment, the OTS-4 and RTI tasks required fewer cognitive resources than the OTS-6. Consequently, despite the additional cognitive load coming from the rapid increase in $T_{\text{skin}}$ upon exposure to heat, there were sufficient resources to successfully complete the OTS-4 and RTI. However, different cognitive tasks assess different areas of the brain and simply comparing task complexity ignores the different cognitive loads placed on the respective brain regions (Gaoua, 2010; Gaoua, Grantham et al., 2011). The dual complexity levels within the OTS task ensures that the mechanism required for successful task performance and the brain area being assessed remain constant, but the cognitive load required to successfully complete the task is being manipulated. The two different complexity levels of the OTS task were assessed in Gaoua, Grantham et al. (2011) and in the current study. Both studies have demonstrated each complexity level has a different threshold of sensitivity to heat exposure, which provides further evidence of a limited cognitive capacity.

Additional support for this hypothesis comes from neurophysiological imaging studies. These have shown a greater use of neural resources, as seen by an initial increase in electrical activity, to maintain the same cognitive performance in a hot environment (Silberstein et al., 1990) until cognitive resources are overloaded (Hocking et al., 2001), at which time cortical activity may decrease (D’Esposito, Bradley, & Rauch, 2000). However, we have shown that these results were obtained on hyperthermic subjects we can only speculate that such neurophysiological alterations would be applicable during short-term heat exposure in the absence of a $T_{\text{core}}$ increase.

The current study revealed that during the more complex OTS-6 task subjects responded faster (speed of response, mean latency to correct, ms) but made more mistakes (accuracy, OTS-6) in the HOT condition. Consequently, although the initial response was faster subjects took more time to provide the correct answers in the OTS-6. This is in accordance with previous studies that have observed an improvement in reaction time that was associated with a loss of accuracy (Simmons, Saxby, McGlone, & Jones, 2008). A possible explanation for the faster reaction times could be the increase of nerve conduction velocity observed during heat exposure that results in a decreased latency of transmission of the motor drive to the finger that presses on the pad/screen during the cognitive tasks (Racinais et al., 2008). However, in the current study no variations in the RTI performance were observed in HOT. Given that the RTI task also requires subjects to press on the screen as quickly as possible in response to a visual stimulus suggests that the reduced initial response time in OTS-6 was related to another trigger. We have previously shown that impulsivity increases with whole-body hyperthermia possibly due to the alterations in frontal lobe functioning as seen in the decrement in cognitive performance during a complex decision-making task (Gaoua, Grantham et al., 2011). In fact, impulsivity is commonly observed after injury to the frontal lobe and is associated with reduced frontal lobe activity (Floden, Alexander, Kubu, Katz, & Stuss, 2008). Given that the OTS-6 is designed to evaluate frontal lobe functioning, the results from the current study suggest that the observed decrement in HOT could be related to higher levels of impulsivity.

The Somatic Marker hypothesis argues that the decision-making process is influenced by physiological changes related to emotion that surface in the body outside of the brain (Bechara, 2004). It could be argued that in the current study the increase in $T_{\text{skin}}$ and the associated alliesthesial response to sudden heat exposure is one such physiological change to affect the subjective state of the participants and consequently decision-making ability. The significant changes in the self-reporting scales certainly attest to the subjects reacting negatively to the heat stimulus. However, further studies utilising EEG and fMRI techniques may shed light on the mechanisms behind this apparent psychological phenomenon.
Such neural techniques will allow for a better understanding of the interaction between the response to heat exposure, the consequent subjective state and its impact on cognitive performance.

5. Conclusion

A rapid increase in $T_{\text{skin}}$ competes with cognitive resources required for the successful completion of complex cognitive tasks, independent of other physiological alterations. This increase in $T_{\text{skin}}$ appears to be a significant physiological response that can alter the subjective state of an individual and impair effective decision-making. This suggests that the enhanced reactivity to sudden heat exposure could have important consequences in occupational and sporting settings.

References


