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An investigation of heat stress effects on time-sharing performance

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A study was conducted to investigate the effects of heat stress on time-sharing performance. Twelve participants performed three dual-task scenarios and a multiple-task scenario for 2 h in each of six climates. The climates were obtained by generating each of three wet bulb globe temperatures (WBGT; 22, 28 and 34°C) with two relative humidity levels (30 and 70%). The dual tasks selected from the Criterion Task Set (CTS) were: (1) display monitoring with mathematical processing; (2) memory search with mathematical processing; and (3) unstable tracking with memory search. The multiple task scenario was generated using the SYNTASK software. The results indicated a significant heat stress effect on CTS display monitoring and unstable tracking performance and on the SYNTASK visual monitoring and auditory discrimination tasks. Additionally, at 34°C WBGT, 70% relative humidity was more detrimental to performance than 30% relative humidity. Results were interpreted using the Maximal Adaptability Model and Shingledecker's information processing stage/resource framework. To describe the results in an orderly manner, the authors propose the concept of *heat stress selectivity effects*. In addition, the results were used to evaluate whether the most recent NIOSH recommended heat stress standard, which is based solely on physiological and medical criteria, protects time-sharing performance. It was concluded that the NIOSH criterion does offer protection up to 28°C WBGT.

1. Introduction

Numerous studies have investigated the effects of heat stress on *simple* mental performance. Although many of these studies have reported some form of performance decrement (Pepler 1958, Wing and Touchstone 1965, Iampietro *et al.* 1972, Mortagy and Ramsey 1973, Ramsey *et al.* 1975), other studies have indicated that performance remains unaffected (Chiles 1958, Bell *et al.* 1964, Colquhoun 1969, Nunneley *et al.* 1979), or even improves upon exposure to hot environments (Poulton and Kerslake 1965, Lovingood *et al.* 1967, Colquhoun and Goldman 1972, Nunneley *et al.* 1979). In contrast to the availability of information on simple

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performance, there are few studies that have examined the effects of heat on *time-sharing* performance. With respect to *dual-task* performance, the classic studies used a dual-task paradigm consisting of a task presented in the central visual field (tracking or choice reaction time) along with a peripheral light-detection task (Bursill 1958, Provins and Bell 1970, Azer *et al.* 1972, Poulton *et al.* 1974). With this paradigm, a progressive 'funnelling' of attention with increasing temperature was observed. This funnelling is characterized by an increasing proportion of light signals missed in the peripheral visual field compared to the proportion missed in the central visual field.

With respect to more *complex time-sharing* performance (i.e. performance involving three or more concurrent tasks), studies are more scarce. In one such study, Iampietro *et al.* (1969) found horizontal tracking performance (when combined with a monitoring and mental arithmetic task) and mental arithmetic performance (when combined with a monitoring task) to be significantly lower during a 30-min exposure at 71°C (160°F) compared to a 15-min pre-exposure period. In a similar study, Chiles *et al.* (1972) combined tracking with three monitoring tasks and with mental arithmetic and monitoring tasks. They found that tracking efficiency declined significantly during a 15-min exposure at 35°C compared to performance in a thermally neutral environment.

The lack of a systematic pattern of heat stress effects on simple mental performance is due to the variety of thermal, experimental and participant variables that may influence performance (Ramsey 1990, 1995). A second problem in heat stress research related to mental performance is the lack of a concise theoretical model upon which to base experimental work and a systematic interpretation of the recorded results. Thus, it is not surprising that current occupational heat stress standards do not regulate cognitive work in the heat. Instead, they are based on the characteristics and limitations of the human physiological system. In the next two sections, the two most recently recommended heat stress standards in the USA (NIOSH 1972, 1986) are briefly discussed from the mental performance perspective, and a theoretical model upon which future time-sharing cognitive performance research in the heat can be based, is summarized. This model was combined with a multiple-resource pool theory of cognitive performance to form the theoretical structure for the experimental study presented in this paper. This study also investigated the adequacy of the NIOSH (1986) recommended standard in protecting time-sharing performance.

2. Heat stress standards and mental performance

A strong correlation has been shown between hot environments and unsafe behaviour (Ramsey *et al.* 1983). Thus, information on time-shared performance patterns is of particular importance for determining workplace design parameters and exposure limits in complex industrial and military systems where a significant portion of the work is of a cognitive nature. Such systems can impose a high cognitive workload on the human operator (Hancock and Meshkati 1988). This increases the possibility for human error. While it may be argued that environments in which heat is still a problem are not as frequently encountered as in the past, the commission of human errors due to the heat may still prove catastrophic in terms of human and monetary cost. Therefore, it becomes apparent that consideration of complex mental performance in hot environments is very important for the safety of the workers and the systems within which they operate.

The only US recommended standard that attempts to regulate worker exposure in the heat for mental performance was developed by the National Institute for Occupational Safety and Health 30 years ago (NIOSH 1972). NIOSH's recommendation was a transcription from Wing (1965) and established upper tolerance limits for single-task situations only. In pointing to factual and interpretational errors in Wing's original work, Hancock (1981) modified this standard towards less conservative (higher) limits.

The most recent NIOSH revised criteria for exposure to hot environments (NIOSH 1986) ignored the issue of mental performance limitations under heat stress in its entirety. Rather, the criteria define the maximum wet bulb globe temperature (WBGT) level allowed under various conditions of manual workload (expressed in terms of body metabolic heat) and 1-h time-weighted averages, based on physiological responses and medical criteria. This limit for unacclimatized workers and for continuous work (referred to as the Recommended Alert Limit) is presented in figure 1. This limit does permit an indirect test as to its adequacy in protecting mental performance as follows (see also Ramsey 1990).

For a standard worker (70 kg body weight and 1.8 m^2 body surface), mental work represents a metabolic heat of approximately 100 kcal/h. It follows from figure 1 that mental performance at an environmental heat load of 31°C WBGT or higher should be avoided. For acclimatized workers, the respective limit is 33°C WBGT. Ramsey and Kwon (1992) reviewed approximately 150 studies and concluded that simple mental and psychomotor performance deteriorates within the range of 30–33°C WBGT regardless of the exposure duration. Thus, the NIOSH (1986) standard, although not by design, appears to offer some protection against simple mental performance deterioration as well. However, there is no information regarding the effectiveness of the NIOSH (1986) limit in time-sharing situations. This issue is addressed by the present study. In particular, testing of the standard was achieved by selecting WBGT levels surrounding the recommended limit of 31°C, and assessing time-sharing performance at these levels.

A variable that has attracted little attention in the heat stress literature is relative humidity. This is a significant issue since a multiplicity of dry-bulb temperature and relative humidity values can be combined with fixed values of air velocity and radiant heat to generate the same WBGT value. At present, there is no reason to assume that for a specified WBGT value every possible combination of dry-bulb temperature and relative humidity will sustain the same effect on performance capability. For example, Pepler (1958) tested tracking performance under both high (80%) and low (20%) relative humidity conditions, each generated at four different effective temperature (ET) levels (72, 79, 84 and 92°F). For the 80% relative humidity environment, he identified a significant performance decline between the levels of 72 and 79°F ET, whereas for the 20% relative humidity environment a significant decrement was obtained between the higher temperatures of 79 and 84°F. However, this is a rare exception in the literature. Consequently, the effects of relative humidity on complex mental performance under the same WBGT levels were also investigated in the current study. It was hypothesized that data describing performance under low and high relative humidity levels for the same WBGT environment would enable an evaluation of the appropriateness of the WBGT index as the preferred index for setting heat stress standards for mental performance.

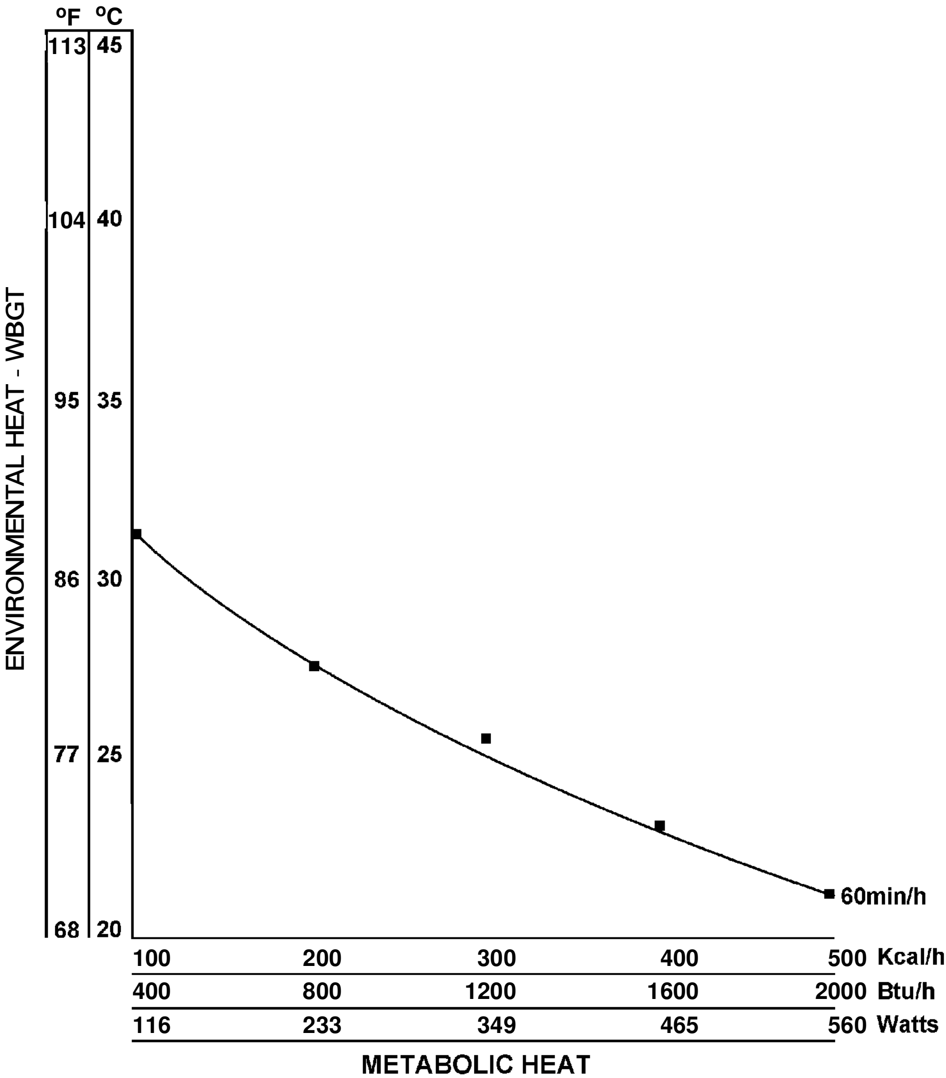

Figure 1. Recommended heat stress alert limits for heat unacclimatized workers and continuous work (NIOSH 1986).

3. Heat stress theories: arousal versus the maximal adaptability model

The lack of a concise theory has been a primary reason for the lack of a systematic interpretation of the literature results on heat stress and mental performance. Such a theory is of paramount importance for guiding future research endeavours. In the past, the inverted-U relationship between mental performance and the arousal level of the performer postulated by the unitary arousal theory (for detailed discussions see Duffy 1951, 1957, 1962, 1972, Lindsley 1951, Hebb 1955) had been used almost exclusively to interpret heat stress effects on cognitive performance (Wilkinson *et al.* 1964, Poulton and

Kerslake 1965, Wing and Touchstone 1965, Griffiths and Boyce 1971, Reddy and Ramsey 1976).

According to this relationship, as the environmental temperature (or body core temperature) rises, the arousal level of the performer increases, which causes performance to improve. At some critical point of ambient (or core) temperature, further improvement in performance is not possible, and performance decreases as heat (and thus arousal) increases further. Provins (1966) was the first to formulate this relationship into a formal hypothesis.

Arousal theory, as related to heat stress research, has undergone substantial criticism, and its validity and robustness have been questioned by various investigators. Hancock (1987) argued that arousal theory is highly descriptive, but its predictive power is very limited. The inverted-U curve has been rarely quantified in the literature, and in general it is freely moved to any location within the performance-arousal domain to fit any available data set (see also Hancock 1984). In another critical review of the arousal construct, Näätänen (1973) argued that it is the qualitative rather than the quantitative aspect of activation of the organism that determines performance efficiency. In other words, at the optimal arousal level, it is not the intensity of activation that guarantees good performance but the elicitation of an optimal pattern of activation with respect to the task situation. According to Näätänen (1973), a performance decrement will be observed when this optimal pattern is altered. For example, in a dual-task situation in a hot environment, performance eventually suffers not because the optimal arousal point has been exceeded, but because heat acts as a distractor that disrupts the optimal pattern of activation corresponding to the optimal time-sharing performance obtained in a thermally neutral environment. Finally, the nature of arousal as a unitary entity has been challenged (a point also made by Hancock 1987). For example, Pribram and McGuiness (1975) proposed three energetical systems that control the function of attention: arousal (centred on the amygdala of the brain), activation (centred on the basal ganglia), and effort (centred on the hippocampus).

A more recent theoretical development is the Maximal Adaptability Model (Hancock and Warm 1989), which attributes performance decrement in the heat to attentional resource depletion. According to this model, illustrated in figure 2, input stress can vary from a negative extreme (hypostress) to a positive extreme (hyperstress). At the middle of this continuum is a region (the normative zone) that requires no compensation on the part of the individual. Surrounding the normative zone is the comfort zone in which cognitive adjustments to task demands are easily obtained, and within which performance remains high. As the level of stress increases (by increasing the exposure duration or the intensity level of the stressor, or both), attentional resources are progressively drained. Initially the remaining resources are effectively utilized by the individual, and the net result is no performance decrement, and sometimes performance improvement. This behaviour is a reflection of psychological adaptability and is observed within the zone of maximal psychological adaptability. At higher levels of stress, the continuous drain of attentional resources eventually hurts performance. At these stress levels, performance deteriorates at an exponential rate. This is shown in figure 2 by the steep fall of the dashed line starting at the boundary of the psychological zone of maximal adaptability. A further increase in stressor intensity eventually moves the body outside the zone of homeostasis (physiological zone of maximal adaptability) toward the region of dynamic instability, a life-threatening condition.

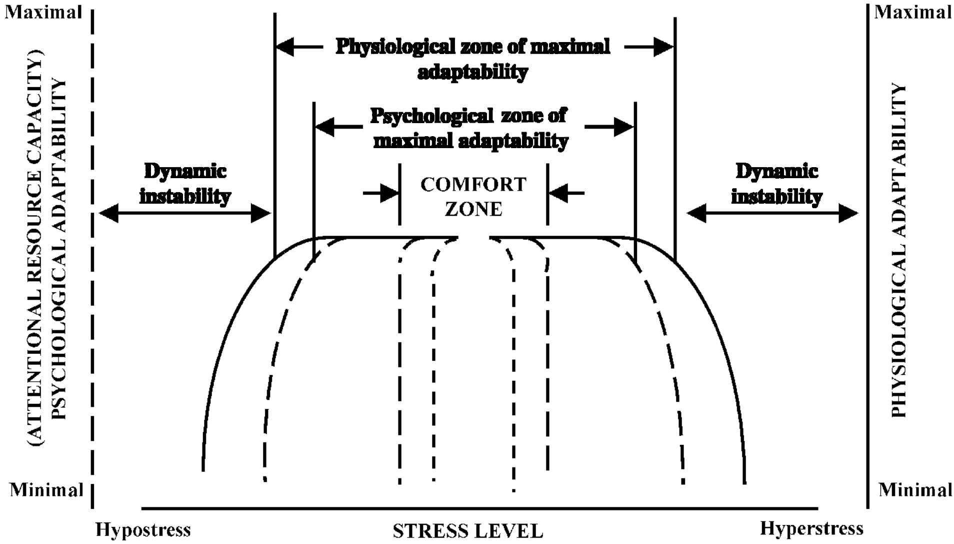

Figure 2. The Maximal Adaptability Model. (Reprinted with permission from *Human Factors*, Vol. 31, No. 5, 1989. Copyright 1989 by the Human Factors and Ergonomics Society. All rights reserved)

An unspecified behaviour of the Maximal Adaptability Model is whether heat drains resources from a global, undifferentiated pool as postulated by single-pool resource theories (Kahneman 1973), or whether the resource depletion is more selective in the sense that some individual resource pools (if one assumes the existence of such pools as in Wickens 1980, 1984, 1987) are more sensitive to heat stress effects than others. Hancock and Warm (1989) reported that at the time of their publication, insufficient experimental information was available to allow even preliminary speculations on this issue. It is interesting to note that, with respect to heat stress, no studies have been conducted since then to address this important research area. Hence, the issue of determining whether a potential pattern exists during cognitive resource depletion under heat stress remains largely unresolved.

Assuming that the mechanism of heat stress-induced performance decrement is cognitive resource depletion, the present study was designed to investigate whether certain types of cognitive resources are more profoundly affected by heat stress than others under time-sharing conditions. Such a differential pattern of effects is designated here as a *heat stress selectivity* pattern.

4. Objectives of the study

The objectives of the present study were to:

(1) determine whether certain cognitive tasks are more profoundly affected by hot environments than are others under dual-task and complex time-sharing conditions (study of the heat stress selectivity pattern);
(2) determine whether different levels of relative humidity contributing to the same levels of WBGT have a different impact on time-shared performance; and

(3) test whether the most recent NIOSH (1986) recommended heat stress standard, based solely on physiological and medical criteria, adequately protects operator time-sharing performance. Performance decrements at temperatures below the upper WBGT limit as specified by the NIOSH criterion would point to the need to augment this criterion.

5. Method

5.1. *Experimental tasks*

Time-sharing performance was assessed using three dual-task scenarios from the USAF Criterion Task Set (CTS; Shingledecker 1984) and the Synthetic Task Set (SYNTASK; Elsmore 1992). The CTS battery was developed with the hypothesis that the human information processing system is comprised of three primary stages: perceptual input, central processing and response output. These stages can be further divided into modes of processing and activities/functions. For the stage of perceptual input, two modes are possible: visual and auditory. The central processing stage involves either spatial/imaginal or abstract/symbolic processing of information (codes), or the activities of working memory. Finally, the modes of operation for the response stage are manual or vocal. This structure is presented in figure 3. Operation of the stages, modes, and activities requires investment of specialized cognitive resources. Thus, the theoretical basis of the CTS battery is a multiple resource pool construct. Assuming resource depletion in the heat according to the maximal adaptability model, employment of the CTS battery allows for an investigation of a selectivity pattern under heat stress.

The CTS dual-task pairings used in the study were as follows.

(1) *Display Monitoring (DM) with Mathematical Processing (MP).* DM requires continuous monitoring of a simulated meter to determine whether a bias condition is present (the pointer stays on one side of the meter's

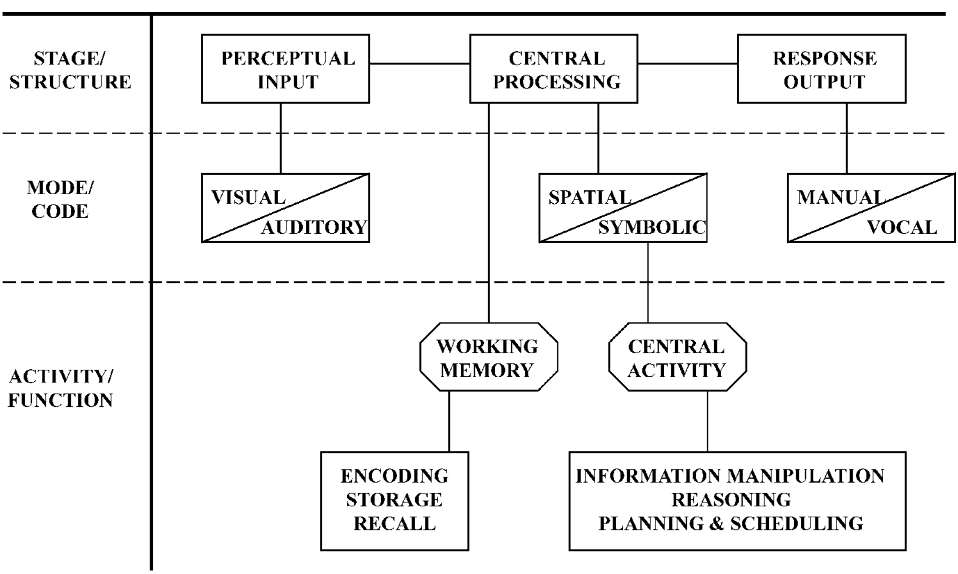

Figure 3. Stages, modes and activities hypothesized in the CTS battery (Shingledecker 1984).

centreline for 95% of the time). MP involves determining whether the result of an arithmetic expression involving three single-digit numbers and two operators (+ and/or −) is greater than or less than the value 5. The DM-MP dual task is illustrated in figure 4(a).

(2) *Memory Search (MS) with Mathematical Processing (MP)*. MS consists of memorizing an initial set of four letters (positive set) and indicating whether subsequent letters presented one at a time are members of the positive set. The MS-MP dual task is illustrated in figure 4(b).

(3) *Unstable Tracking (UT) with Memory Search (MS)*. In UT, the participant attempts to keep the horizontal position of a cross-shaped cursor aligned with a defined line in the centre of the screen. The dynamics of the task magnify the control error to prevent stable control. The degree of instability can be controlled by adjusting the instability factor lambda (λ). In the experiment, λ was fixed at 3.0. The UT-MS dual task is illustrated in figure 4(c).

Responses to the CTS tasks were made using a push-button device (DM, MP and MS) and a rotary control (UT).

Within the framework of Shingledecker's model, the specific cognitive resources required by each of the selected CTS tasks can be expressed as follows.

(1) *Display monitoring:* A predominantly visual perceptual input (visual vigilance) task.
(2) *Mathematical processing:* A central processing, working memory task that also involves symbolic code manipulation.
(3) *Memory search:* A working memory (storage and recall) central processing task.
(4) *Unstable tracking:* A predominantly manual, response-output task, that also involves perceptual input.

The SYNTASK software consists of four simultaneous tasks, each presented in a separate quadrant of the computer screen (figure 5). Responses to the tasks are made using a mouse. The four tasks are summarized below.

(1) *Sternberg Memory Search (upper-left quadrant)*. This task is similar to the CTS MS task. An additional feature in SYNTASK is the ability to retrieve the memorized set at any time by clicking the mouse on a 'RETRIEVE LIST' button. During task performance, the letters presented on the screen are selected randomly from a positive set and a negative set (i.e. a set of distracters) of equal size. In the experiment, a set size of four was selected. In

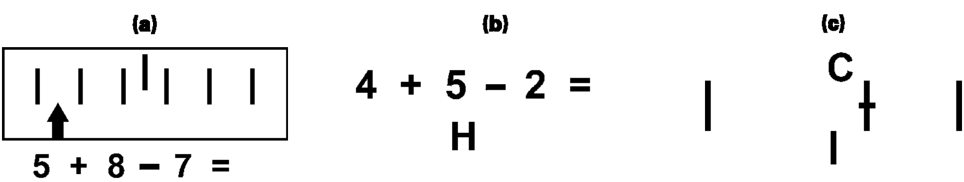

Figure 4. The CTS dual tasks used in the study: (a) DM with MP; (b) MS with MP; (c) UT with MS.

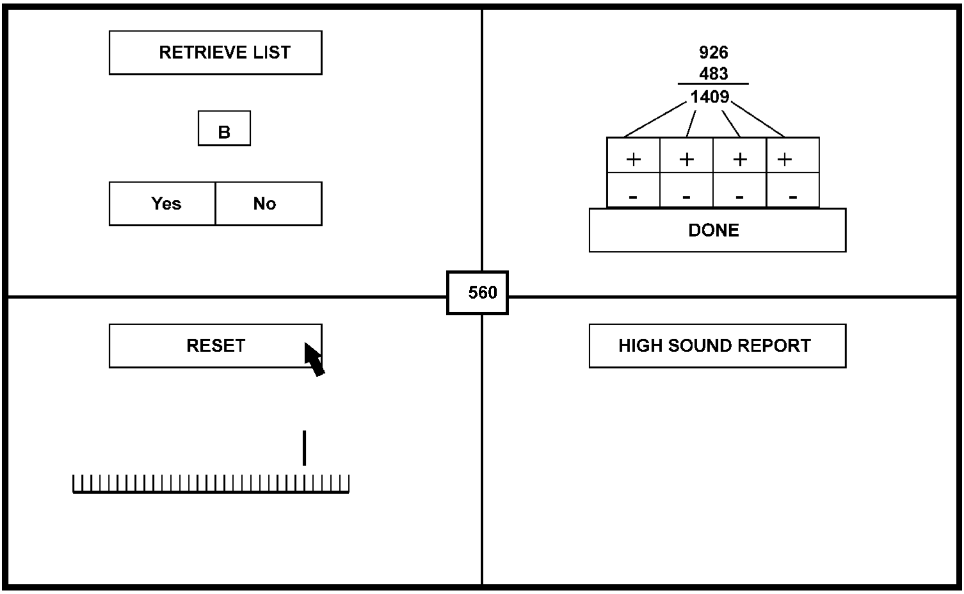

Figure 5. The SYNTASK software used in the study.

addition, the letter presentation time on the screen before timing-out was adjusted to 10 s.

(2) *Arithmetic (upper-right quadrant)*. This task requires the addition of two, three-digit numbers arranged vertically. Completion of each arithmetic problem is signalled by clicking the mouse on a 'DONE' button.

(3) *Visual monitoring (lower-left quadrant)*. In this task, a pointer starts at the centre position of a horizontal scale and moves with a fixed speed right or left. The goal is to reset the pointer at the farthest possible distance from the centre, but before it reaches a boundary, by clicking on the 'RESET' button. In the experiment, the speed of the pointer was set to 150 ms per pixel.

(4) *Auditory discrimination (lower-right quadrant)*. This task consists of discriminating two tones differing in frequency. The tones are presented periodically through a speaker. The goal is to detect the high frequency tone (signal), and indicate the detection by clicking the 'HIGH FREQUENCY REPORT' button. In this experiment, 1046 Hz and 1450 Hz were the frequencies selected for the low and high frequency tones, respectively. The probability of a high frequency tone was set to 0.3, and the rate of presentation was one tone per 5 s.

In SYNTASK, separate performance measures were obtained for each task. In addition, a composite score was used to measure overall time-sharing performance. The composite score was calculated by awarding 10 points to each correct response and penalizing each incorrect response by subtracting 10 points (Sternberg, arithmetic, and auditory discrimination tasks). For visual monitoring, points were accumulated, up to a maximum of 10 per reset period, based on the distance of the pointer from the centre of the scale at the time of the reset. Failing to reset the pointer after it reached the end of the scale was penalized by subtracting 10 points per second. The SYNTASK environment is illustrated in figure 5.

Within the framework of Shingledecker's model, the Sternberg memory task is a working memory, central processing task; the arithmetic task is a symbolic code manipulation central processing task that also involves working memory; the visual monitoring task is a spatial, perceptual input central processing task; and the audio discrimination task is an auditory, perceptual input task.

5.2. *Participants*

Twelve unacclimatized male participants 22 to 30 years old (mean = 25.8 years) participated in the study. They were recruited from the student population at the University of Oklahoma, and were paid for their participation. All participants were required to fill out an informed consent form and a heat disorder questionnaire. All participants indicated no past heat disorder or illness experience, reported normal hearing, and had normal (or corrected-to-normal) vision. Approval for the use of human participants was granted by the University of Oklahoma Institutional Review Board — Norman Campus.

5.3. *Experimental conditions*

An environmental chamber was used to generate six climates (table 1). These climates represented three different WBGT values (22, 28 and 34°C), each generated with two relative humidity (RH) levels (30 and 70%). The specific dry-bulb temperatures combined with each of the relative humidity levels to yield the prescribed WBGT levels, were determined by using the procedure described by Vasmatzidis and Schlegel (1994a).

The 22°C WBGT environment falls within the thermal comfort range (Beshir and Ramsey 1981) and served as the baseline condition. The 28°C WBGT environment is 3°C WBGT below the NIOSH 1986 recommended limit for continuous sedentary activity and unacclimatized workers. Thus, this environment allowed an evaluation of the NIOSH recommendation with respect to time-sharing performance. Finally, the hottest environment of 34°C WBGT was expected to be associated with performance decrements for the most heat-sensitive tasks, and thus allow an investigation of the heat stress selectivity pattern. The chamber's WBGT level was monitored using the Reuter-Stokes RSS-217 WIBGET device. The chamber's WBGT level was stabilized 30 min prior to starting each experimental session. The dry bulb temperature and relative humidity were controlled and adjusted by means of a 7716 Process Control Unit (CSI - Control Systems International, Dallas, Texas, USA) interfaced with an IBM 386SX computer.

Table 1. The six climates used in the study.

Climate	Wet bulb globe temperature (°C)	Relative humidity (%)	Dry-bulb temperature (°C)
1	22	30	30.1
2	22	70	24.8
3	28	30	36.3
4	28	70	31.0
5	34	30	44.0
6	34	70	37.0

5.4. *Experimental procedure*
Each participant was exposed to each of the six environments for a total of 2 h. The order of the six climates was counterbalanced across the 12 participants using a Latin Square design. Participants were exposed to only one climate on any experimental day. To minimize heat acclimatization, a rest period of 1 day was provided between any two consecutive experimental days. In addition, the experiment was conducted in the period between January and March to minimize natural acclimatization effects.

Prior to starting the experiment, each participant underwent a 3-day training period with the experimental tasks. Testing took place inside a $3.4 \times 3.4 \times 2.8$ m environmental chamber. The participants performed the tasks while seated in a chair mounted on a $1.1 \times 1.2 \times 0.2$ m wooden platform constructed especially for the experiment. The CTS tasks were presented using a Commodore 64 computer and a Commodore 1702 monitor (Commodore Business Machines, Inc., West Chester, Pennsylvania, USA). SYNTASK was presented on the screen of a Zenith 386 computer Zenith Data Systems Heath Company, Benton Harbor, Michigan, USA). Both computers were mounted on a cart situated outside the environmental chamber. The participants viewed the monitors from inside the chamber through a 38×63 cm window and responded to the tasks by using the response devices (CTS) and the mouse (SYNTASK) laid on a desk in front of the participants. The experimental layout is shown in figure 6.

All participants were dressed in shorts and short-sleeved shirts. This amount of clothing represents an insulation of approximately 0.4 clo. During the experimental sessions, both heart rate and ear temperature were recorded to ensure safety. In particular, the experimental session was to be terminated immediately if the participant's heart rate exceeded 150 beats min^{-1}, or if the participant's ear temperature exceeded 38.5°C (101.3°F). Heart rate was monitored using the POLAR

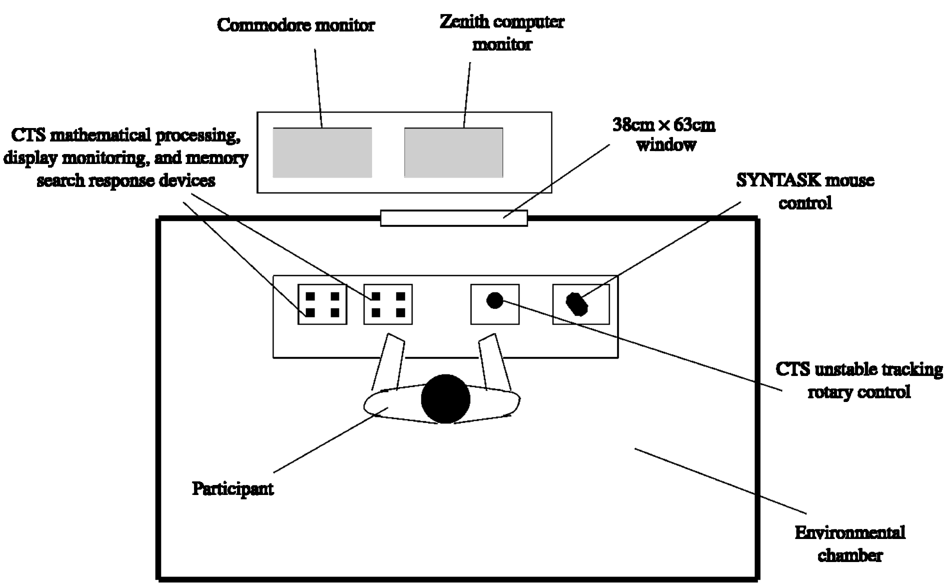

Figure 6. The experimental layout.

heart rate monitoring system. Tympanic membrane temperature was measured using a commercial ear thermometer. During the exposure, ear temperature was taken manually 15 times, at the 1-min breaks between tasks.

The 2-h exposure period was divided into four, 30-min cycles. During each cycle, all tasks were performed in the following sequence:

DM with MP (3 min); MS with MP (3 min); UT with MS (3 min); SYNTASK (5 min); DM with MP (3 min); MS with MP (3 min); UT with MS (3 min).

A break of 1 min was allowed between consecutive task trials for resetting and switching the computers and for taking the ear temperature measurement. During the 2-h exposure period, each dual task was performed eight times (once every 15 min), and SYNTASK was performed four times (once every 30 min). An important issue in time-sharing performance studies is controlling cognitive resource allocation among the time-shared tasks. In the present study, the participants were instructed to allocate cognitive resources among the time-shared tasks equally. Otherwise, the heat stress selectivity pattern could reflect changes in the resource allocation strategy initiated by the participant, rather than depletion of cognitive resources. Past studies (Gopher 1980, Gopher and Brickner 1982) have reported that participants can follow resource allocation instructions successfully. The same approach was employed in the present study. Participants were reminded several times during the experimental sessions that performance on all time-shared tasks was to remain as high as possible.

6. Training

All participants performed seven training trials with each CTS pair and eight trials with SYNTASK. To evaluate the stability of performance toward the end of the training period, inter-trial Pearson correlation coefficients were calculated for the following criterion measures:

(1) mean reaction time for the CTS display monitoring, mathematical processing and memory search tasks;
(2) root mean square error for the CTS unstable tracking task; and
(3) composite score for SYNTASK.

In all cases, high correlations were obtained (at least 0.93), indicating that a satisfactory level of differential stability was reached prior to starting the experimental session. The inter-trial Pearson correlation coefficients for the last three sessions for the above measures are shown in table 2.

7. Results

A repeated measures design with climate (6 levels) and 15-min period (30-min period for the SYNTASK) as the within-subjects factors was employed to analyse the data. This analysis allowed an evaluation of the relative humidity effects for a given WBGT value. To study the effects of WBGT regardless of the relative humidity, a second repeated measures analysis was conducted with WBGT as a within-subjects factor (3 levels) in place of climate. Period effects and period × climate (or period × WBGT) interactions were rarely found. In these cases, no pattern emerged to suggest performance alterations due to fatigue or climate exposure duration. Therefore, period effect results are not reported. A summary of the results for the

Table 2. Pearson correlation coefficients (Prob $r > |\rho|$ under Ho: $\rho = 0$) for the last three training trials (trials 5, 6 and 7 for CTS; trials 6, 7 and 8 for SYNTASK).

	Trials 5–6 (6–7 for SYNTASK)	Trials 5–7 (6–8 for SYNTASK)	Trials 6–7 (7–8 for SYNTASK)
Display monitoring mean RT (DM-MP Pair)	0.9434 (0.0001)	0.9550 (0.0001)	0.9763 (0.0001)
Mathematical processing mean RT (DM-MP Pair)	0.9655 (0.0001)	0.9581 (0.0001)	0.9929 (0.0001)
Memory search mean RT (MS-MP Pair)	0.9513 (0.0001)	0.9347 (0.0001)	0.9824 (0.0001)
Mathematical processing mean RT (MS-MP Pair)	0.9871 (0.0001)	0.9917 (0.0001)	0.9945 (0.0001)
Unstable tracking RMS error (UT-MS Pair)	0.9790 (0.0001)	0.9835 (0.0001)	0.9833 (0.0001)
SYNTASK composite score	0.9624 (0.0001)	0.9703 (0.0001)	0.9896 (0.0001)

DM: display monitoring; MP: mathematical processing; MS: memory search; UT: unstable tracking; RMS: root mean square; RT: reaction time.

Table 3. Climate and wet bulb globe temperature (WBGT) effects on the CTS performance measures.

Performance measures	Climate effects	WBGT effects
DM-MP pairing		
DM mean RT for correct responses	$p<1.00$	$p<1.00$
DM missed biases	$p<0.80$	$p<0.60$
DM false alarms	$p<0.10$	*$p<0.05$
MP mean RT	$p<0.90$	$p<0.70$
MP percentage correct	$p<0.90$	$p<0.70$
MS-MP pairing		
MS mean RT	$p<0.50$	$p<0.80$
MS percentage correct	*$p<0.05$	*$p<0.05$
MP mean RT	$p<0.20$	$p<0.70$
MP percentage correct	$p<0.20$	$p<0.20$
UT-MS pairing		
UT RMS error	*$p<0.05$	$p<0.20$
UT edge violations	$p<0.10$	$p<0.05$
MS mean RT	$p<0.20$	$p<0.60$
MS percentage correct	$p<0.30$	$p<0.10$

*denotes significant effect at the $\alpha = 0.05$ level.
DM: display monitoring; MP: mathematical processing; MS: memory search; UT: unstable tracking; RT: reaction time.

CTS task pairs is presented in table 3. The results for SYNTASK are presented in table 4.

7.1. *CTS pairings*

7.1.1. *DM-MP*: DM performance was measured in terms of mean reaction time (RT) for correct responses, number of missed biases and number of false alarms. As revealed by Analysis of Variance (ANOVA), none of these measures was

Table 4. Climate and WBGT effects on the SYNTASK performance measures.

Performance measures	Climate effects	WBGT effects
Composite score	$p < 0.90$	$p < 0.60$
Memory search		
Correct response latency	$p < 0.20$	$p < 0.30$
Percentage correct	$p < 0.30$	$p < 0.20$
Arithmetic task		
Correct problem time	$p < 0.70$	$p < 0.90$
Percentage correct	$p < 0.60$	$p < 0.50$
Visual monitoring		
Pointer average inter-reset time	$p < 0.20$	$p < 0.50$
Pointer lapses	$p < 0.30$	*$p < 0.05$
Auditory discrimination		
Detection latency	$p < 0.70$	$p < 0.60$
Percentage correct	$p < 0.70$	*$p < 0.05$
False alarms	$p < 0.70$	$p < 0.10$

*Denotes significant effect at the $\alpha = 0.05$ level.

significantly affected by climate. In contrast, WBGT was found to significantly affect the number of false alarms ($p < 0.05$). RT and number of missed biases were not affected by WBGT. The effect of WBGT on false alarms is illustrated in figure 7. False alarms increased from 0.38 at 22°C WBGT to 0.54 at 28°C WBGT, and to 0.90 at 34°C WBGT. Tukey's *post-hoc* test showed that the number of false alarms was significantly higher at 34°C WBGT than at 22°C WBGT.

MP performance was measured in terms of mean RT and percentage correct. Neither climate nor WBGT had a significant effect on either of these measures.

7.1.2. *MS-MP*: Mean RT and percentage correct were the performance measures for the MS task. None of the main effects was found to be significant for mean RT. With respect to environmental effects on percentage correct, both the climate effect ($p < 0.05$) and the WBGT effect ($p < 0.05$) were significant. In addition, the difference between climate 1 (22°C WBGT-30% RH) for which percentage correct was over 98.0%, and climate 6 (34°C WBGT-70% RH) for which percentage correct dropped to 95.8% was statistically significant, but the difference between climates 1 and 5 (34°C WBGT-30% RH) was not. This is also illustrated in figure 8. Given that both climate 5 and climate 6 represent the same WBGT temperature (34°C WBGT), this finding suggests that at this WBGT level the 70% RH was more detrimental to performance than was the 30% RH. The effect of WBGT on percentage correct is also shown in figure 8. Tukey's *post-hoc* test confirmed significant percentage correct differences between 22°C WBGT (97.9%) and 34°C WBGT (96.2%).

With respect to MP performance, neither climate nor WBGT had a significant effect on mean RT or percentage correct.

7.1.3. *UT-MS*: Unstable tracking performance was assessed by means of Root Mean Square (RMS) error and edge violations. Climate was found to exert a

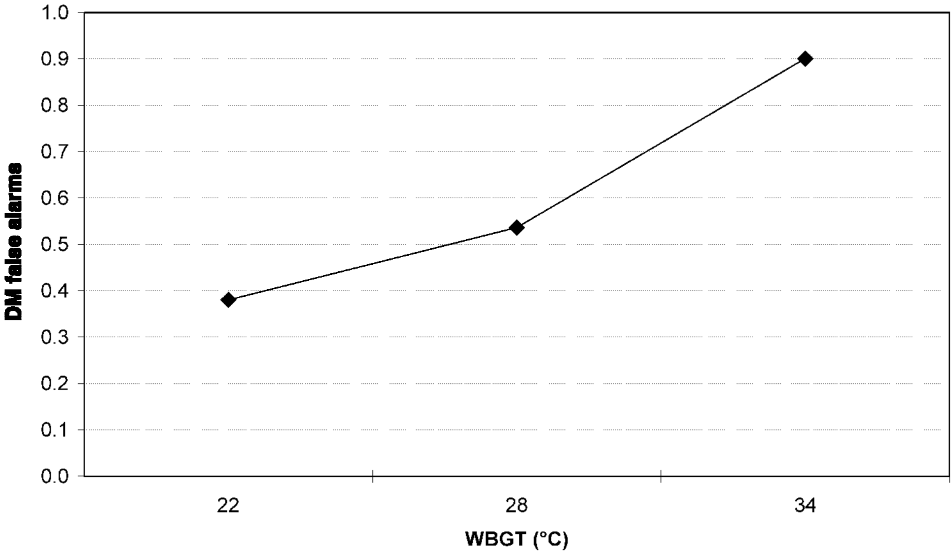

Figure 7. DM false alarms (DM-MP CTS pairing) as a function of WBGT.

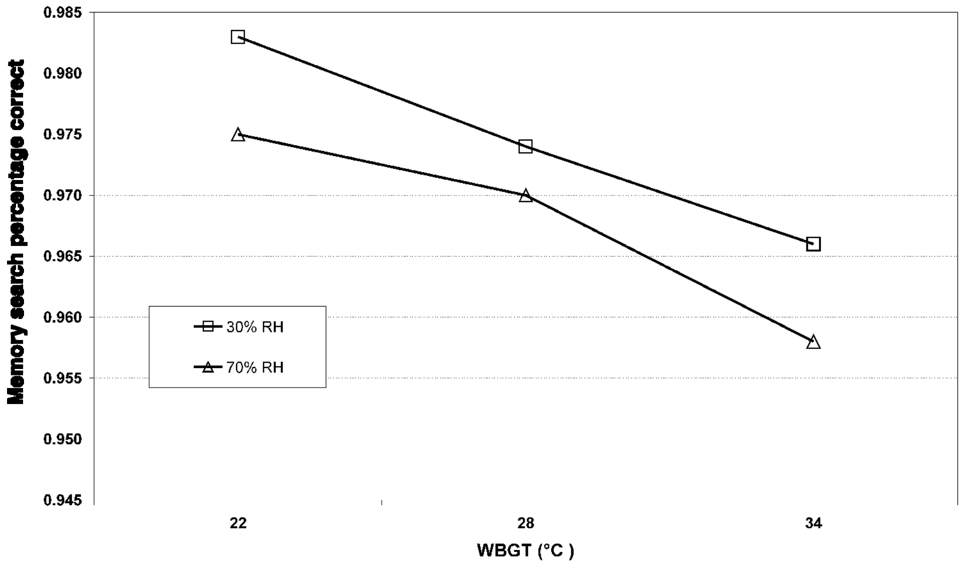

Figure 8. MS percentage correct (MS-MP CTS pairing) as a function of WBGT and relative humidity (RH).

significant effect on RMS error ($p < 0.05$). However, the WBGT effect was not significant. As shown in figure 9, RMS error was the highest (27.66) for the 34°C WBGT-70% RH climate (climate 6) and lowest (21.75) for the 28°C WBGT-70% RH climate (climate 4). Tukey's *post-hoc* test confirmed that the 34°C WBGT-70% RH climate (climate 6) was more detrimental to performance than any other condition, including the 34°C WBGT-30% RH climate. The 34°C WBGT-70% RH condition was also associated with the highest number of edge violations (12.45), twice as many as for the 34°C WBGT-30% RH (figure 9). However, this climate effect was not statistically significant at the $\alpha = 0.05$ level, although it was significant at the $\alpha = 0.10$ level. In contrast, the WBGT effect on edge violations was significant ($p < 0.05$). At 34°C WBGT, the number of edge violations (9.37) was significantly higher than at 22°C WBGT (3.98) and at 28°C WBGT (5.63). This effect is illustrated in figure 9.

For the memory search mean RT, neither the climate main effect nor the WBGT main effect was significant. The same was true for the climate and WBGT effects on the memory search percentage correct, although this performance measure decreased, in general, with increasing levels of heat stress.

7.2. *SYNTASK*

7.2.1. *Composite score*: In general, the SYNTASK composite score decreased with increasing level of heat stress. It was highest (901.5) for the 22°C WBGT condition, and lowest (884.7) for the 34°C WBGT condition. However, none of the environment main effects on this measure was statistically significant.

7.2.2. *Sternberg Memory Search*: Performance on this task was measured in terms of correct response latency and percentage correct. Neither climate nor WBGT was found to significantly affect these measures.

7.2.3. *Arithmetic task*: Performance on this task was assessed using the criterion measures of correct problem time and percentage correct. Similar to the Sternberg memory search task, neither climate nor WBGT produced a significant effect on either of the performance measures.

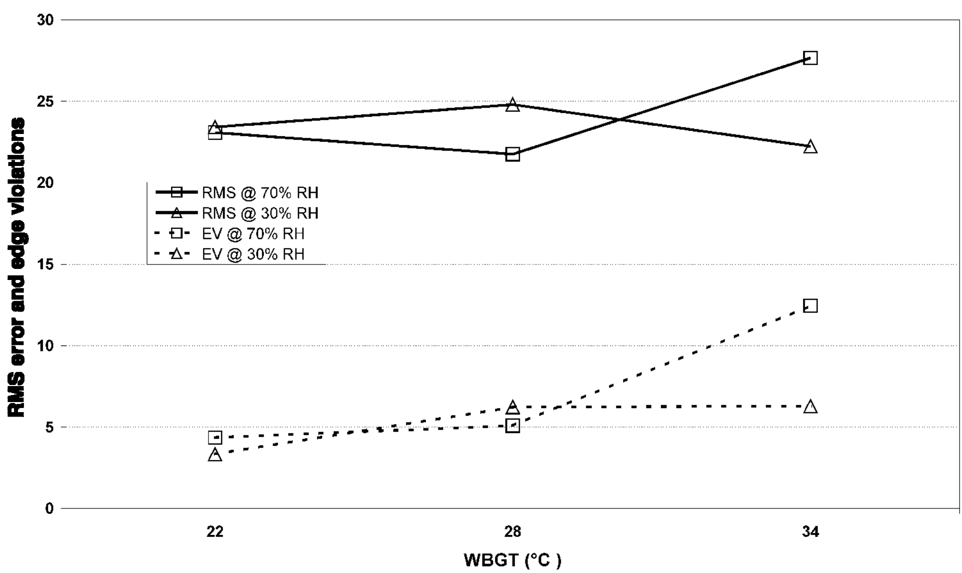

Figure 9. UT RMS error and edge violations (UT-MS CTS pairing) as a function of WBGT and relative humidity.

7.2.4. *Visual monitoring*: The criterion measures for this task were pointer average inter-reset time (average time between successive pointer resets) and pointer lapses (number of times the pointer reached the end of the scale without being reset within 2 s). Neither the climate effect nor the WBGT effect on the pointer average inter-reset time was significant. For pointer lapses, the WBGT effect was significant ($p < 0.05$). Pointer lapses increased from an average of 0.13 for the 22°C WBGT condition to an average of 0.29 for the 34°C WBGT condition (figure 10). The climate effect on pointer lapses was not significant ($p < 0.05$).

7.2.5. *Auditory discrimination*: Performance on this task was assessed in terms of detection latency, percentage correct, and false alarms. Of these measures, only percentage correct was significantly affected by WBGT ($p < 0.05$). At 34°C WBGT, percentage correct was the lowest (95.78%), and significantly lower than percentage correct at 28°C WBGT (97.64%). This result is illustrated in figure 10.

8. Discussion

8.1. *General findings*

Among the CTS tasks utilized in the experiment, unstable tracking was the task most profoundly affected by the heat. More specifically, performance measured by both criterion measures for this task (RMS error and edge violations) was impaired in the hottest conditions. Using the information processing stage/resource categorization of Shingledecker (1984, figure 4), and adopting the maximal adaptability model (figure 2, this paper) according to which heat stress causes deteriorated performance by draining attentional resources, this finding implies that in time-sharing conditions, manual response output resources are particularly susceptible to heat stress effects. Some evidence that perceptual input resources are sensitive to heat was

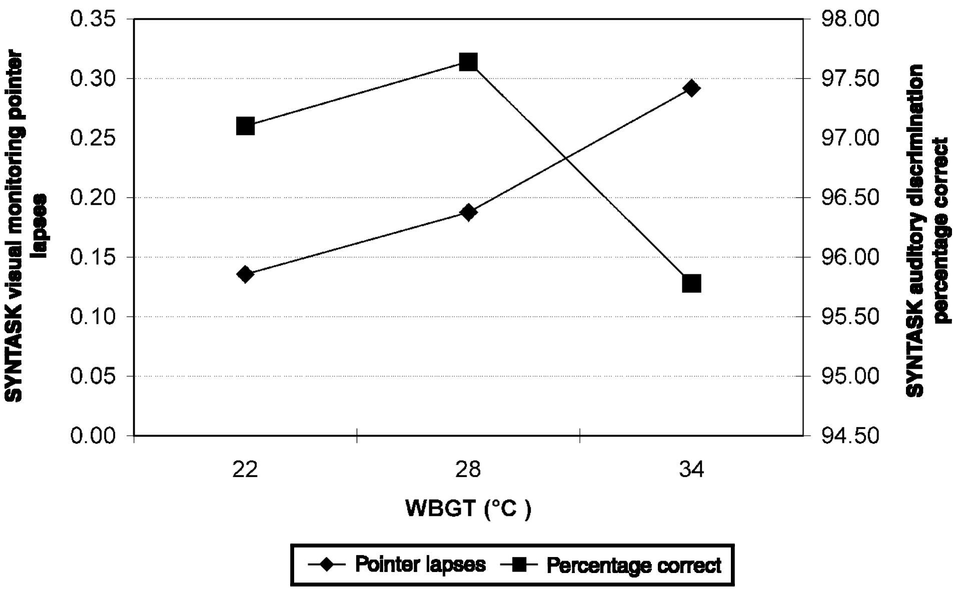

Figure 10. SYNTASK visual monitoring pointer lapses and SYNTASK auditory discrimination percentage correct as a function of WBGT.

also provided. Display monitoring (a predominantly perceptual input task) false alarms were found to increase significantly at 34°C WBGT when this task was time-shared with mathematical processing, a working memory task.

On the other hand, working memory resources appeared to be the least affected by heat stress. No impairment of memory search (a working memory task) was observed when this task was paired with unstable tracking, a task not involving working memory. Similarly, mathematical processing was not affected by high temperature when it was combined with display monitoring, another task not involving working memory. Collectively, the above results suggest a *heat stress selectivity effect* in dual-task situations by which working memory resources are more heat resistant (to use the maximal adaptability analogue) than manual response output resources and perceptual input resources. When the two working memory tasks were paired (i.e. competing for the same type of resources), memory search percentage correct for the MS-MP pair decreased significantly at the 34°C WBGT-70% RH climate compared to the 22°C WBGT-20% RH climate. This result suggests that storage and recall working memory resources might be more vulnerable to heat stress effects than symbolic code manipulation working memory resources. However, additional research is required to confirm this finding.

Overall SYNTASK performance as reflected by the composite score did not deteriorate in the heat. A plausible explanation for this result is the use of a score window which continuously provided information to the participants regarding their level of performance. This feedback may have acted as a motivating factor that helped the participants to maintain a high level of performance regardless of the environment. Indeed, most participants when asked to comment on the experimental tasks upon completion of the experiment, reported that the score information motivated them to improve performance with each trial, regardless of the environment.

Among the four SYNTASK tasks, visual monitoring and auditory discrimination were affected by the environment. Visual monitoring can be considered to be a perceptual input task. However, in the multitask environment of SYNTASK, performance on this task also requires good time estimation skills. Thus, it seems more realistic to interpret poor performance on this task as evidence for diminished time estimation rather than as evidence for depletion of perceptual input resources. This observation is deserving of further evaluation. The auditory performance decrement, however, does reflect depletion of auditory perceptual input resources. The percentage correct for this task was significantly lower at 34°C than at 28°C. This suggests that in multiple task situations similar to those of SYNTASK, auditory perceptual input resources may be among the most vulnerable to heat stress effects.

The Sternberg memory search task and the arithmetic task were the two SYNTASK tasks not affected by the environment. This result could be interpreted as additional support for the relative resistance of working memory to heat stress. However, there is a crucial difference between performance on these two tasks and performance on the similar memory search and mathematical processing CTS tasks. The CTS tasks are both presented in the central visual field of the performer, and practically simultaneous responses to these tasks are possible through the two independent response devices used with these tasks. With the SYNTASK tasks, the performer concentrates on one task at a time, while the second task (as well as the third and the fourth tasks) occupies the peripheral visual field. In addition, the use of a mouse as the only response device precludes concurrent responses to any two

SYNTASK tasks. Thus, SYNTASK requires some organization of behaviour and planning beyond what is needed in the time-sharing environment of the CTS pairs. Therefore, conclusions based on performance of the SYNTASK tasks should be contrasted with caution against conclusions drawn from CTS performance. At this point, it is suggested that CTS pairs are more suitable than SYNTASK for interpreting time-sharing performance changes in the heat using Shingledecker's (1984) framework.

With respect to relative humidity effects, this research provided evidence that at the highest WBGT temperature (34°C WBGT), the 70% relative humidity level was more detrimental to dual-task performance than the 30% RH level. In particular, memory search percentage correct for the MS-MP CTS pair was significantly lower at the 34°C WBGT-70% RH condition than at the 22°C WBGT-30% RH condition, whereas the difference between the 34°C WBGT-30% RH climate and the 22°C WBGT-30% RH climate was not significant. Also, unstable tracking RMS error was significantly worse for the high relative humidity 34°C WBGT climate than for the low relative humidity 34°C WBGT climate and for the 28°C WBGT-70% RH climate. In the past, only Pepler (1958) had reported differences in (simple) psychomotor performance due to differences in relative humidity levels. The present research expands investigation of relative humidity effects in time-sharing situations and suggests that high relative humidity causes performance to decline to a greater extent than low relative humidity levels for the same (high) WBGT temperature.

In general, this study failed to find any time-sharing performance decrement at the 28°C WBGT environment as compared to 22°C WBGT. This finding indicates that the NIOSH (1986) recommendation regulating sedentary work in the heat by unacclimatized workers does protect time-sharing performance, at least for stress levels up to 28°C WBGT and for an exposure duration of up to 2 h. This result is in agreement with Ramsey and Kwon (1992) who reported a mental performance decrement between 30°C WBGT and 33°C WBGT regardless of the exposure duration. However, the issue of heat stress standards for regulating cognitive work in the heat is still under discussion. Recently, Hancock and Vasmatzidis (1998) recommended a new approach for regulating cognitive performance under heat stress, which presents a synthesis and extension of all previous methods.

8.2. *Further research*

The present study demonstrated a heat stress selectivity pattern using Shingledecker's (1984) information processing stage-resource construct. Replication of this study is suggested using tasks that map onto resource pools postulated by other multiple-resource pool models, such as the Wickens (1987) categorization or the left hemisphere-right hemisphere model suggested by Polson and Friedman (1988). Furthermore, a different approach for investigating heat stress selectivity patterns on mental performance could be adopted based on the notions of the performance-resource function (PRF) and performance operating characteristic (POC). This approach was initially suggested by Vasmatzidis and Schlegel (1994b).

Another possible extension of the present research is to assess time-sharing performance at specified WBGT levels under varying levels of radiant heat-air temperature combinations. Results from such a study can then be combined with the results of the present work to provide a more complete evaluation of the WBGT index with respect to its suitability for protecting mental performance in the heat.

9. Conclusions

The conclusions of the present study can be summarized as follows:

(1) With respect to CTS dual-task performance, working memory resources (as reflected by memory search and mathematical processing performance) appeared to be the most resistant to heat stress effects. On the other hand, manual response output resources (as reflected by performance on unstable tracking) exhibited the highest degree of sensitivity to heat stress. Furthermore, this study suggests that visual perceptual input (CTS display monitoring), auditory perceptual input (SYNTASK auditory discrimination), and time estimation (SYNTASK visual monitoring) are affected negatively by heat in time-sharing conditions.

(2) Overall, complex time-sharing performance (SYNTASK), as measured by a composite score index, was not affected by the heat. A tentative explanation for this result is the immediate feedback that participants received through the score window, which motivated participants to maintain a high level of performance.

(3) For the highest WBGT level (34°C), evidence was found that high relative humidity (70%) is more detrimental to performance than 30% relative humidity. This has implications regarding the appropriateness of using the WBGT index alone for setting occupational standards regulating cognitive work in the heat.

(4) For the WBGT levels investigated, no evidence was obtained to contra-indicate the use of the NIOSH (1986) standard for protecting time-sharing performance. This conclusion was reached based on the lack of any performance differences between the 22°C and 28°C WBGT temperatures.

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