PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Sustained Performance and Some Effects on the Design and Operation of Complex Systems

M. F. Allnutt, D. R. Haslam, M. H. Rejman and S. Green

Phil. Trans. R. Soc. Lond. B 1990 **327**, 529-541
doi: 10.1098/rstb.1990.0096

Phil. Trans. R. Soc. Lond. B **327**, 529–541 (1990)
Printed in Great Britain

Sustained performance and some effects on the design and operation of complex systems

By M. F. Allnutt, D. R. Haslam, M. H. Rejman and S. Green
Army Personnel Research Establishment, Ministry of Defence, Farnborough,
*Hants GU*14 6*TD, U.K.*

Man, increasingly the limiting element in the military man–machine system, must often operate for several days in a high-risk environment with little or no sleep. It is necessary, therefore, to have some knowledge of the likely effects of sleep deprivation to predict his behaviour and minimize the adverse effects of sleep loss. The early work of the Army Personnel Research Establishment (APRE) concentrated on studying the infantryman in field trials, characterized by more realism and of greater length than previously attempted. Although measures of cognitive functioning were included in these trials, continuous cognitive performance was not assessed, nor was performance on complex tasks. An opportunity to remedy this situation arose because of a newer study concerned with controlling a removely-piloted air vehicle from a ground control station (GCS). A 65-hour experiment was designed during which subjects performed continuously either on the GCS simulator or on a battery of cognitive tests, mood scales, and physiological assessments. Results showed that whereas performance showed the usual deterioration in the test battery, it held up remarkably well on the simulator. Several reasons for this difference are suggested.

Introduction

Man, increasingly the limiting element in the military man-machine system, must often operate for several days in a high-risk environment with little or no sleep. To make optimum use of this limiting resource we must be able to make a fairly accurate prediction about his likely behaviour, so allowing procedures and equipment to be designed to minimize the negative effects of sleep loss. When neither extrapolation from laboratory experiment nor collated observations from real-world situations are sufficient to answer specific questions, we must resort to field trials or simulation. A series of such trials, started in the 1970s, and also a full simulation, form the substance of this paper.

Our work has not been an attempt to confirm or deny any theoretical prediction about sleep loss or stress (see Hartley *et al.* 1989), but by field trial, simulation, extrapolation from other researchers' experiments and evidence from real-life military and analogous situations to provide best evidence as to how soldiers are likely to behave in specific operational situations. Any such work in this area must of necessity lack two critical elements, perhaps best described as fear and the chaos of war, and there is evidence both from real-life observation (Marshall 1947; Bourne 1969) and experiment (Berkun *et al.* 1962; Baddeley 1972) that these elements have a profound effect on behaviour. We can make some general predictions about the likely direction of such effects, for example, a narrowing of focus that might lead to improved performance, irrelevant behaviour, or escape, but the magnitude of such effects is likely to be situation specific.

The field trials

About 14 years ago, the Army Personnel Research Establishment (APRE) was asked a very specific question, 'How much sleep do soldiers require to remain militarily effective for up to 9 days?' The literature, which had been recently reviewed by Johnson & Naitoh (1974), provided a wealth of laboratory data almost exclusively devoted to experiments of less than 48 h duration. Examples of slightly longer duration were provided by Murray & Lubin (1958), Wilkinson (1962, 1964) and Williams & Lubin (1967). The few field trials there were (Banks *et al.* 1970; Haggard 1970; Dudley *et al.* 1974) had been of relatively short duration (less than 5 days) and only two had aimed at military realism (Drucker *et al.* 1969; Ainsworth & Bishop 1971). Historical evidence from battle and expert opinion gave widely differing answers as to how much sleep was necessary to remain militarily effective for nine days, and so we embarked on a series of five trials, two in the field, two in the laboratory and one combined, to provide best estimates of likely performance under agreed military scenarios. Our approach throughout was to use experienced infantrymen as subjects and expose them to a multidisciplinary battery of measures that included military performance, military judgement, cognitive, subjective and physiological measures. The data are necessarily full and complex and are to be found in Haslam (1981, 1982, 1983, 1985*a*, *b*); the aim here is to provide an overview of the earlier work as a lead in to more recent work.

Taking into consideration the results from earlier studies, the conditions for the first field trial were 0, 1.5 and 3 h sleep per 24 h. All the 0-h sleep platoon were judged to be militarily ineffective after 48 h without sleep and had withdrawn from the trial after 100 h, while 50% of the 1.5-h platoon survived the 9 days but with major degradation of performance; 90% of the 3-h platoon survived, and with less deterioriation in performance. Figure 1 shows a typical result, this being for a vigilance shooting task that required sustained attention for 20 min. In this first trial we allowed unlimited recovery sleep while in a subsequent one we studied the

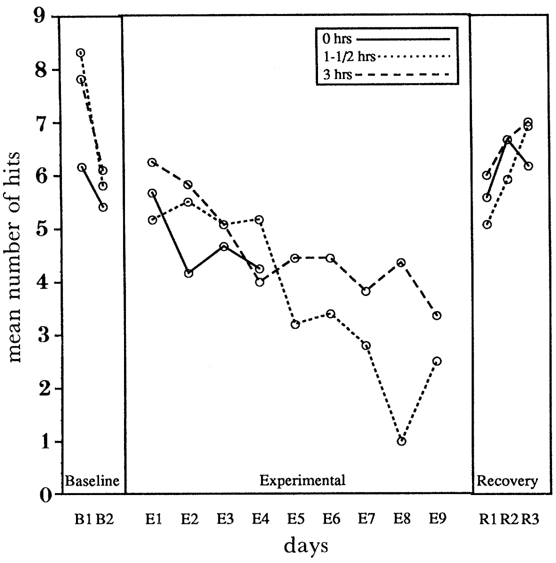

Figure 1. The effect of varying amounts of sleep loss upon 'vigilance' rifle-shooting performance, mean number of hits for the three platoons.

more likely regime of total followed by partial sleep loss (Haslam 1982). Four hours sleep after 90 sleepless hours was very restorative, while three 4-h sleep periods over 72 h after 90 h without sleep restored performance on a battery of tasks to 88 % of its baseline value. Figure 2 shows a typical result, this one being for a military de-coding task. In a further trial another realistic regime was followed, namely, partial followed by total sleep loss (Haslam 1985*b*).

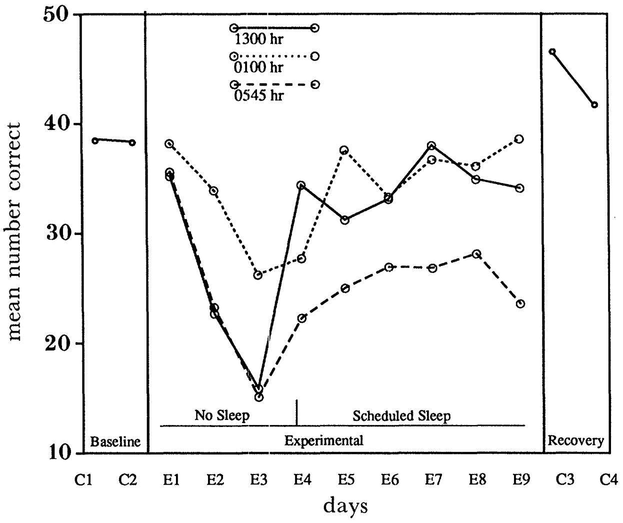

FIGURE 2. The effect of sleep loss and 'recovery' sleep upon decoding grid references, mean number correct for 10 subjects at different times of day.

A question often asked by military commanders is whether several short periods of sleep are as beneficial as one longer uninterrupted one. The results from a 5-day laboratory trial (Haslam 1985*a*) showed that there were no significant differences in cognitive and mood scores between two groups, one of whom was scheduled 4 one-hour naps, and the other one 4 h continuous sleep per 24 h. Further, neither group showed a significant difference from baseline values, showing the value of 4 h sleep either in one uninterrupted block or in 4 scheduled one-hour naps per 24 h.

From this series of trials and incorporating data from sister establishments in the U.S.A. and Canada, APRE has been able to produce two simple, pocket-sized guides for the military, one on the likely effects of sleep loss and the other on sleep management. These have been issued widely throughout the Army.

The link to more complex tasks

The recent rapid proliferation of high technology equipment on the battlefield now means that nearly all soldiers have to operate complex systems. A common and most critical example of this is the small team who must collate and act upon a wealth of data generated by sophisticated sensor systems. These personnel must maintain a constant high level of performance, be flexible in their approach, and be able to operate in isolation for extended periods.

In parallel with our work on sustained operations, APRE has had a long-standing commitment to design a ground control station to acquire and process data gathered from a remotely piloted air vehicle system. A comprehensive task analysis, attention to ergonomics, and experimentation on the man–computer interactions produced a prototype system that has been steadily improved over the years by being operated in realistic laboratory simulations by teams of soldiers who will operate the real system when it enters service in two years' time (Rejman & Ford 1986). Thus the current ground control station is the product of an iterative design process by psychologists and military specialists, and is being used as the generic basis for several other future systems. By now we were fairly confident about predicting the main effects of sleep loss on basic military tasks but were unhappy about extrapolating to a team operating such a complex system. Therefore, as a final check and validation of our ground control station, we decided to combine these two strands of work and study the performance of teams operating the facility for an extended period. This work, which will now be briefly described, has been conducted by Rejman & Green.

The ground control station trial

The ground control station

The simulation facility consists of a distributed microprocessor system containing a fully interactive ground control station (GCS) containing three workstations, a higher level of command facility with one workstation, and an aerial-imagery generation system. This latter sub-system consists of a camera mounted above a moving table on which are displayed aerial reconnaissance photographs. Further microprocessors are devoted to running a mathematical model of the air vehicle characteristics and handling the communications traffic. Tasks were in the form of areas to be overflown and reported upon. Thus a representative GCS crew can plan and execute target acquisition and intelligence-gathering missions realistically, including complex tasks such as mission allocation, based on temporal and geographical considerations, photographic interpretation, map reading, navigation, and air vehicle control.

Subjects

Five 3-man crews were used as subjects. They consisted of experienced non-commissioned officers from the projected user population. While highly skilled in many aspects of the task, they were entirely new to this simulation.

Procedure

The Army wished us to investigate a 3 day/2 night scenario of 65 h continuous operation. Training time had to be limited to 10 days. The pattern was then 2 days of baseline measures with up to 7 h sleep a night, 65 h of continuous operation, unlimited recovery sleep, and 2 further days (up to 7 h sleep a night) for recovery measures.

It was anticipated that in operational use the GCS would have to move to a new location fairly frequently. We simulated this schedule, while endeavouring to provide a link to more basic laboratory research, by alternating 5-h sessions on the GCS with 5-h sessions in our adjacent laboratory throughout the period, with 1-h meal breaks in between. For each session on the GCS, crews were confronted with a new area of terrain (photograph) and a fresh set of tasks.

Measures

(i) *System measures*

The subjects' work was complicated but in essence consisted of a series of tasks in which they were required, as a team, to fly the air vehicle tactically from a launch point to the target area while making various observations such as target detections and reporting on these. All keystroke data were logged, and from this several measures were derived, including throughput (tasks per hour), time on task, timeliness, and navigational accuracy. Each task was accorded one of three priorities (P1, P2, P3), the team being told that the higher priority tasks should take precedence. Although all these measures are relevant to the operation of such a system in real life, only a selection taken from the keystroke data can be presented at this time.

(ii) *Laboratory measures*

A battery of tests of cognitive function were used. Some tasks were selected because they represented standard laboratory paradigms, while others were chosen because they appeared to be analogous to aspects of the GCS operation. An example of the first category is the Five Choice Serial Reaction Time Task, but including an error detection measure. Examples of the second category are the Manikin Task (Benson & Gedye 1963), and a Data Entry Task. In the Manikin Task, subjects are presented with line drawings of a figure (the Manikin) holding a circle in one hand and a square in the other. One of these symbols is also present below the figure. The subject's task is to show in which hand (left or right) the Manikin is holding the symbol depicted below. The Manikin can be either facing or rear view and either upright or inverted. The task is therefore one of spatial decision-making. The Data Entry Task merely required the inputting of grid references via a keyboard. Discussion here will be confined to these three tasks.

(iii) *Subjective measures*

Mood was assessed during each laboratory session by using a computerised version of the UMACL, which was derived from Matthews (1983). This scale provides measures of arousal derived from Thayer's (1978) Dimension A (vigour–fatigue), Dimension B (tension–relaxation), plus Hedonic Tone (pleasure–displeasure) scales. Sleepiness was assessed every 2 h by using the Stanford Sleepiness Scale (Hoddes *et al.* 1973).

(iv) *Physiological measures*

Three physiological measures were taken, the first two being included primarily to provide additional data for other programmes. Saccadic eye movements were recorded during every laboratory session and analysed for sleep-loss effects by a componential technique (Green 1986); also, every 2 h throughout the trial, a 1 ml saliva sample was obtained for cortisol determination (Walker *et al.* 1978), and oral temperature was measured.

Results

(i) *System measures*

Systems measures were analysed by using Analysis of Variance (ANOVA); a full account will appear in papers by Rejman & Green (in preparation). In general, crew performance on the system held up very well throughout the trial. Thus the total mean number of tasks (P1, P2, P3) accomplished per hour, a direct measure of crew–system throughput, remained relatively constant. However, when the task is broken down into the three priorities the results are as shown in figure 3.

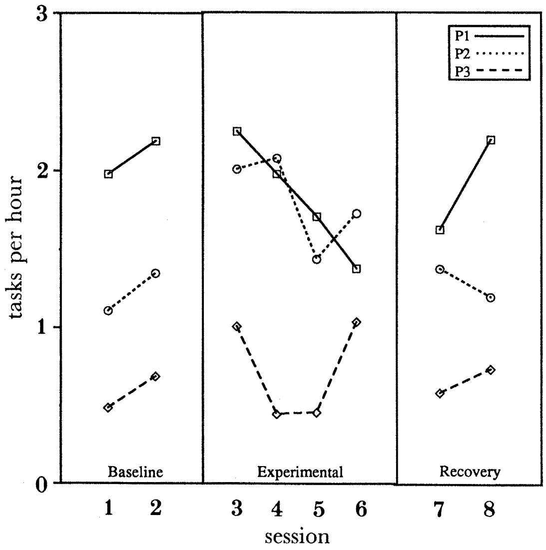

FIGURE 3. The effect of sleep loss on task throughput (tasks per hour) by priority.

Baseline sessions clearly show crews adhering to the priority scheme, with performance for the three priorities clearly separated ($F\,2,8 = 47.5$, $p < 0.001$). This situation alters subtly under conditions of sleep loss. First, performance of P2 tasks is elevated beyond control levels to the extent that there is no significant difference between P1 and P2. Thereafter P1 and P2 tasks decline together as a function of sleep loss, with P3 task performance lower and less consistent ($F\,7,\ 28 = 6.36$, $p < 0.001$). However, main effects should be treated with caution because of the significant interaction ($F\,14,\ 56 = 2.71$, $p < 0.01$) between task priority and sleep loss. Recovery performance shows a virtual return to baseline levels for all three priorities. Subjects appeared to be attempting to keep up performance on both P1 and P2 tasks, but one result of such a combination was that P1 tasks suffered.

Despite these changes to the number of tasks accomplished, subjects did not appear to alter the mean time they devoted to each task once they had started it. As can be seen from figure 4 this measure changes very little (no significant differences) across the experiment, with, in general, P1 tasks receiving slightly more time than P2 tasks, which in turn receive more time than P3 tasks.

Finally, on timelinesss, figure 5 shows 'minutes late on task'. Here again performance can be seen to be governed by the priority scheme, with P1 tasks always being performed closer to the requested time than P2 and P3 tasks ($F\,2,\ 8 = 7.26$, $p < 0.05$). An exception to the priority pattern occurs towards the end of the experimental period when P3 takes precedence over P2. There was a significant interaction ($F\,14,\ 56 = 1.95$, $p < 0.05$) of priorities and sessions, although no significant differences were found between control, experimental, and recovery periods. A further blurring of the priority distinctions occurred in the last recovery session.

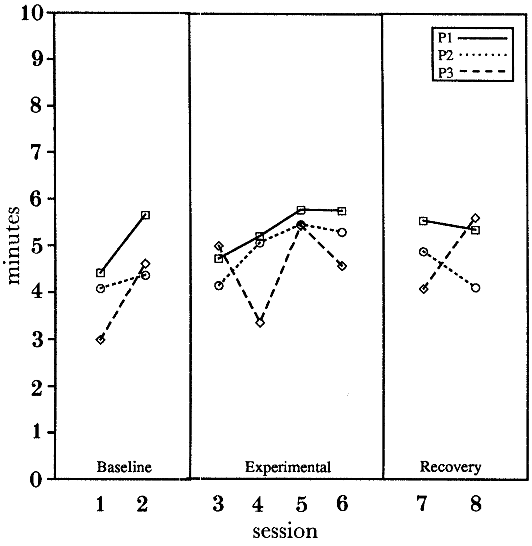

FIGURE 4. The effect of sleep loss on time spent on task by priority.

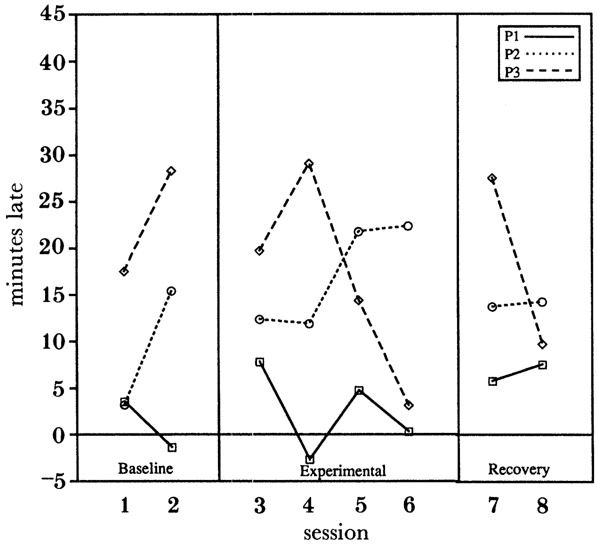

FIGURE 5. The effect of sleep loss on 'minutes late on task' by priority.

(*ii*) *Laboratory measures*

The cognitive tests were analysed using Analysis of Variance; a full account will appear in papers by Rejman & Green (in preparation). Data from the Five-Choice Serial Reaction Time Task (figures 6 & 7) are shown.

Figure 6 shows a significant increase ($F\,5, 85 = 15.21$, $p < 0.001$) in choice reaction time with sleep loss, and also a practice effect across sessions. A further finding was that there was a significant decline ($F\,5, 85 = 34.83, p < 0.001$) during sleep deprivation in error detection on this task (figure 7).

The Manikin Task also showed some evidence of learning throughout the trial on the latency score, a fact which appeared to offset the increase in reaction time with increasing sleep loss. However, errors did increase significantly during the sleep loss phase ($F\,6, 42 = 5.48$,

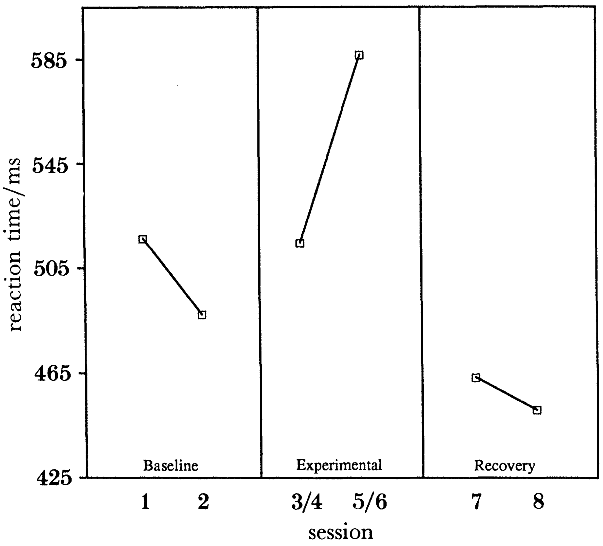

FIGURE 6. The effect of sleep loss on 5-choice reaction time.

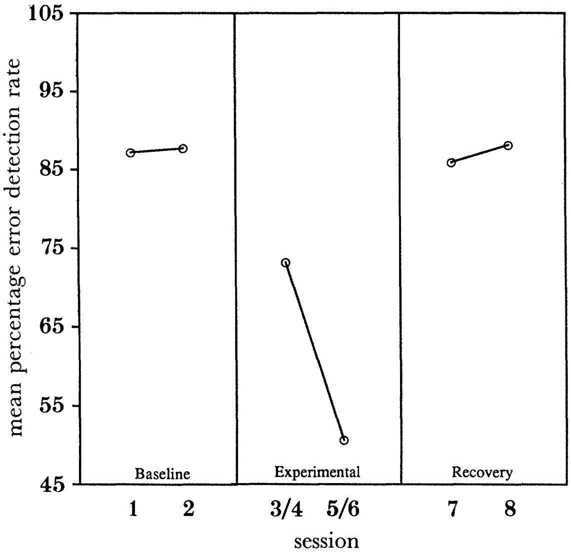

FIGURE 7. The effect of sleep loss on error detection rate in the 5-choice reaction time test.

$p < 0.001$). Thereafter they remained at this level into initial recovery, after which they returned to baseline levels. The Data Entry Task showed most effect on the latency measure with the time taken to input numbers significantly higher after sleep deprivation (F 6, 54 = 5.67, $p < 0.01$).

Finally, although tentative at this stage, there may be some indication that aspects of performance are still vulnerable to errors after the recovery sleep that follows a period of deprivation. This needs further investigation but if borne out would have both theoretical and practical significance.

(*iii*) *Subjective measures*

ANOVA of the UMACL data showed the expected rise in self-reported fatigue with increasing sleep loss (F 5, 35 = 19.38, $p < 0.001$); it also showed an increase in tension (F 5, 35 = 10.53, $p < 0.001$) and a decrease in hedonic tone (F 5, 35 = 10.32, $p < 0.001$). Data from the Standford Sleepiness Scale are shown in figure 8, which show, as would be expected, increasing sleepiness with increasing loss of sleep (F 6, 736 = 35.35, $p < 0.001$).

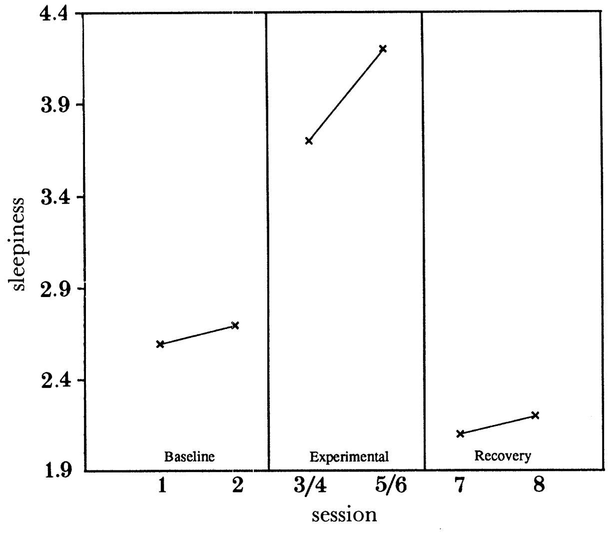

FIGURE 8. The effect of sleep loss on self-rated sleepiness.

(*iv*) *Physiological measures*

A typical result for the peak velocity component of the saccadic eye movement data is shown in figure 9, which shows the significant reduction (F 15, 75 = 9.12, $p < 0.001$) during sleep loss

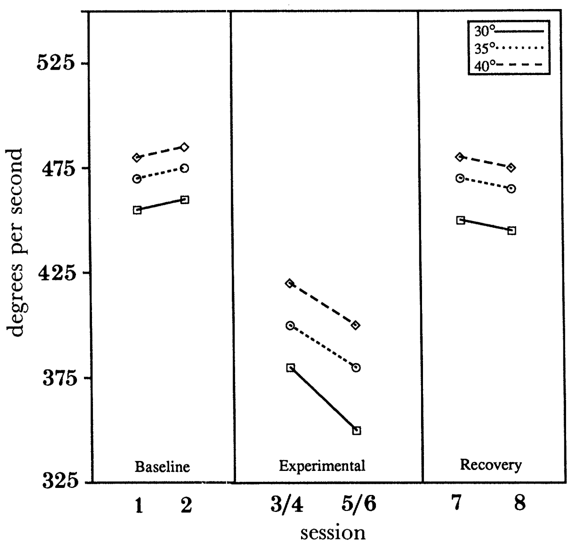

FIGURE 9. The effect of sleep loss on saccade peak velocity (degrees per second).

periods. With regard to cortisol, the baseline rhythm was as classically described by Kreiger (1979). Figure 10 shows that sleep loss rapidly perturbed the rhythm ($p < 0.01$) but with apparently unaltered total adrenocortical activity. After recovery sleep the normal rhythm was re-established but with evidence of increased adrenocortical activity as shown by a greater volume of secreted cortisol over the waking hours as compared with baseline ($p < 0.001$). The results for core temperature showed that as sleep loss increased there was a slight overall rise, with a forward phase shift. Recovery was marked by a rapid re-establishment of the normal circadian rhythm.

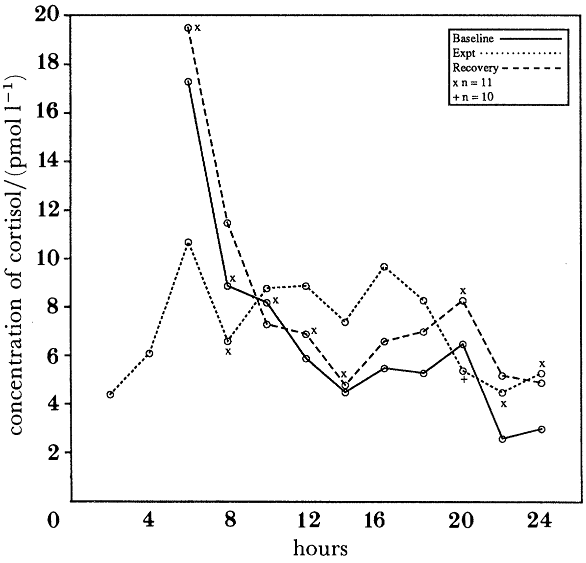

FIGURE 10. The effect of sleep loss on salivary cortisol secretions.

DISCUSSION

The primary purpose of the trial was to see whether the GCS could be operated satisfactorily in accordance with an agreed operational scenario. The subjects, task, workspace and scenario were realistic; fear and the chaos of war were necessarily absent.

Our main finding was that performance on the system showed relatively little change over the 65 h of sleep loss, whereas cognitive, subjective and physiological measures showed changes that would have been expected from our earlier work and that of many other researchers. It should, however, be noted that fine-grain analysis of the system measures is still going on. However, at this stage of analysis it can be said that following sleep loss the importance of the given priorities seems to become blurred (figure 3). This might be because of impairment of the ability to maintain a complex planning schedule based on priorities. Subsequent design work has tackled some of these difficulties.

We must now ask why performance on the system held up so well. There are three likely reasons. The first is that the subjects were benefiting from micro-sleeps and so were not as tired as we thought they were. The evidence against this is that they were very closely monitored at all times and that their performance on the other measures and recordings in the observers' log showed them to be behaving as if they were indeed getting tired. Electroencephalogram (EEG) recordings from earlier field trials, where the monitoring was slightly less intense, showed that subjects averaged 18 min unscheduled sleep on the second day of total sleep loss (Haslam 1982). However, it seems difficult to sustain the view that micro-sleeps were responsible for maintaining performance on the simulation, while clear decrements are revealed in the laboratory task performance. A second explanation is that the demands made on the subjects were not sufficiently taxing. Our only counter to this argument is that performance under both control and experimental conditions was still far from perfect, as the crew were kept in a state of permanent overload; however, under this sleep regime, it was sufficiently good to satisfy the Army that it would be adequate for their worst anticipated operational scenario.

The third explanation, and the one to which we subscribe, is that performance held up well because of the nature of the situation. This we believe to be a function of four factors.

(i) *Task design*. The human factors of the task had been optimized over several years by an iterative process with the future operators. Thus we had looked carefully at crew size, composition and interaction, task allocation, the working environment, situational awareness and man–hardware and man–software interactions, etc. Walker & Burkhardt (1965) have shown that performance decrement under stress on complex weapon systems is greater for those which were less well human engineered.

(ii) *The nature of the task*. The Ground Control Station was operated in 5-h bursts and the tasks were stimulating, varied, provided good feedback and required the active involvement of the subjects in most operations. Relatively few aspects involved either passive or repetitive action as we deliberately resisted the pressures to automate ('thereby removing human error'!) except to help overcome operator overload. Support for this approach comes from research, which shows that taking away functions from the operator makes him into a monitor and people do not make very good monitors (cf. Wickens 1984) in such circumstances.

(iii) *The motivation of the subjects*. Our subjects were very interested in their task and saw themselves as pioneers in a novel and important system, which they were likely to have to operate in the future. They were well trained professionals who reported that they welcomed the challenge of the trial.

(iv) *The group effect*. The system measures were, unlike those for cognitive, subjective, and physiological performance, based on group performance, and, as Morgan & Alluisi (1965), Davies & Tune (1969) and others have shown, group performance is often better than that of the individual. In addition, the system required the subjects to operate as a team, constantly interacting with each other to achieve group goals. One effect of this is that there were many times when it was observed that one crew member compensated for the flagging performance of a colleague who was going through a bad patch. The cohesion of service personnel is probably relevant here as this is their normal *modus operandi*. Certainly, when we tried to form a team of three civilians for a pilot study we could, even after prolonged training, only get them to function as three individuals.

CONCLUSIONS

The accumulated data from several laboratories on the effects of sustained operations on human performance did not allow behaviour in two archetypal military scenarios to be predicted with sufficient confidence, although they did provide a wealth of invaluable background material. A series of multidisciplinary trials did allow such predictions to be made and the data relating to the fairly severe field trials, augmented by information from many other sources, were translated into practical guidelines for military commanders.

The performance of three-man teams deteriorated as expected with increasing sleep loss when assessed singly by standard cognitive, subjective and physiological measures. But when assessed as a group on the system itself, such deterioration was far less, and it is concluded that the maintenance of performance (despite sleep loss) was a function of an ergonomically designed system, with active participation in a stimulating task by well-motivated subjects acting as a team.

We express our thanks to the Cranfield Institute of Technology, especially to Dr J. Ford and his staff, for software and hardware support and for assistance in running the trials. We are deeply grateful to Dr V. Schmit, Assistant Director, APRE, for much advice and assistance. Our thanks go also to Dr R. Edwards, APRE, who was responsible for the salivary cortisol study. Last, but not least, we thank the subjects, who showed such enthusiasm for the work.

REFERENCES

Ainsworth, L. L. & Bishop, H. P. 1971 The effects of a 48-hour period of sustained field activity on tank crew performance. *Hum. Resour. Res. Org. Tech. Rep.*, no. 71–16.

Baddeley, A. D. 1972 Selective attention and performance in dangerous environments. *Br. J. Psychol.* **63**, 537–546.

Banks, J. H., Sternberg, J. J. & Farrell, J. P. 1970 Effects of continuous military operations on selected military tasks. *U. S. Army BESRL Tech. Res. Rep. no. TR*–1166.

Benson, A. J. & Gedye, J. L. 1963 Logical processes in the resolution of orientational conflict. *IAM Rep.* no. 259. RAF Institute of Aviation Medicine, Farnborough, Hants.

Berkun, M. M., Bialek, H. M., Kern, R. P. & Yagi, K. 1962 Experimental studies of psychological stress in man. *Psychol. Monogr.*, no. 15, vol. **76**.

Bourne, P. G. 1969 *The psychology and physiology of stress: with reference to special studies of the Vietnam war*. New York: Academic Press.

Davies, D. R. & Tune, G. S. 1970 *Human vigilance performance*. London: Staples.

Drucker, E. H., Cannon, L. D. & Ware, J. R. 1969 The effects of sleep deprivation on performance over a 48-hour period. *Hum. Resour. Res. Org. Tech. Rep.* no. 69–8.

Dudley, R. C., Brown, K. & Croton, L. M. 1974 The effect of five days' continuous day and night operations on Chieftain tank crew performance (Exercise Package Tour). Unpublished Ministry of Defence Report.

Green, S. 1986 Saccadic eye movement analysis as a measure of sleep loss effects on the central nervous system (CNS). In *Trends in ergonomics/human factors III* (ed. W. Karwowski), pp. 379–387. Amsterdam, Holland: Elsevier Science Publishers.

Haggard, D. F. 1970 Human Resources Research Organization studies in continuous operations. *HUMRRO Professional Paper*, no. 7–70.

Haslam, D. R. 1981 The military performance of soldiers in continuous operations: Exercise Early Call I and II. In *Biological rhythms and shift work* (ed. L. C. Johnson, D. I. Tepas, W. P. Colquhoun and M. J. Colligan), pp. 435–458. New York: Spectrum Publications.

Haslam, D. R. 1982 Sleep loss, recovery sleep and military performance. *Ergonomics* **25**, 163–178.

Haslam, D. R. 1983 The incentive effect and sleep deprivation. *Sleep* **6**, 362–368.

Haslam, D. R. 1985*a* Sleep deprivation and naps. *Behav. Res. Meth. Instru. Comp.* **17**, 46–54.

Haslam, D. R. 1985*b* Sustained operations and military performance. *Behav. Res. Meth. Instr. Comp.* **17**, 90–95.

Hartley, L. R., Morrison, D. & Arnold, P. 1989 Stress and skill. In *Acquisition and performance of cognitive skills* (ed. A. M. Colley and J. R. Beech), pp. 265–300. New York: John Wiley & Sons.

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R. & Dement, W. C. 1973 Quantification of sleepiness: a new approach. *Psychophysiology*, **10**, 431–436.

Johnson, L. C. & Naitoh, P. 1974 The operational consequences of sleep deprivation and sleep deficit. *AGARDograph* no. 193. AGARD-AG-193.

Kreiger, D. T. 1979 Rhythms in CRF, ACTH and corticosteroids. In *Comprehensive endocrinology series 1: endocrine rhythms* (ed. D. T. Kreiger), pp. 123–141. New York: Raven Press.

Marshall, S. L. A. 1947 *Men against fire*. New York: Morrow.

Matthews, G. 1983 Personality, arousal states and intellectual performance. Ph.D. thesis. University of Cambridge.

Morgan, B. B. Jr & Alluisi, E. A. 1965 On the inferred independence of paired watchkeepers. *Psychon. Sci.* **2**, 161–162.

Murray, E. J. & Lubin, A. 1958 Body temperature and psychological ratings during sleep deprivation. *J. Exp. Psychol.* **56**, 271–273.

Rejman, M. H. & Ford, J. 1986 System simulation development as a tool in system design: a case history and a methodology. In *Trends in ergonomics/human factors* III (ed. W. Karwowski), pp. 163–171. Amsterdam, Holland: Elsevier Science Publishers.

Thayer, R. E. 1978 Towards a theory of multidimensional activation (arousal). *Motiv. Emot.* **2**, 1–33.

Walker, N. K. & Burkhardt, J. F. 1965 The combat effectiveness of various human operator controlled systems. In *Proceedings of the 17th US Military Operations Research Symposium.*

Walker, R. F., Riad-Fahmy, D. & Read, G. F. 1978 Adrenal status assessed by direct radio-immunoassay of cortisol in whole saliva or parotid fluid. *Clin. Chem.* **24**, 1460–1463.

Wickens, C. D. 1984 *Engineering psychology and human performance.* Colombus, Ohio: Merrill.

Wilkinson, R. T. 1962 Muscle tension during mental work under sleep deprivation. *J. exp. Psychol.* **64**, 565–571.

Wilkinson, R. T. 1964 Effects of up to 60 hours' sleep deprivation on different types of work. *Ergonomics* **7**, 175–186.

Williams, H. L. & Lubin, A. 1967 Speeded addition and sleep loss. *J. exp. Psychol.* **73**, 313–317.