ARTILLERY TEAMS IN SIMULATED SUSTAINED COMBAT: PERFORMANCE AND OTHER MEASURES

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Scientific and Military Rationale

In modern war, military units are likely to be engaged in intense sustained operations which permit at best only brief, fragmented sleep. Army ground combat depends heavily on team functions which involve complex interactions of individual performance capability (both mental and physical), psychosocial behavior, biological responses to stress and fatigue, and system (team task) organization. Command/control and communications elements may be especially vulnerable to performance degradation, since their roles often keep them continuously occupied, while their critical tasks are ones especially sensitive to sleep loss and the physiological consequences of the battlefield environment (Johnson & Naitoh, 1974; Woodward & Nelson, 1974).

In evaluating the impact of such conditions upon one's ability to perform, the scientific literature (Johnson & Naiton, 1974; Woodward & Nelson, 1974; Davis & Behan, 1962; Horrocks & Gayer, 1959; Glanzer) indicates the importance of task, personnel, and organizational variables. These include: task complexity, feedback pacing, level of training, intrinsic interest in the task, prior experience, motivation, and social factors. Such variables are considered critical determinants of performance capability under a variety of conditions. Furthermore, in both modern Industrial Society and in the Armed Forces, tasks are increasingly organized around teams rather than individuals. In the military community, concerns are often expressed as to the generality and predictive validity of past studies which have not included such variables inherent in many military tasks. To address these issues and provide a framework for communicating research results to the military community the Field Artillery Fire Direction Center (FDC) was selected by the US Army Research Institute of Environmental Medicine (USARIEM) as a "model" team for study. It was postulated that such complex issues could be studies in a laboratory simulation which would use actual Army teams performing their normal functions, yet permit control and replication of environmental and situational conditions and measurement and correlation of mission effectiveness, behavior and biological process (Davis & Behan, 1962; Glanzer, Finan, 1962). This approach capitalizes on preexisting training, professional pride, social support and military task organization. Such factors are critical in the study of group military task performance, contribution of individual performance to system (team) output (Davis & Behan, 1962; Finan, 1962), and physiological as well as psychological responses to stress (Bourne; Mason, 1968).

The FDC team seemed well suited for scientific study and laboratory simulation since 1) FDCs are common and critical to successful ground combat operations, 2) FDC teams are located immediately behind the front lines and are exposed to most extent stresses, 3) FDC include tasks common to other command/control and communication elements, 4) Detailed scenarios can be developed to provide content validity and calibrated performance demands, 5) The task output provides quantifiable measures of both individual and team performance, 6) The compactness of FDCs allows collection of a wide range of biomedical and psychosocial data, 7) Many variables which influence performance capability are inherent in FDCs, and 8) The FDC provides a performance paradigm with operational criteria, recognized by the military community, with which various data arrays can be correlated.

FDC Tasks and Organization

In the Field Artillery, the FDC is a service center which receives requests from various individuals and agencies who require artillery shells to hit target areas. These targets are typically kilometers away and out of sight of the guns. In the US Army (at the Artillery battery level) 5 to 7 individuals work together as a team to process these requests. Manual FDCs have exhisted since World War I and have evolved to minimize errors and to insure that performance is extremely robust under a variety of adverse conditions. Roles, tasks, communication sequences and content, error detection and resolution capabilities, information readback procedures, etc. are well specified and practiced. Given this high degree of task and organizational specification, at both the individual and system levels, deviations from these guidelines can be used as another means for assessing operational efficiency. In order to understand variations in system output, individual team member task contributions and interactions can be isolated and analyzed.

A variety of tasks and functions are assumed by various FDC members (see Table I). These include: sending and receiving information with various radio sets, encoding and decoding numerical/cipher codes, maintaining current information on unit position and movement, plotting target coordinates on grid sheets and maps, measuring target distances and directions from the firing battery, determining ballistic factors with nomograms and slide rules, selecting correct courses of action according to prescribed standing operating procedures (SOP), detecting and correcting discrepant or erroneous information, and communicating relevant information to the firing battery. Many of these tasks are similar to classical laboratory tests of performance. In the FDC these tasks are sometimes embedded in contexts where conflicting priorities and interferences limit interpretation, but they do provide a basis for comparison with the scientific literature.

Project History and Purpose

Preliminary studies (Stokes, Banderet, Francesconi, Cymerman & Sampson, 1975; Francesconi & Cymerman, 1975) of FDC teams in 1974 were conducted at USARIEM at simulated altitudes of 400 and 4300m. These studies indicated that although FDC team members experienced acute mountain sickness (AMS) and were obobviously ill and uncomfortable, most continued to perform reasonably well. Furthermore, performance appeared more influenced by acute hypoxia than by AMS symptomatology. Subsequently the FDC team simulation was updated with the as-

Table 1

Major Duties for Field Artillery Fire Direction Center (FDC) Personnel

TEAM MEMBER	DUTY CODE	MAJOR DUTIES
Radio-Telephone Operator (RTO)	10	receives, transmits, reads back information with radio sets
	11	requests caller authentication
	12	gives radio caller information (when rounds fired, when rounds will impact, when mission complete, etc)
	13	decodes radio messages
	14	communicates decoded information to appropriate individuals
Horizontal Control Operator (HCO)	20	plots targets or adjustments and shifts from known locations
	21	determines target range and direction
Vertical Control Operator (VCO)	20	plots targets or adjustments and shifts from known locations
	21	determines target range and direction
	22	determines altitude difference between target and guns
	23	calculates altitude correction, i.e. site
	24	plots unit location and direction of movement
Computer (COM)	31	communicates fire commands to guns
	32	calculates ballistic correction factors
	33	calculates gun tube displacement (lateral and vertical)
	34	plots meteorological correction factors on graphical firing tables
	35	specifies priority target data to guns
	36	sends preplanned target data to guns
	37	cancels old preplanned targets
	38	sends updated ballistic data to guns
Fire Direction Officer (FDO)	41	specifies fire commands for guns
	42	calculates ballistic correction factors
	43	calculates gun tube displacement (lateral and vertical)
	44	plots meteorological correction factors on graphical firing tables

NOTE: Duty codes are used in another Table.

sistance the US Army Field Artillery School (USAFAS) and the 82d Airborne Division to reflect current emphases on sustained combat and target preplanning, a technique to achieve speed and accuracy of Artillery fire for suppression of enemy weapons.

In 1977 multidisciplinary studies of FDC teams in simulated, sustained operations were conducted jointly by USARIEM, the Walter Reed Army Institute of Research (WRAIR),and the Naval Health Research Center(NHRC). These studies were to evaluate the FDC experimental model for future studies of environmental stress effects and countermeasures (USARIEM), physiological and social factors related to neuropsychiatric "combat exhaustion" (WRAIR), and "sleep logistics" (NHRC). Of principle concern to USARIEM was whether simulation of FDC operations would yield sensitive indices of individual and team efficiency related to hours in the sustained operations, task characteristics, level of training, etc. If so, such operational changes could be evaluated for correlation with biological, psychological, social, and/or organizational factors.

Methods

Standardization of Task Demands

Much of the precision of conventional laboratory performance paradigms was applied to the complex mission demands of the Field Artillery to document changes in FDC performance and to reduce extraneous variance. This methodology was incorporated into a detailed script ("scenario") of radio messages which provided the task demands, as well as the supporting documents for various situations, e.g. map overlays and unit SOP. The scenario represented a tactical battle played on 1:50,000 scale maps and followed current doctrine for light infantry with armored cavalry advancing against a well-equipped screening force. Task demands were communicated by role players to the FDC over three simulated radio nets; other role players provided the telephone communications of the nearby gun crews and controlled the sound effects of the firing guns.

To permit performance assessment with time the scenario was organized into equivalent 6 h epochs of mission demands. In each 6 h, events of differing importance complexity, and urgency, requiring different individual and team responses, recurred with sufficient frequency to permit event pooling for analysis of performance data.

Standard scenario mission demands (events) are summarized in Table II. Also shown for each major scenario mission demand are the immediacy of the required actions, the associated task demands, responsible team member(s), and feedback characteristics. Mission demand classes included: 1) Unplanned Missions--Calls for Artillery fires on an intial target which were often followed by several subsequent adjustments, i.e. repetitions with small variations. These missions involved targets not specified to the FDC previously. These demands were externally initiated and required immediate responses. Such demands evoked serial and task processing; timeliness could be sacrificed to maintain accuracy. Positive and negative feedback were given to the FDC from simulation role players based upon the timlines and accuracy of the FDC's responses. 2) Preplanning -- These tasks were initiated by the receipt of encoded preplanned target messages but required a delayed response from most team members. All team members were involved. Ultimately, firing data for each target, including 2 correction

Table 2

Major Mission Demands and Associated FDC Duties, Immediacy of Actions Required, Responsible Personnel, and Feedback Criteria

		REQUIRED ACTIONS[1]		MAJOR DUTIES[2, 3]					FEEDBACK	NEGATIVE FEEDBACK CRITERIA[4]	
MAJOR MISSION DEMANDS	No.	IMMEDIATE	DELAYED	RTO	HCO	VCO	COM	FDO	GIVEN?	ACCURACY (DEV. ≥ MILS)	LATENCY (≥ SEC)
1. UNPLANNED MISSIONS											
a) Initial Target	4	1,2,3,4,5	——	10,11,12	20,21	20,21	31,32,33	42,43	YES	30	120-180
b) Subsequent Adjusts	22	1,2,3,4,5	——	10,12	20,21	20,21	31,33	43	YES	30	60-90
2. PREPLANNING (Encoded Message Targets)	28	1	1,2,3,4,5	10,11,13,14	20,21	20,21,22,23	32,33,36,37	42,43	NO	NA	NA
3. PRIORITIZING (Priority Targets)	22	1,4	——	10,11	——	——	35	——	NO	NA	NA
4. ON CALL MISSIONS											
a) Preplanned Target	16	1,4,5	——	10,11,12	——	——	31	——	YES	30	20-60
b) Subsequent Shifts	8	1,2,3,4,5,	——		20,21	20,21	31,32,33	42,43	YES	30	60
5. REVISING (Caused By Battery Moves)	12	——	2,3,4,5	——	21	21,22,23	32,33,36	42,43	NO	NA	NA
6. UPDATING (Caused by Weather Changes)	12	1	4,5	10	——	——	34,32,33,38	44,42,43	NO	NA	NA
7. MULTIPLE SESSION SEQUENCES											
a) Unplanned Missions	variable	1,2,3,4,5,	——	10,11,12	20,21	20,21	31,32,33	42,43	YES	30	60-180
b) On Call Missions	7 - 9	1,2,3,4,5	——	10,11,12			31		YES	30	20-60
c) Nonstandard Missions	variable	1,2,3,4,5	——	10,11,12	20,21	20,21	31,32,33	41,42,43	NO	NA	NA
d) Adjusts & Shifts	15 - 23	1,2,3,4,5	——	10,12	20,21	20,21	31,32,33	42,43	NO	NA	NA
8. POSITION REPORTS	9	1	1,3	10,11,13,14	——	24	——	——	NO	NA	NA
9. LULLS (No New Mission Demands)	2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10. NONSTANDARD MISSIONS	6 - 8	1,2,3,4,5	1,2,3,4,5	10,11,12,13,14	20,21	20,21,22,23	31,32,33	41,42,43	NO	NA	NA

FOOTNOTES:

[1] Team Member Codes
1 — RTO
2 — HCO
3 — VCO
4 — COM
5 — FDO

[2] Duty Codes (See Personnel Duties Table)

[3] Work-breakdown structure assumes teams followed SOP and they were also current in their preplanning.

[4] The most demanding criteria are shown; additional negative feedback for continued inadequacy on a mission would also be given.

factors, were to be computed and sent to the guns as time permitted. No external feedback was given to the FDC. 3) Prioritizing -- At any time, 2 of 16 preplanned targets were designated as having priority to emphasize that an especially rapid and accurate response might be required on these targets. As with preplanning no feedback was given. 4) On-call Missions -- These demands were calls for Artillery fires on preplanned targets. Typically, they occurred at least 15 min after receipt of encoded preplanned target messages. These missions probed and reinforced the state of readiness achieved by target preplanning. External positive and negative feedback were given for timeliness and accuracy, but timeliness criteria were more demanding than those for the unplanned missions. 5) Revising -- These initial 12 preplanned targets were encountered at the beginning of each 6 h epoch. Task demands differed somewhat from those of preplanning. Target information was given to the FDC as a written list so that decoding and involvement from the RTO were not required. The targets were also preplotted on the chart sheets so the HCO and VCO did not have to plot them. In addition, since these mission demands were encountered immediately after the "battery move" personnel were reorienting and processing information associated with a new "terrain" location. 6) Updating -- These mission demands occurred approximately 150 min into each epoch. Updating was to improve ballistic correction factors on 12 preplanned targets. This task was the responsibility of the COM, but failure to perform this task resulted in only inaccuracies in the preplanned target data.

As with other target preplanning activities (preplanning, prioritizing, and revising) no negative feedback was associated with inadequate updating performance. 7) Multiple Mission Sequences -- Periods of intense fire mission activity included: unplanned missions, on-call missions, non-standard missions, adjusts and shifts. These simultaneous demands were not as well matched as single events since interactions were unpredictable. External negative feedback was given less consistently for these events. 8) Position Reports -- These less important demands required decoding maneuver units' positions and plotting their locations. Such demands had minimal consequences for inadequate performance. 9) Lulls -- These were two 10-12 min intervals in which no new mission demands were sent to the FDC although irrelevant radio traffic continued. These events created a standardized setting, embedded among other demands, where social interactions might be more likely to occur. Such intervals could also be used to complete prior preplanning activities. 10) Nonstandard Fire Missions -- These demands occurred occasionally to provide content validity, add variety, make the sequence of standard events less predictable and evoke special responses. Such events were unmatched as to kind and difficulty but required similar durations to complete them.

Experimental Designs

Two experimental designs were utilized. The designs differed only in number of sustained challenges and their durations. Design I had a single 86 h operational challenge; whereas, Design II had two 38 h challenges separated by a 34 h rest and relaxation interval. Both designs had identical, pre-challenge familiarization and training trials. Design I was intended to produce serious or total breakdown in performance capability which would require major reorganization of team structure. This design was essentially an "open ended" challenge since 86 h was judged to be beyond the limits for sleep deprived subjects to perform such cognitive tasks. Design II was to evaluate the potential of the experimental model for use in repeated-measures designs.

Subjects and Simulation Facilities

The 5-man, FDC teams were males aged 18-24 and fully informed volunteers from two battalions of the 82d Airborne Division. These teams used manual fire direction procedures exclusively, without the assistance of digital computers. Accordingly, standard manual FDC equipment was assembled in a tent inside a 6.1 x 2.7 x 2.4 m climate-controlled chamber at USARIEM. Ambient temperature was maintained between 20 and 24°c and relative humidity between 35 and 50%. Lighting conditions were superior to those in field FDCs so that continous videotaping could be accomplished. Each subject was instrumented with a microphone and small radio transmitter for individual voice reproduction, a small physiological cassette recorder, wrist actograph, ECG electrodes and, in some instances, EEG electrodes.

Simulation Procedures

Each team received an inital 5 h orientation followed by 3 days of operations (8 h/day) at the work load used in subsequent sustained trails; this training was intended to teach the common SOP for message formats and fire commands. It also minimized practice and novelty effects. Teams 1 and 4 then underwent a single challenge which they were told could run 86 h (Design I). Teams 2 and 3 underwent two 38 h challenges separated by a 34 h rest (Design II); they were told the challenges would each run 36 to 42 h. All challenges began at 0700 h.

Prior to sustained operations challenge all FDC personnel were awakened at 0500 h. Subjects were fed and outfitted with the recording and monitoring equipment. The FDC personnel then entered the simulation facility and completed pre-challenge questionnaires and self-rated scales. Afterwards, at 0700 the operational portion of the simulation was begun. This corresponded to the beginning of a 6-h scenario epoch. Subjects in Design I were instructed not to set shifts or withdraw to sleep, but received no instructions about job rotation. Subjects in Design II were also instructed not to set shifts or sleep. In addition, they were not to rotate tasks. In the FDC the team and its individual members were challenged and driven by the scenario demands described previously. During the simulation performance-contingent, positive and negative feedback were given to the FDC for certain scenario events from simulation role players (see Table II). Accuracy deviations were defined as the algebraic difference in mils [The mil is a unit of angular displacment; 6400 mils = 360°] between each FDC team's firing data and the correct solution for the shell and propellent charge specified, as computed manually by the Department of Gunnery, USAFAS. Timeliness was the latency between mission input and the team's output.

Each 6 h approximately 48 min were spent in non-operational, administrative activities. These periods, in the final portion of each 6-h epoch, corresponded to the time required for the guns and FDC to make a tactical move. Team members went into an adjacent environmental chamber configured like the interior of a vehicle and heard recorded helicopter sounds. During the simulated move, self-report questionnaires and psychological tests were administered, urine and sometimes venapuncture samples were collected, electrodes and instrumentation were maintained by "field medics" and meals and snacks were eaten. During the simulation the FDC teams did not physically move the FDC, erect camouflage, or dig emplacements. Suplemented C-rations, hot coffee and soda were available ad lib throughout the simulation.

Between simulated operational challenges each team was housed in a dormitory and ate cafeteria food or t.v. dinners. All team members completed sleep logs upon awakening; EEG, EOG, ECG were recorded from selected subjects. Although investigators from WRAIR also collaborated in the design and conduct of the study, only selected data obtained by USARIEM and NHRC investigators will be presented in this report.

Performance Assessment

Performance indices were derived for system (team) output as well as individual performance. After the studies, accuracy and timeliness data were scored from an audio recording with time code and compared with a second independent determination. Any discrepancies were resolved by further rescoring of the audiotapes. Other performance indices were derived from the examination of FDC records, e.g. radio-log book, chart operators' plotting sheets, and COM records. For data analysis/reduction, accuracy criteria were established and applied to all studies, i.e. $\leq \pm 3$ mils in horizontal and vertical gun tube displacement was considered accurate. Deviations $> \pm 3$ mils were grouped into classes depending upon the magnitude of the product of deflection and quandrant errors. In deriving other performance indices various metrics were utilized: differences between matched pairs, median values with 25th and 75th percentile values, percentage of uncompleted task demand, number of occurrences, and cumulative occurrences.

Results and Discussion

Overview

The teams differed substantially in organizational style, social history, prior experience, and mastery of the simulated mission demands. Generally, teams 1 and 4 showed less initial mastery and greater performance changes over time (Design I). All teams responded to the competitive challenges and became quite involved with the simulation (Stokes & Banderet, 1978; Annual Progess Report FY 77, 1978; Francesconi, Stokes, Banderet, & Kowal, 1978).

Team 1 exercised the right to withdraw from the study at 0700 h after 48 h. The VCO appeared somnolent in the last 6 h, resolved to terminate, and the FDO decided that the team should leave together. The team had also made several errors in the previous 8 h which "endangered" friendly troops; the FDO expressed concern that his team would soon be ineffective. Team 4 withdrew voluntarily at 0400 h after 45 h. The younger enlisted personnel of this team had the least field experience and were very fatigued. The FDO showed signs of being especially fatigued from his continuous supervision but persevered until the COM prompted him for the decision to stop.

Team 2 completed both 38 h challenges without gross performance deterioration. The FDO, COM, and the VCO slept very poorly the night before the second 38 h challenge. Some napping in place did occur during the final 18 h of the second challenge with limited substitution or switching of roles. Team 3 also completed both 38 h trials with little performance deterioration; they slept well in the interim. The VCO terminated ater 6 h of the second trial; the remaining four men took this as a challenge and continued with the FDO operating the chart.

System Output: Accuracy

For all teams, accuracy of firing data for unplanned missions was generally well maintained, even until termination. In contrast, accuracy of firing data for preplanned targets fired upon during on-call missions was less for all teams and deteriorated progressively over time in Teams 1 and 4. Figure 1 shows the distribution of errors of different magnitudes for all Teams during the simulations.

Teams 1 and 4 showed clear, progressive increases of 7-14 mil errors. These occurred most frequently in preplanned target events and usually involved omissions of correction factors under circumstances which could be considered speed-accuracy tradeoffs. Generating preplanned target data required increased effort in comparison to unplanned mission calculations, e.g. decoding of grid coordinates inclusion and updating of correction factors. In addition, negative feedback criteria for the on-call missions involving preplanned targets were more demanding, e.g. 20-60 vs 60-180 sec. Hence, many errors reflected deliberate omissions or misapplications of correction factors and produced errors of 7-14 mils. Teams 2 and 3 showed greater variability in accuracy for the on-call missions than for the unplanned missions, but no progressive deterioration.

Team 1 showed an increase of serious errors (30-1798 mils) from 24 to 48 h. For the other teams such an increase does not occur. These larger errors covered a wide range of FDC functions, e.g. incorrect copying or decoding of target coordinates, incorrect plotting of coordinates or reading of range or the deflection values, incorrect setting or reading of nomogram scales, digit reversals in the transmission of data to the guns, specification of the wrong propellant charge for the data sent, and sending data for a different preplanned target than intended.

The magnitude of any given error in ballistic firing data depends in part on the nature of the mistake and chance. In spite of this somewhat arbitrary relationship between error magnitude and psychophysiologic function, it is still valuable to examine these "outliers" because of their very serious potential consequences in live-fire training and combat. Since it is reasonable to expect the FDC team, especially the FDO and COM, to detect particularly large errors, the occurrence of such errors may imply a lapse in short-term memory, perception, or higher cognitive functioning.

System Output: Timeliness

Accuracy for firing data for unplanned missions was generally well maintained for all teams; however, timeliness for these missions suffered in all but one team. For example, Figure 2 shows median latencies to accomplish the most standard and predictable subset of these demands, the subsequent adjustments, increased more than 35% from initial values during sustained operations for Teams 1, 2, and 4. The differences within each team between initial and final 6-h performance latencies were statistically significant ($p \leq 0.05$ for Teams 1 and 2; $p \leq .01$ for Team 4).

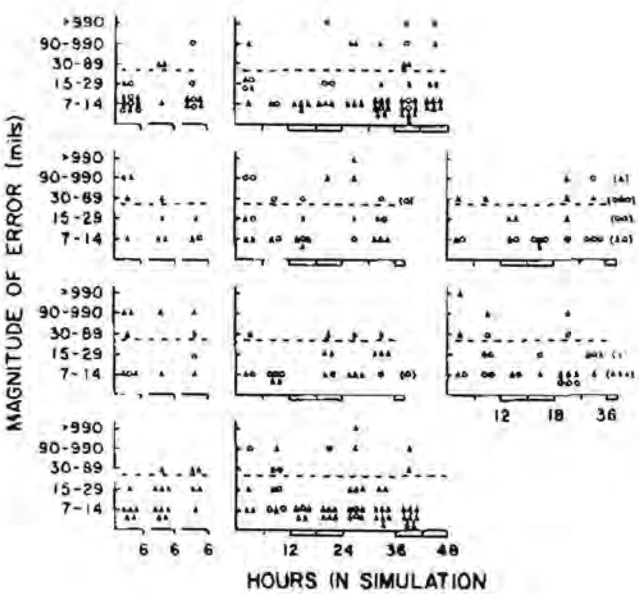

Figure 1. Errors in ballistic data (deviations from correct values) sent for firing by the four FDC teams. Errors were grouped in classes according to magnitude and are shown as a function of h in the simulation. Closed triangles indicate preplanned target errors; open circles, unplanned fire mission or subsequent adjustment errors. Errors > ± 30 mils (above the broken line) usually incurred negative feedback from scenario role players regarding inaccuracy. Results for Teams 1,2,3, & 4 are arrayed from top to bottom; respectively.

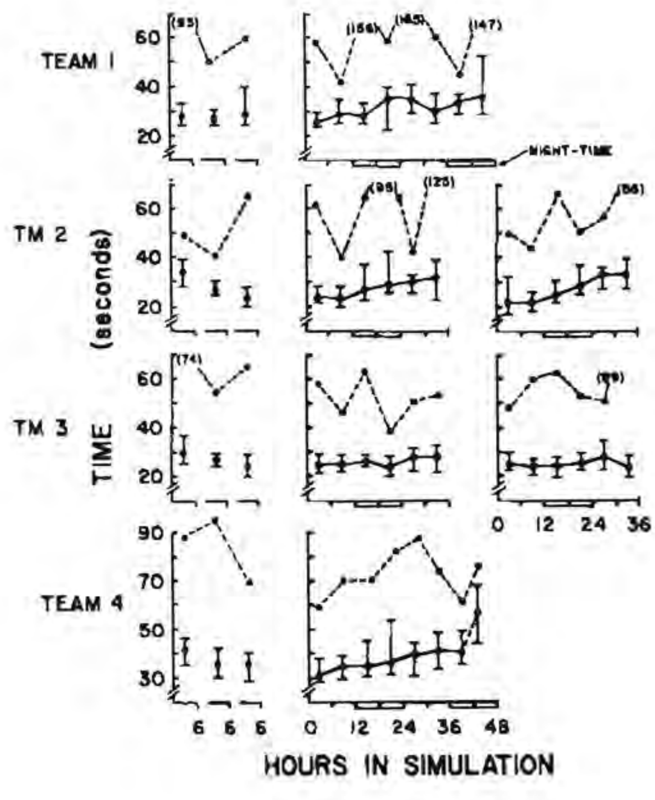

Figure 2. Computation latencies (standard adjustment sequences) for unplanned missions are shown as a function of h in the simulation for all four teams studied. Each data point with lower and upper bracket represents the 50, 25, and 75th percentile scores for a 6 h epoch. Maximum values are connected by the broken line.

The finding of increased latencies with little change in accuracies in the unplanned missions are as expected (Johnson & Naitoh, 1974; Woodward & Nelson, 1974) for highly overlearned tasks: 1) initiated by arousing external cues, 2) accomplished during a brief period of mobilization, and 3) which received prompt feedback for inadequate performance. It was apparent on the veido record that speed was sometimes sacrificed for accuracy through increased individual latencies and demands upon the team's internal double-check procedures. Such increased latencies are tactically significant. They indicate a loss of combat effectiveness for engaging battlefield targets and would increase FDC and battery vulnerability for detection and destruction by the enemy.

Timeliness for on-call missions, as well as accuracy, suffered in Teams 1 and 4, the teams undergoing the 86 h challenges (Design I). Latencies for firing upon preplanned targets (Figure 3) increased significantly after 42 h in Team 1 and after 30 h in Team 4 ($p < 0.01$). Teams 2 and 3 did not show a deterioration in speed of response to on-call missions although there was a period of slower responses from 18 to 30 h during Teams 2's second challenge ($p < 0.05$). These delays would also have serious tactical consequences in combat where delivery of Artillery fires within seconds on preplanned targets is essential to suppress hostile, wire-guided weapons.

As will be shown subsequently, Teams 1 and 4 were often behind on their preplanning. When an on-call mission was requested preplanned target data were often not precomputed nor available at the guns. This required data computation "on the spot". Increased latencies sometimes resulted for these teams; they also were more likely to make errors in haste or through deliberate omissions as they sought to respond quickly to on-call missions.

Systems Output: Preplanned Processing Efficiency

Examining the efficiency of preplanned target processing activities, (i.e. preplanning, prioritizing, revising, and updating) suggests how the observed differences in team effectiveness in responding to on-call mission events occurred. It has the added virtue of assessing the risk of serious mission failure for the total population of preplanned targets. Operationally, preplanning required processing target messages and sending the firing data for each target to the guns as soon as possible. Ideally, this was done well before a preplanned target was requested in an on-call mission, if indeed the target was requested (50-70% chance). Functionally, preplanning involved all team members; most individuals had to complete their work on a target before others could proceed (serial processing). Finally, unless quickly completed, other scenario events would inevitably interrupt the process.

One way to determine FDC efficiency was to apply queuing theory. For these analyses, the FDC was viewed as a service center to which users sent requests to be processed. Once processed, the resultant firing data for each target were called to the guns ready for delivery during possible subsequent on-call missions. The efficiency index of FDC performance was principally influenced by the number of requests in the queue and the processing time for each request. If the number of unprocessed preplanned targets increased and/or the interval between the request and when the data were called to the guns (processing time) increased, efficiency was decreased. Therefore, 0% efficiency meant no requests were ever processed; whereas, 100% implied instantaneous processing of each request.

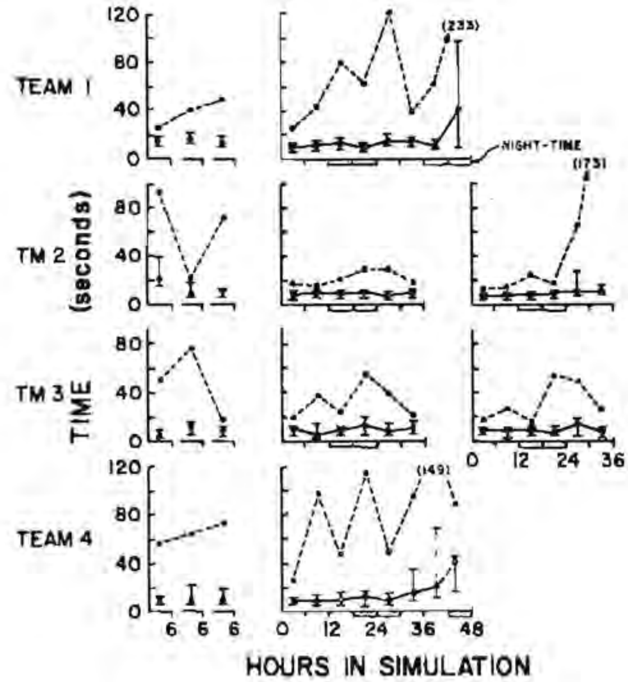

Figure 3. Latencies to on-call missions against preplanned targets as a function of h in the simulation are shown for all four teams studied. Each data point with lower and upper brackets represent the 50, 25, and 75th percentile scores for a 6- h epoch. Maximum values are connected by the broken line.

Figure 4 shows FDC efficiency with time for the four teams considering: 1) all preplanning, i.e. all targets sent in encoded target messages, 2) only prioritizing, i.e. those targets designated as having priority, 3) revising, i.e. the initial 12 preplanned targets after a battery move, and 4) updating, i.e. application of new weather correction factors to 12 preplanned targets for which data should have been generated previously by preplanning. All teams showed increased efficiency after the pretraining. During the sustained operations, Team 1's preplanning efficiency fell from a maximum of 77 to 33%, with most of that decrease in the last 6 h. For Team 4 the decrease was more gradual from 77 to 42% over 42 h, then falling to 18% in the last 3 h before termination. In contrast, Teams 2 and 3 processed preplanned targets more efficiently. Since Team 2 was usually prepared when preplanned target data were requested in an on-call mission they rarely made errors in haste, nor did they have to omit correction factors when called upon. Their efficiency in the second trial was slightly less; their minimum also occurred at 24-30 h. They also showed a greater decrease at 30-36 h than in the first challenge. Team 3's efficiency was between 75 and 68% during the first challenge, but was more variable (85 to 61%) in the second trial when functioning with only four men.

These results also indicated that in most cases, the teams maintained higher efficiency covering priority targets than the total population of targets. This would be expected given the operational significance of priority targets. The exception is Team 4, the least experienced team, who actually accomplished the priority target task less adequately than the preplanning task from 18 to 42 h. It is also of interest that prioritizing efficiency decreased with h in the simulation in Teams 1, 2 (2nd challenge), and 4. This occurred even though, on several occasions, preplanned data were already at the guns when a target was specified as priority by a simulation role player. Under these circumstances, each COM only needed to announce the priority target number to the guns, but 3 of the 4 COMs increasingly failed to do so. Additional analyses are underway to determine why such changes occurred.

The importance given to a task by the initial instructions, the task's consequences, and the number of FDC team members involved with the task generally had a strong influence on the performance observed. The results of queuing analyses of the two less important tasks, revising and updating, are also shown in Figure 4. Failure to perform either task incurred only minor errors, i.e. 3-10 mils. Teams 1 and 4 both showed less efficiency in revising; Team 4 demonstrated <50% efficiency at the beginning of the challenge. Teams 2 and 3 were almost as efficient at revising as preplanning during both challenges. On the other hand, updating was rarely done by Team 1 and was quickly abandoned by Team 4 after initial token performance. For Team 2, updating was less efficient in the first and final 6 h of the first challenge; updating was the preplanning activity most sensitive to decrement between 24 and 30 h of the second challenge. For Team 3, updating was generally performed less efficiently than other preplanning activities and deteriorated more after 18 h in each challenge.

System Output: Unprocessed Preplanned Target Demands

The quantity of work never done may be more useful as an index of depletion of team reserve and decreased performance capacity than increased errors of latencies. Table III highlights the differences between the 4 teams on several preplanned activities for various duration comparisons. Table entries

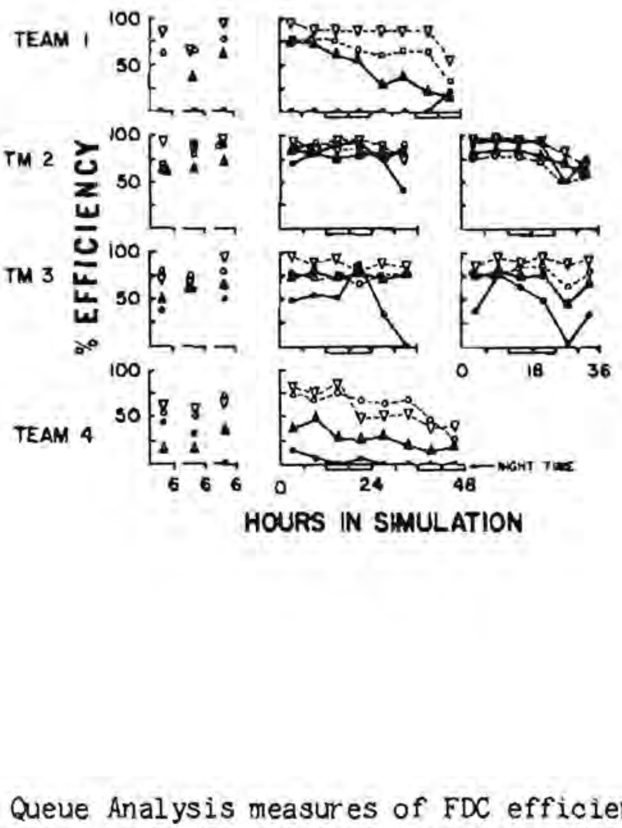

Figure 4. Queue Analysis measures of FDC efficiency for four preplanned target activities are shown for all four teams as a function of h in the simulation. Efficiency for targets which required updating are shown by closed circles; of targets which required revising, by closed triangles. Efficiency for preplanning new targets from encoded messages and for targets designated as priority are shown by open circles and open triangles, respectively.

Table 3

Percentages of Various Uncompleted, Preplanned Target Tasks. Values Are Shown for the 4 Teams Studied for the Initial 36 h in the Simulation. Second Challenge, 36 h Comparisons Are Also Shown for Teams 2 & 3. Team 1 & 4, 48 h Comparisons Are Also Indicated. Team 4 Values from the 45-48 h (Interval after Team 4's Termination) Were Extrapolated.

TEAM	PREPLANNING	PRIORITIZING	REVISING	UPDATING	% TOTAL TARGET PROCESSING NEVER COMPLETED
		INITIAL 36 HOUR COMPARISON (CHALLENGE 1)			
1	4	8	4	100	21
2	2	5	0	12	4
3	9	10	0	36	12
4	9	27	28	86	30
		SECOND 36 HOUR COMPARISON (CHALLENGE 2)			
2	2	11	0	11	6
3	12	7	0	19	10
		INITIAL 48 HOUR COMPARISON			
1	11	14	14	95	26
4	19	34	49	88	40

show the percentage of various preplanned target activities, as well as percentage of total target processing never completed. Several trends are evident. Preplanned target processing was less adequate at 36 h for Teams 1 and 4 (Design I) than for Teams 2 and 3 (Design II). Although one cannot rule out level of training, experience, and organizational variables these data suggest that uncertainties, expectancies, and demands of an 86 h challenge took an early toll on Teams 1 and 4. (This observation is further supported by trends in the biochemical and interaction process analysis data). Secondly, Team 4, the least experienced team, was the team with demonstrated the least adequate total target processing. Third, the challenge 1 and 2 data from Teams 2 and 3 indicated similiar outcomes on repeated measures. Lastly, this Table is consistent with the queuing analysis in that the updating task was the preplanned target activity most frequently not completed by all 4 teams. It is of interest, in contrast to other preplanned activities that the updating task was done by a single team member, and was not solicited, probed, or given external feedback. This provides a fitting lead into analysis of individual team performances.

Individual Team Member Performances

It is axiomatic that group performance is some complex resultant of the performances and interactions of the individual team members (3-5, 6). Hence, specific questions for these studies were: 1) Could meaningful individual performance data be extracted from the FDC simulation? 2) How does knowledge of an individual's performance increase understanding of system output? and 3) What are the characteristics of mission tasks which were sustained or degraded with time? Initial analyses have concentrated on Team 4 since they showed the greatest changes in system output and terminated in the middle of an operational epoch. Team 4's changes also occurred earlier in the simulation and were greater in magnitude.

The RTO is characteristically the newest member of the FDC but has a challenging task as a monitor and dispatcher of information. Table IV shows several measures of RTO performance deteriorated with increased h in the simulation even though each time period involved approximately equivalent message input and demands. Failures of the RTO to respond to the FDC's call sign are similar to the findings of classical vigilance studies (Johnson & Naitoh, 1974; Woodward & Nelson, 1974). Indeed, some occurrences appeared from observation of the video records to have reflected lapses into microsleep. Failure of the RTO to record the sender's call sign in the log book also increased after 24 h; such omissions contributed to confusion in the FDC if it became necessary to contact the sender. Other sensitive measures, e.g. the RTO's requests for the sender to "say again" items of information, and corrections in his log book, are behaviors which may compensate for microsleep, increased distractability or difficulties in perception. A fifth measures, the number of undecoded position reports in the log, was for a task which, like updating, was done by a single team member and had minimal consequences for inadequate perforformance. The numbers shown for this performance represented a rise from approximately 30% to 80% non-completion of task demand over the duration of the simulation. It must be emphasized that numerous measures of RTO perform ance did not change with time. For example, Table IV shows that the RTO almost always decoded preplanned target grids from the radio messages and passed this information to the HCO and VCO.

Table 4

Individual Performance Measures for Various Team 4 Members

PERFORMANCE MEASURE	STATISTIC	TEAM MEMBER	HOURS IN THE SIMULATION 0-12	12-24	24-36	36-48
Unresponsiveness to Call Sign	No.	RTO	1	7	8	6
Requests for "Say Again"	No.	RTO	1	12	28	27
Omissions In Logbook (Call Sign)	No.	RTO	0	2	6	4
Changes in Logbook Entry	No.	RTO	1	1	4	11
Undecoded Position Reports	No.	RTO	17	27	34	36
Undecoded Targets from Messages	No.	RTO	0	0	4	0
Inaccurate Target Plots	%	HCO	8	16	26	36
		VCO	6	4	6	10
Unfinished Site Computations	%	HCO#	100	100	98	97
		VCO	15	18	20	63
Unplotted Targets From Messages	%	HCO	5	0	6*	48
		VCO	5	0	8*	61
Unprocessed Targets From Messages	%	COM	9	4	10*	51
Adjustment Information ratio (No. recorded/No. not recorded)	Ratio	COM	2.6	0.7	0.3	0.2
Changes Communicated To Guns	No.	COM	56	31	88	240

The HCO normally does not perform this task.

*Excludes 4 targets not decoded by RTO.

Only one exception involving 4 targets occurred near the end of a 6 h epoch, a period when the team had little time for processing. It was shown in SYSTEM OUTPUT: PREPLANNED PROCESSING EFFICIENCY that Team 4's preplanning was one aspect of system performance which showed greatest differences from other teams. Less efficient processing, more errors, and failure to complete more and more targets were especially marked after 18 h in the simulation. As noted above, the RTO was consistent in completing his part of the task, although he contributed some longer latencies and committed some decoding errors.

The performance of the next team members in the serial preplanning tasks, the HCO and VCO, are also shown in Table IV. For % unplotted targets the performance of HCO and VCO was identical up to 30 h even though all task demands were rarely completed. This nonasymptotic correspondence suggests the influence of social and organizational factors. After 36 h, both showed decreased output, with the VCO completing substantially less of the task. However, the VCO's output presumably has a greaster influence on Team 4's accuracy for preplanned targets since he was consistently more precise in plotting than the HCO. Indeed, the probability that the HCO would produce an inaccurate plot increased progressively with time ($p=0.08$ to 0.36). Each time the values from the two charts failed to correspond within acceptable limits, extra time and involvement were required by the FDO, HCO, and VCO, while the COM had to wait.

Although the VCO was accurate and plotted a smaller number of targets, Table IV indicates he completed fewer site computations after 36 h. This measure of VCO performance suggests that the observed decrease in accuracy of Team 4's preplanned target data partially resulted from the failure of the VCO to compute this important correction factor. Thus, Table IV also highlights individual proficiency differences and performance changes with time which contributed to increased workload and disrupted information flow as the sustained operation continued.

Analysis of the COM's role in preplanning (Table IV) indicates that the COM consistently processed fewer targets from target messages than did the VCO except in the last epoch where their outputs were identical. Examination of the specific targets indicated that indeed, the COM allowed his performance at this task to be limited by the VCO, the chart operator who processed fewer targets, but more accurately than the HCO. Other measures of COM performance, i.e. adjustment information ratio and the number of changes communicated to the guns showed dramatic changes with h in the simulation, especially after 24 h. These trends are consistent with the time courses of many system output measures. This is not surprising. The COM has one of the more continuous tasks and is the person in the FDC who usually communicates with the guns. As his individual performance deteriorated, system output was also impacted. As the senior ranking enlisted person, the indirect impact on the team resulting from his losses in personal efficiency and his increased attention to task matters cannot be ignored either. Additional measures of COM performance are being derived from each COM's written records and from his verbal communications with the gun role players, to further document changes in efficiency of this critical individual.

Assessment of FDO performance over time presents the greatest challenge. The FDO's style of leadership and level of involvement in specific tasks properly varies depending upon the initial skills of team members and prior experiences of the team, as well as on any changes in individual/team efficiency with time. The Team 4 FDO provided task direction, double-checked charts, computed data, and showed concern for clearance of targets in restricted areas (another FDO responsibility) until he concurred with the COM's assessment that "the men have had it." Since the FDO was responsible for the team's output, the observed decrements technically represented decreased performance of his duties. It is moot whether this was due to degradation of his psychophysiological status or whether task demand (due to the decreased efficiency of the team) rose to exceed his span of control. Work is continuing to identify measures of FDO performance which can provide evidence of changes with time in sustained operations. Perhaps indices of FDO functioning may eventually be found in the analyses of team social processes currently underway.

The examples given for Team 4's RTO, HCO, VCO, and COM show how the present level of analysis enables one to infer differing organizational styles, individual capabilities and liabilities, and to determine how different members influence and set limits on team output. It should be emphasized again that the data arrayed were measures that changed with time; many others did not. This is an important observation since it suggests that when many of the real-world variables are incorporated into a performance study, (e.g., objective contingencies, task feedback, opportunities for "say again" requests, and double-checks), performance is likely to be more robust than that predicted by more traditional approaches to individual performance assessment.

Neuroendocrine, Physical Fitness and Sleep Findings

In addition to the evaluation of team and individual performance, many other biological and psychological measures were determined. These included: assays of urinary neuroendocrine hormones, tests of aerobic physical fitness and self-reports of sleep. For all measures it was recognized that individual differences would probably be important. The purpose of arraying these data was not to show universal relationships, but to illuminate patterns of change in the physiological and psychological statuses of individuals which would add perspective to the observed performances of teams and individuals. Only data from Teams 1 and 2 will be presented.

For Teams 1 and 2, aerobic fitness ($\dot{V}O_2$ max) of each individual was initially determined using the modified Taylor interrupted treadmill test. Subsequently, oxygen uptake ($\dot{V}O_2$ submax) and heart rate (HR submax) were measured using the Astrand bicycle ergometer at 60% of each individual's maximum capacity. These tests were conducted during the familiarization and pretraining week, immediately after each sustained operation, and after post-challenge (recovery) sleep. Each man's total urine output was collected every 6 h for 48 h during the familiarization week (after novelty effects were assumed to have attenuated). Urine collections continued every 6 h throughout the sustained operations. Aliquots were analyzed for 17-hydroxcosteroids (17-OHCS) and total catecholamines (Francesconi et al., 1978). Following every period of sleep in the dormitory all subjects filled out the NHRC Sleep Log.

Several explanatory hypotheses from the literature regarding the effects of sleep deprivation and stress on neuroendocrine response and on aerobic fitness may be helpful in interpreting the sometimes opposing responses of individual subjects. Urinary 17-OHCS have been related to generalized "stress" and especially to the perception of novelty, uncertainty or threat (Bourn). Total urinary catecholamines generally have been related to arousal level (Mason, 1968). Increased oxygen uptake at rest and during submaximal work (Harris & O'Hanlon, 1972) after sleep loss or in other stress situations has been interpreted as reflecting a metabolic shift from carbohydrate to fat utilization, presumably in response to neuroendocrine effects.

The results for Team 1 are summarized in Table V. four individuals showed increases in total catecholamine excretion over the 48 h sustained operation compared with the control period. Three also had elevated 17-OHCS excretions, although COM, the sergeant, showed a decrease. Urine collections were incomplete for the HCO, but in 6-h samples from equivalent times of day, he too tended to show higher catecholamines and 17-OHCS during the sustained operation. The 17-OHCS rise was especially great (55%) in the RTO, who had not been with the team long but had been picked to come to USARIEM (at his own request) in place of the regular RTO.

Team 1's junior enlisted men (RTO, VCO, HCO) had increased VO_2 submax and HR submax at the end of the 48 h challenge, implying decreased aerobic fitness (i.e. increased physiological "cost" to perform the same work". The change in team mean HR was significant ($p<.05$), but notably the FDO and COM showed little change in HR and decreases in $\dot{V}O_2$ submax. Following a day and a night of recovery sleep, the HCO and VCO showed further increases in $\dot{V}O_2$ submax and COM's values were now increased, although the RTO had improved. It is interesting that the HCO, the man whose voluntary termination precipitated the team's withdrawal, showed the greatest relative increases in $\dot{V}O_2$ and HR. The Sleep Log indicated that the HCO slept less than usual the night before the trial and reproted himself less than fully alert upon awakening; this may have contributed to his apparent greater fatigue in the hours before termination. However, motivational factors clearly exerted an influence. The RTO (who, as noted above, had shown high motivation to participate) slept poorly throughout the entire baseline period (4 h vs his reported usual 8.5 h), but began the test reporting peak alertness. He, in contrast to the HCO, expressed disappointment when the challenge terminated at 48 h.

Team 2 results are also arrayed in Table V. Like Team 1, physical fitness after the first sustained challenge varied compared with control. However, all five members of Team 2 demonstrated increased $\dot{V}O_2$ submax and HR submax at the end of the second 38 h test and following the subsequent night's sleep; these changes were highly significant for both $\dot{V}O_2$ and HR ($p<.001$). The effect was evident in the FDO, COM, and RTO, individuals with the most continuous tasks. Sleep Logs showed that Team 2's FDO and VCO slept poorly and reported feeling sleepy before the first 38 h challenge. All team members slept well immediately after the first trial, but the FDO, VCO, HCO, and COM slept poorly the night before the second challenge and gave ratings of fatigue. Clearly, in the final hours of the second 38 h challenge, these team members (especially FDO and VCO) had accumlated sleep debts substantially greater than from just one night of deprivation.

In Team 2 the FDO consistently excreted less 17-OHCS and less catecholamines during the sustained operations than during the control period. The RTO showed even greater decreases in 17-OHCS as well as decreased catecholamines. The COM's excretion of 17-OHCS first increased in Challenge 1, but decreased

TABLE V — Individual Neuroendocrine, Aerobic Physical Fitness, and Self-Reported Sleep Indices for Team 1 & 2 Members.

		TEAM 1 MEMBERS					TEAM 2 MEMBERS				
MEASURE	CONDITION	FDO	COM	RTO	VCO	HCO	FDO	COM	RTO	VCO	HCO
Total Sleep (h) from NHRC Log	Control ($\bar{X}$ 5 nights)	6.4	6.2	4.2	7.1	7.2	6.7	5.8	7.0	7.2	7.1
	Pre-Challenge 1	6.5	7.0	5.5	7.0	5.5	4.5	6.0	6.5	3.0	6.5
	Post-Challenge 1	13.0	14.5	13.0	12.0	13.0	12.5	11.0	12.0	12.0	14.0
	Pre-Challenge 2	——	——	——	——	——	1.0	4.5	6.5	3.5	5.0
Urinary 17-OHCS (total mg)	Control*	12.7	14.2	13.7	10.2	——	10.4	8.9	11.0	——	7.5
	Challenge 1*	15.8	13.7	21.2	12.2	——	7.4	12.0	7.0	——	10.6
	Challenge 2*	——	——	——	——	——	6.0	7.2	2.5	——	10.8
Urinary Catechols. total μgm)	Control*	353	179	246	192	——	153	115	121	——	80
	Challenge 1*	365	202	307	267	——	116	181	104	——	87
	Challenge 2*	——	——	——	——	——	125	196	112	——	84
Submaximal Work $\dot{V}O_2$ (ml/kg·min)	Control	24.2	30.9	25.3	32.7	29.4	34.9	39.3	38.5	38.2	30.0
	Post-Challenge 1	20.5	29.5	32.2	34.9	31.1	37.2	42.6	38.4	32.2	30.6
	Post-Rest 1#	24.0	33.7	23.3	36.7	37.7	32.6	32.0	38.2	36.3	25.9
	Post-Challenge 2	——	——	——	——	——	41.4	41.5	45.5	37.1	30.2
	Post-Rest 2#	——	——	——	——	——	44.6	47.9	44.6	44.2	34.3
Submaximal Work Heart Rate (bpm)	Control	148	143	150	150	135	120	165	157	164	153
	Post-Challenge 1	147	145	157	168	160	115	170	169	152	156
	Post-Rest 1#	150	147	160	166	168	110	168	180	170	160
	Post-Challenge 2	——	——	——	——	——	135	180	181	174	168
	Post-Rest 2#	——	——	——	——	——	137	181	183	170	175

NOTES: *48 h for Team 1, 36 h for Team 2

#Sleep and light activity totalling 27 h for Team 1, 13 h for Team 2 during Challenge 2, compared to control. His catecholamines excretion, however, was elevated throughout both tests. The HCO had elevated urinary 17-OHCS during both challenges with negligible increases in total catecholamines. Collections from the VCO were inadequate in all conditions; his catecholamines appear consistently decreased in both experimental challenges compared with control, while there was no clear trend for 17-OHCS.

In summary, findings in Teams 1 and 2 suggest that sustained operations involving high mental workloads which preclude sleep may temporarily reduce physical aerobic endurance, and that this may not be reversed by a single night's sleep. Neuroendocrine responses during sustained operations ranged widely, with most Team 1 members showing increased excretions while most Team 2 members had decreases. The elevations of catecholamines and 17-OHCS in Team 1 may reasonably be attributed to the arousal, novelty and uncertainty inherent in the 86 h "openended" design and the fact that Team 1 was the first team to participate in the simulation. Interestingly, the HCO, the only member of Team 2 who showed elevations of both catecholamines and 17-OHCS, verbalized doubts after 28 h in the second challenge that the COM could finish. The HCO was answered by the FDO, that the COM had gone 38 h before and could do it again.

It might be argued that those individuals who showed decreased 17-OHCS were not "stressed" by the sustained operations. However, other evidence documents that they were certainly uncomfortable from the sleeplessness and confinement in the simulation. Furthermore, the sleep disturbances in Team 2 prior to the second challenge suggested a high level of anticipatory anxiety, especially in the FDO. Interpersonal tension between Team 2's FDO and the four enlisted men was high and persisted after the study was over. However, novelty and uncertainty were minimized in Design II, especially in the second challenge. Indeed, Team 2 complained that they knew all too well what they were in for. The finding of decreased 17-OHCS in some Team 2 subjects (and in the Team 1 COM) is therefore consistent with the reports (Bourne) that this biochemical indicator may show suppression in experienced Army team members who are concentrating on well-learned tasks in spite of stress, espeically if the situation is relatively predictable and they are confident they can cope.

It should not be concluded from these findings, or from the performance results, that 48 h is a true limit for adequate sustained operations for FDCs (or for other teams with similar functions and tasks). It is likely that the circadian low which normally occurs between 0300 and 0700 h had a role in the decisions of the Design I teams to terminate. Had combat contingencies been involved, the teams could have continued for some uncertain time, perhaps with cycling or progressively deteriorating effectiveness. This study does support the expectation that well-trained manual FDC teams can function effectively in high task load situations for 38 h without sleep (assuming they are not chronically fatigued at the outset and that environmental conditions are benign). This may require increased reliance on double-check procedures and some trade-off speed to maintain accuracy. A rest interval of 34 h (and probably less) should be adequate to restore the ability to sustain another 38 h challenge. However, Team 2 demonstrated the problem in "sleep logistics" that simple provision of time, even in a favorable environment, cannot assure good quality sleep. Recurrent stress without adequate recovery may result in greater physiological "cost" and eventual performance degradation.

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