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29. Visual-Motor Response of Crewmen During a Simulated 90-Day Space Mission as Measured by the Critical Task Battery*

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In order to test various components of a regenerative life support system and to obtain data on the physiological and psychological effects of long-duration exposure to confinement in a space station atmosphere, four carefully screened young men were sealed in the McDonnell-Douglas Astronautics Space Station Simulator for 90 days with no pass-in's allowed. Under contract to the NASA-Ames Research Center, Systems Technology, Inc., administered a tracking test battery during the above experiment. The battery included a "clinical" test (critical instability task) related to the subject's dynamic time delay, and a conventional steady tracking task, during which dynamic response (describing functions) and performance measures were obtained. The subjects were extensively trained prior to confinement and generally reached asymptotic performance levels.

Good correlation was noted between the clinical critical instability scores and more detailed tracking parameters such as dynamic time delay and gain-crossover frequency. The levels of each parameter spans the range observed with professional pilots and astronaut candidates tested previously. The chamber environment caused no significant decrement on the average crewman's dynamic response behavior, and the subjects continued to improve slightly in their tracking skills during the 90-day confinement period. Some individual performance variations appeared to coincide with morale assessments made by other investigators. The comprehensive data base on human operator tracking behavior obtained in this study demonstrates that sophisticated visual-motor response properties can be efficiently and reliably measured over extended periods of time.

INTRODUCTION

A 90-day sealed chamber test of a regenerative life-support system was performed at the McDonnell-Douglas Astronautics Corporation (MDAC) under NASA Contract NAS1-8997 from the Langley Research Center. Among the stated objectives of the official test plan and procedures (ref. 1) were the following:

. . . D. To demonstrate man's capability . . . for in-flight monitoring of necessary human . . . parameters.

E. To obtain . . . data that will assist in determining the precise role of man in performing in-flight experiments . . . and . . . in validating mathematical models of [manned] space missions.

F. To obtain data on physiological and psychological effects of long-duration exposure to confinement in the cabin atmosphere . . .

To accomplish these objectives, four men, carefully screened for compatibility with each other and with a confined environment, were sealed in the MDAC space station simulator (SSS) for 3 months with no pass-in's allowed, and only a limited number of pass-outs allowed for medical sampling purposes. The primary workload of the subjects included monitoring and maintenance of SSS life support equipment and monitoring and recording their metabolic, medical, and mood characteristics. The SSS environment was "closed-cycle" and included a subnormal air

* This research was sponsored by the Man-Machine Integration Branch of the NASA-Ames Research Center under contract NAS2-4405 (modification-5). The tasks and associated hardware used in this study were previously developed under the same contract.

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pressure of **3/4** atmosphere with normal oxygen partial pressure. A complete description and preliminary results of this simulated mission are given in reference **2.**

This program also provided a unique opportunity to evaluate certain other psychomotor and cybernetic functions in a realistic space station environment (except for zero-gravity) and under operational type work-rest cycles and ambient stresses. Among the more important of such psychomotor tasks are the broad class of tracking tasks: star tracking for navigation or astronomical purposes; telescope pointing for earth-resource or reconnaisance purposes; fine tuning of apparatus for research or communications purposes; and, last but not least, piloting tasks such as rendezvous in orbit and reentry into the earth's atmosphere. (At least one of the crew members is likely to be a pilot or trained as a pilot for such emergencies.)

In order to measure behavior appropriate to such tracking tasks, Systems Technology, Inc., under sponsorship by the NASA-Ames Research Center's Man-Machine Integration Branch, provided a battery of tracking tasks to be performed during the 90-day mission. The objectives of this experiment were:

(1) To obtain a simple "clinical" measure of the crewmember's visual-motor dynamic performance on a routine basis using the so-called "critical instability task" (ref. **3).**

(2) To obtain comprehensive measures of the intrinsic dynamic response properties on a less frequent basis by means of advanced cross-correlation techniques, and to correlate this standard tracking-task data with the critical instability measure.

(3) To present data obtained in this tracking experiment for correlation with medical physiological and psychological data from other experiments run concurrently.

The tracking task test battery and associated apparatus employed in this experiment were developed under NASA sponsorship and are detailed in references **3** through **6.** Systems Technology's role in the present experiment was to provide test specifications, experimental design and procedures; to participate in indoctrination and training; and to reduce and analyze the data. Douglas personnel were responsible for integrating the equipment and tests into the 90-day Experiment, and for administering the control task test sessions.

CONTROL TASKS AND EXPERIMENTAL SETUP

Control Tasks

The psychomotor tests used in this experiment are continuous, compensatory visual-motor tracking tasks. A general block diagram representation of these tasks and associated data measures and analysis is shown in figure **1.** Further details on these tasks are given in reference **6.** Basically, the subject is required to control the motion of a luminous horizontal CRT line with an isometric (force) control stick whose output controls a dynamically unstable controlled element (first-order: $Y_c=\lambda_1/(s-\lambda_1)$ **;** second-order: $Y_c=\lambda_2/s(s-\lambda_2)$). If the subject provides the appropriate dynamic equalization behavior he will be able to not only stabilize the man-machine system, but also to minimize CRT line motions away from the null point or reference line. Two variations of this unstable tracking task employed in the present experiment are described below:

Critical instability task.—The subject is required to maintain stable control as the controlled element's instability is steadily increased. No external disturbance need be introduced in this task because '(remnant" noise sources internal to the human operator (e.g., unsteadiness, tremor) provide ample excitation for the unstable element. In the face of the increasing instability the subject will lose control of the task at some

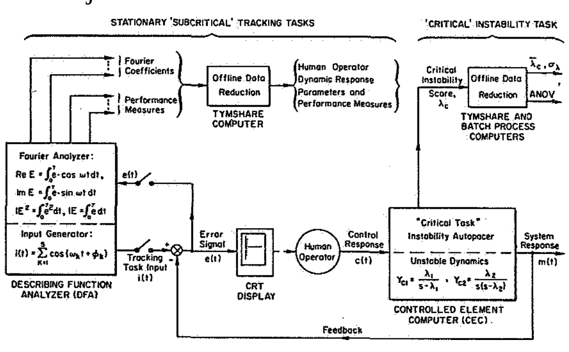

FIGURE 1.—Tracking tasks, *data* measurements, **and** analysis.

point because the line diverges off the CRT more quickly than he can exert compensatory control action. The degree of instability, λ_c, at which the subject loses control is termed his "critical instability" score. It is roughly equal to the inverse of the operator's dynamic time delay as shown in references **3** through **6.**

The control of simple first-order divergent dynamics is called the *first-order critical task,* and requires the operator to act **as** a simple gain (i.e., the operator's stick output looks like a scaled version of the system error signal including a time shift equal to the operator's dynamic time delay). Controlling a first-order divergence in series with a pure integrator is called the *second-order critical task.* In controlling these dynamics the operator must effectively cancel out the effect of the integrator by providing what we term *first-order lead* equalization in order to stabilize the control dynamics. (Lead equalization is equivalent to rate perception or error signal prediction.) Generation of this lead equalization requires additional mental processing time (ref. **7)** which increases the operator's effective dynamic time delay. Thus for the second-order critical task the operator can't achieve as high a critical instability score as with the first-order task.

The operator's basic effective time delay, as measured by the first-order critical task, is composed primarily of neural conduction time delays and neuromuscular dynamics of the arm. Thus performance on first-order critical task is a measure of basic neuromuscular dynamics, while the second-order task measure includes a component due to higher center involvement.

The critical task is easily administered since it only requires about one minute per trial and a single number is recorded at the end of each trial. Therefore, the first- and second-order critical instability tasks were selected to be administered routinely during the 90-day confinement test.

Xteady "subcritical" tracking tasks.—For steady tracking tasks the instability level of the unstable dynamics is held constant at a value well below the typical subject's critical instability score. An unpredictable command input is introduced into the tracking loop as shown in Fig. **1,** and the subject is asked to maintain minimum tracking error during runs lasting approximately 2 min. Using special apparatus to be described later, the error signal is Fourier analyzed and performance data are computed during the run. These data are further reduced off-line, via a time-sharing computer program, to obtain the subject's open-loop describing function and task performance. The describing functions are fitted with a three-parameter dynamic response model, and the resulting loop closure properties are interpolated. Key parameters presented herein include

Crossover frequency (ω_c).—The unity-amplitude frequency of the open loop describing function; determines the closed-loop bandwidth.

Phase margin (φ_M).—A measure of system stability margin related to the closed-loop damping ratio.

Dynamic time delay (τ_e).—The subject's visual-motor time delay in a continuous tracking task including neural and mental delays and neuromuscular lags.

The performance measures include

Normalized error variance (σ_e^2/σ_i^2).—the ratio of tracking error variance to the variance of the task input.

***Error** coherence* (ρ_e^2).—the percentage of total variance predicated by (correlated with) the describing function measurements. The remaining error power $(1-\rho_e^2)$ is due to the subject's internal noise (remnant).

For this experiment we chose to include both first- and second-order subcritical tracking tasks that are dynamically equivalent to the first- and second-order critical instability tasks. The first-order instability was set at $\lambda=2$ rad/sec, and the second-order case was set at $\lambda=1.25$ rad/sec. Although these tasks allow a detailed assessment of the subject's dynamic response and noise properties, they require longer trial durations and a large amount of on-line data collection and reduction. For this reason they were run less frequently than critical tasks during the 90-day test, and were employed to provide realistic tracking task data to correlate with the critical instability scores.

Test Setup and Equipment

The experimental layout and apparatus are shown in figure **2.** The test administrators con-

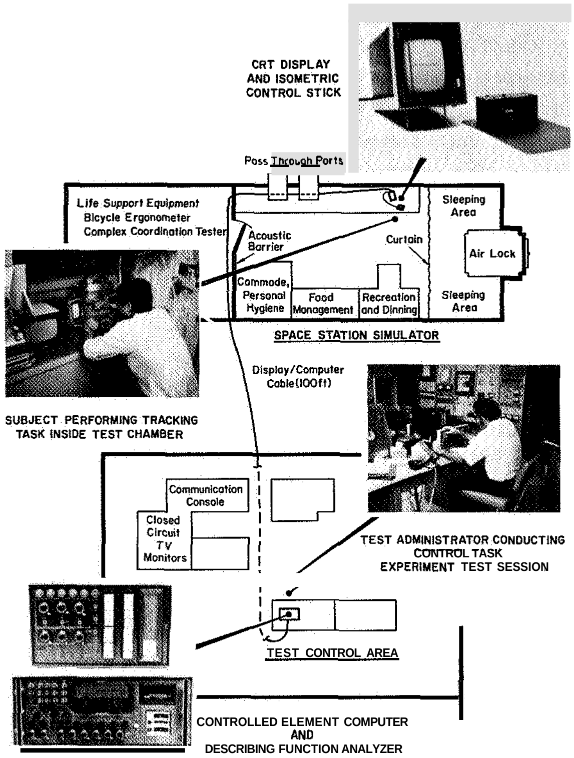

FIGURE 2.—Control task apparatus and experimental setup for the 90-day confinement study.

ducted the experiment from the control room where the task computers were located. The controlled element computer (CEC) provided the unstable dynamics for the tracking tasks, and automatically increased the instability during critical task runs as shown in figure **1.** The describing function analyzer (DFA) provided the subcritical tracking task input, Fourier analyzed the tracking error signal, and measured various performance parameters.

The display and control stick, connected to the computers through a 100 ft cable, were located in the space chamber recreation area. The Douglas Test Administrator communicated with the crewmen through an intercom, and also via interconnected "ready" lights located on the subject's display and the controlled element computer.

TRAINING

Crewmen began training on the first- and second-order critical tasks four months prior to commencing the 90-day confinement period. This training consisted of approximately thirty 1-hr sessions spanning a 5-wk period. At each session the crewmen would track **2** three-trial blocks of the first-order critical task and **2** five-trial blocks of the second-order critical task. These λ_{c1} and λ_{c2} training scores are plotted in figure 3(a). **It** is evident that all crewmen reached stable levels of critical instability within about **100** trials of distributed practice.

Training of the steady tracking tasks was commenced immediately after critical task training. Because of the dynamic similarity between the critical and subcritical tasks, a favorable transfer of training is assured. The crewmen tracked three first-order and three second-order runs per session for approximately ten sessions spanning a four-week period. Dynamic response data for the first- and second-order tasks is plotted in figure 3(b) and 3(c). From figure 3(b) and 3(c) the crossover gain, ω_c, shows a gradual increase with training, while the stability margin, φ_M, shows a concurrent decrease. Stable training levels were achieved in all cases except for crew-

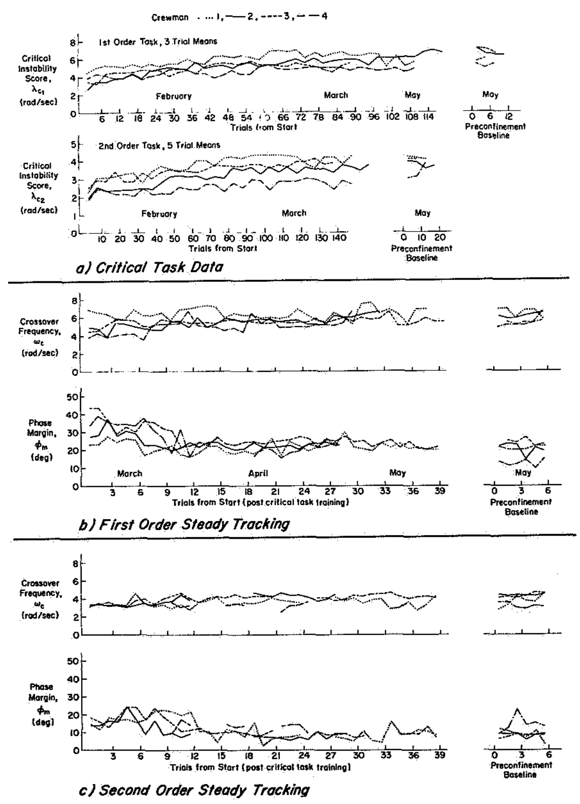

FIGURE 3.—Training data.

man 4 on the second-order task. He had significantly less exposure to this task than the other crew members, and he later exhibited correspondingly larger learning effects during the confinement period.

90-DAY CONFINEMENT TESTS

General

During the confinement period, three trials of first-order and five trials of second-order critical instability task were administered routinely every Monday, Wednesday, and Friday, following the midday meal. These data formed the core of our experimental design, and represent a base from which other tracking data can be compared and extrapolated. Steady tracking sessions were performed twice a week, one session for each order. These sessions began with the critical instability trials of the equivalent dynamics in order to provide a warmup and also to provide concurrent correlations between λ_c and the more comprehensive measures of steady tracking behavior.

The crewmen were split into two shifts, with crewmen 1 and 2 on a nominal day shift (0700 to 2300 hr) and crewmen 3 and 4 on a graveyard shift (2100 to 1300 hr). Illumination was held constant inside the simulation chamber, and all indications are that crewmembers 3 and 4 quickly adjusted to their abnormal work shift. Test sessions were conducted after the midshift meal (nominally 1300 hr for crewmen 1 and 2, and 0200 hr for crewmen 3 and 4). All test sessions began with a warmup critical instability trial.

Critical Instability Results

Weekly mean critical task scores (averaged across the solely λ_c sessions for each week) are plotted in figure 4. Generally, these scores were very reliable (low residual variance) and show a consistent stratification among crewmen. There is a consistent, albeit small, improvement trend apparent over the 90-day period in all cases except for crewman 3 on the second-order task. Experience suggests that this reflects a residual improvement in the neuromuscular system due to continuous practice beyond the initial training asymptote—much as in any athletic skill involving strength. Crewman 1 evidenced the most variable performance, with a definite dip in scores during the initial confinement period compared with his preconfinement baseline. This dip was followed by a return to performance levels significantly above his preconfinement baseline.

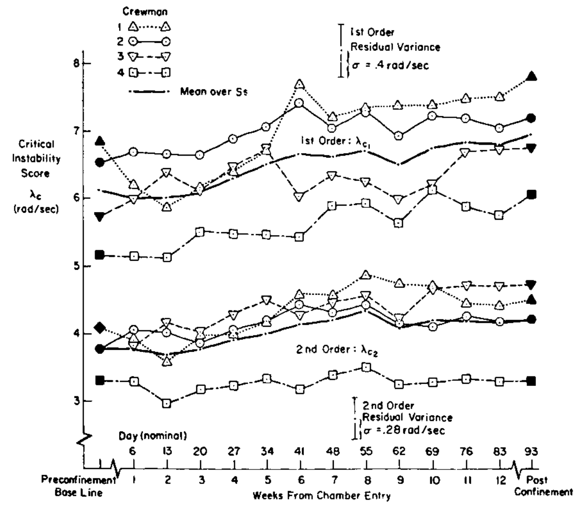

FIGURE 4.—Weekly mean critical instability scores during the 90-day confinement period.

There is one very consistent dip in performance for all crewmembers during week 9, with a preceding performance peak during week 8. These results appear to correlate with assessments of crew psychological status obtained by other investigators (references 8 and 9). Positive "affect" among crew members increased sharply dueing week 8, which was associated with passing the midpoint of the mission. During week 9 the measure of positive affect took a sharp drop and reached a mission low point, accompanied by a corresponding increase in the hostility index among crew members and a drop in reported sleep time. Although the changes in critical task performance which accompanied these behavioral symptoms are not large, operationally, the sensitivity of the subjects' critical task scores to the psychological climate is interesting.

Analysis of variance procedures applied to the data showed subjects and weeks to be significant main effects. The subjects-by-weeks interaction was also statistically significant. The residual variance obtained from the ANOV was quite small, with the standard deviation being on the order of only 7 percent of the mean score for each task as shown in figure 4. This low variability is one of the virtues of critical task which allows for the efficient measurement of small changes in visual-motor behavior.

Steady Tracking Results

The steady tracking behavior and performance data are plotted in figure 5. (The critical instability data shown here were obtained at the beginning of each subcritical tracking session, and were not included in fig. 4.) The steady tracking data are often missing because these sessions had a somewhat lower priority than the critical task sessions, and were sometimes not performed.

The dynamic response data ω_c and φ_M and critical task scores (λ_c) seem to remain fairly consistent and similar in level over the 90-day period. The normalized error and error coherence performance measures (σ_e^2/σ_i^2 and ρ_e^2) show considerable variations, however. Crewman 4's tracking errors are significantly higher than that of the other crew members. This result seems to be due primarily to an intrinsically higher remnant level (as evidenced by his lower error coherence) and to a poorer loop closure (evidenced by low λ_c and low φ_M).

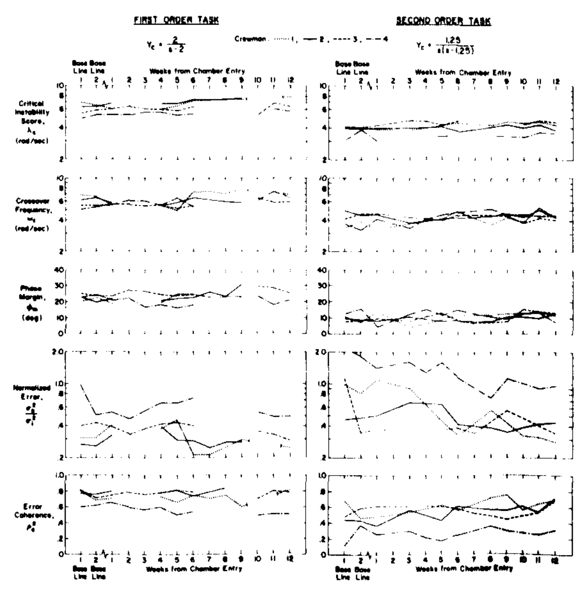

FIGURE 5.—Comparison of tracking-session data for the 90-day test.

Crewman 1 and 4 were still learning the second-order steady tracking task during the first half of the confinement period, as reflected in their normalized error scores. This result seems to be primarily due to dynamic response effects as both subjects show a corresponding increasing trend in crossover gain during the first half of the mission.

Correlation Between Subcritical and Critical Task Results

One of the objectives of this experiment was to tie in the dynamic response measurements with the critical instability scores obtained during the steady tracking sessions. The describing function parameters, performance measures and critical task scores from these sessions were entered in a computer file and subjected to correlation analysis.

The correlation matrix for this data is given in table 1. The inverse dynamic time delay τ_e^{-1} was used for the correlation analysis, because this is the parameter linearly correlated with λ_c, as shown in reference 6. A scatter diagram showed σ_e^2/σ_i^2 to be hyperbolically related to λ_c, so the inverse of this parameter was also employed in the correlation analysis.

As shown in table 1, λ_c is highly correlated with the more detailed steady tracking measures. This indicates that the easily administered critical task can reliably monitor a subject's basic tracking behavior. Furthermore, a network of λ_c runs can be used to supplement a limited number of detailed steady tracking measurements, thereby providing a comprehensive picture of a subject's dynamic response and remnant characteristics over extended time periods. The one describing function measure not correlated with λ_c is the "low-frequency phase droop" parameter, α. This is not surprising since λ_c is primarily dependent on crossover-region phase effects which depend mainly on the time delay τ_e and only secondarily on α (ref. 4).

A scatter plot of the τ_e^{-1} versus λ_c scores obtained during each subcritical tracking session is shown at the top of figure 6 for both first- and second-order tasks. Because it is ultimately bounded by τ_e^{-1} and hence by λ_c, crossover frequency ω_c has also been shown to correlate

TABLE 1.—*Correlation Matrix—90-day Confinement Study Dynamic Response Data*

	Variable	λ_c	$\left(\frac{\sigma_e^2}{\sigma_i^2}\right)^{-1}$	ρ_e^2	ω_c	φ_M	τ_e^{-1}	α	ω_u
	Critical instability score, λ_c	1.000	0.632	0.706	0.801 *	0.813 *	0.859 *	−0.028	0.890 *
Steady tracking data: Performance	Inverse normalized error var., $\left(\frac{\sigma_e^2}{\sigma_i^2}\right)^{-1}$		1.000	0.651	0.406	0.351	0.357	−0.015	0.430
Steady tracking data: Performance	Error coherence, ρ_e^2			1.000	0.379	0.498	0.499	0.131	0.554 *
Steady tracking data: Dynamic response parameters	Crossover frequency, ω_c				1.000	0.684	0.799	−0.169	0.838 *
Steady tracking data: Dynamic response parameters	Phase margin, φ_M					1.000	0.925 *	−0.280	0.923
Steady tracking data: Dynamic response parameters	Inverse dynamic time delay, τ_e^{-1}						1.000	−0.010	0.940 *
Steady tracking data: Dynamic response parameters	Low freq. phase droop parameter, α							1.000	−0.122
Steady tracking data: Dynamic response parameters	Upper phase crossover freq., ω_u								1.000

Note: N = 65 degrees-of-freedom
P = 0.001 for $R > 0.475$
* Denotes $R \geq 0.80$

with λ_c (ref. 6), and this scatter diagram is shown at the bottom of figure 6. Also, the present regression relationships, with initially naive subjects, are quite similar to those given in ref. 6 among professional pilots, as shown in figure 6.

A high correlation is noted in table 1 between inverse dynamic time delay τ_e^{-1} and phase margin φ_M. Time delay is a basic limiting factor in the human operator's visual-motor dynamic response, whereas phase margin is related to how high a gain (effort) the operator is willing to produce. The theoretical relationship between φ_M and τ_e, obtained from closed-loop analysis using the "crossover-model" for the man/machine system, is (see ref. 3, appendix A):

$$\varphi_M \doteq \tan^{-1}\frac{\omega_c}{\lambda} - \tau_e\omega_c - \frac{\alpha}{\omega_c}$$

where ω_c is related to the subject's gain. The above relationship shows φ_M proportional to τ_e, while the data plotted in figure 7 show a linear correlation with inverse time delay τ_e^{-1}. This behavior was achieved mainly by a covariation of ω_c with τ_e since the α term is small. This effect may represent some form of optimum behavior given the present task and should be further investigated.

Data obtained in a previous experiment with pilot-subjects (ref. 6) has been added to figure 7. The data from the two experiments show good agreement, which implies the universal applicability of results obtainable with the tracking task battery employed in this experiment.

CONCLUDING REMARKS

Crewmen performance in this experiment agrees quite favorably with that of experienced pilots and test subjects tested previously (ref. 6). No serious degradations in performance were noted during the mission, and in fact there appeared to be a slight improvement trend throughout the 90-day period. Some dips in individual performance seem to correlate with crew psychological status as measured by other investigators. While these effects were not operationally serious, they do demonstrate the capability of critical task to efficiently measure small changes in visual-motor response behavior.

The dynamic response psychomotor tests used in this experiment have a well developed theoretical basis and have been thoroughly validated (references 3 through 6). With the present experimental results we have demonstrated that sophisticated human visual-motor properties can be efficiently and reliably measured over an extended period and in spite of adverse living conditions. The control task equipment functioned properly throughout the mission, even though the CRT display and control stick were subjected to the simulator sub-atmospheric pressure. In spite of the apparent complexity of the equipment and test protocols, both the crewmen and test administrators quickly became proficient in the experiment procedures. Test sessions for one subject typically required less than 15 min. Thus the simpler equipment and tests

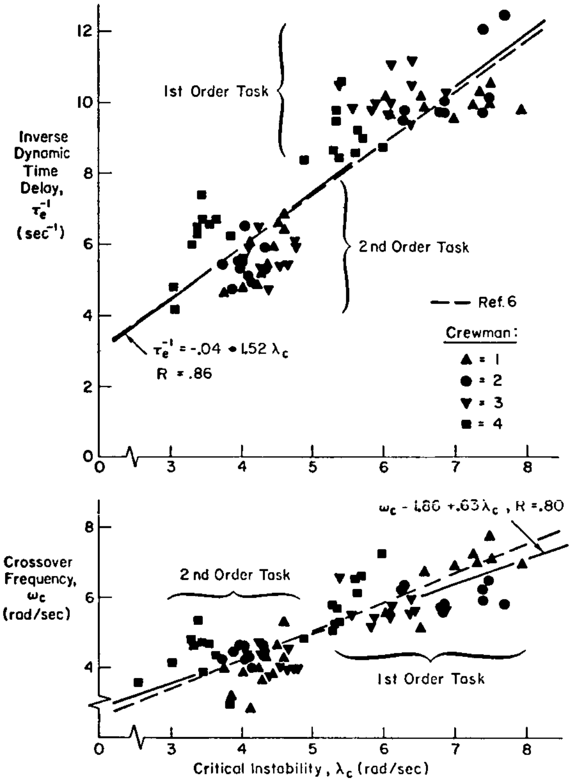

FIGURE 6.—Correlation between critical instability score and steady tracking data.

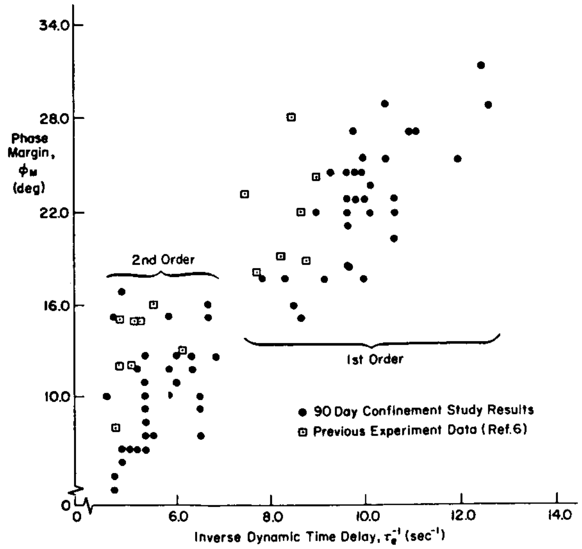

FIGURE 7.—Correlation between 90-day confinement study and reference experiment dynamic response data.

being planned for future orbital use by astronauts should meet with good acceptance and allow us to obtain in-depth information regarding the space environment's effect on human dynamic response properties.

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