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EFFECTS OF HELICOPTER NOISE AND VIBRATION ON PILOT PERFORMANCE

(AS MEASURED IN A FIXED-BASE FLIGHT SIMULATOR)

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Summary

This report describes a study of the effects of noise and vibration on pilot performance. Pilot subjects were required to fly VTOL commercial IFR schedules using the computer simulation facilities at Sikorsky Aircraft. The routes flown simulated closely metropolitan routes flown currently by a helicopter airline. The duration of simulator flights ranged from 3 to 8 hours. Subjects were exposed to noise sound pressure levels ranging from 74dB (ambient) to 100dB and 17 Hz vibration stimuli ranging from .1 g to .3 g measured at the floor directly beneath the pilot's seat. Measures were taken of the vibration transmissibility of the pilot's seat, so that vibration level at the subject/seat interface could be determined. Performance was evaluated by measuring flight path deviations from a 6° ILS type approach beam and from desired airway navigation routes.

Despite subject reports of extreme fatigue in these long flights, performance did not degrade. A curve of performance shows a slow improvement for the first three hours of exposure and a slight loss in performance during the remainder of the flight. As environmental stress conditions (noise, vibration, and time in the simulator) increased, subject performance improved. Within the limits of this study, the higher the stress the better the performance.

While performing in the simulator, pilot subjects suffered from lapses in ability that resulted occasionally in poor scores. These lapses are probably of very short duration (seconds in length) and occur at unpredictable times. If such lapses occur in actual flight, they could form an explanation for many so called pilot error accidents.

Subjects flew experimental runs on the average of once per week. The conclusions of this study may not therefore apply to situations wherein pilots are required to repeat flights at intervals shorter than once a week.

The basic conclusion of this study is that the key parameter in performance measurement is motivation. As long as motivation is maintained, pilot performance is independent of fatigue.

INDEX

LIST OF FIGURES

Page

LIST OF TABLES

INTRODUCTION

This report describes the results of a three year study of the effects of noise and vibration on pilot performance. The goal of the study was to explore the effects of each parameter so that limits could be placed on acceptable cockpit environments.

PROBLEM:

Pilots presently flying helicopter commercial routes spend about eight hours each day flying passengers between airports primarily used by fixed wing aircraft. During this time, the crew usually accomplishes about thirty landings and takeoffs. Future plans call for continuation of this type of operation even if weather conditions degrade to zero-zero.

Experience has shown that pilot performance is not unacceptable in current helicopter cockpit environments under VFR conditions. It has been shown in other contexts that noxious stimuli, such as noise and vibration, do reduce human efficiency (69, 70). This has apparently not affected helicopter/pilot performance in the past, probably because pilots have been able to compensate for loss of efficiency by increasing their personal effort.

The concern in the current study was that IFR approach tasks would increase pilot workload and require close to maximum effort on the part of the crew. The approach task in a helicopter is inherently more complex than in a fixed wing aircraft. In a fixed wing approach, the pilot maintains constant airspeed, rate of descent, and heading. The only variable he must control is altitude. In a helicopter approach, the pilot must control varying airspeed, heading, and altitude. This is required because the end point of a VTOL approach is a stationary hover. Even with auto-pilot assistance, pilots will still have to monitor system performance for proper functioning of all elements. With this increased crew workload, any loss in efficiency through cockpit environment could degrade human performance, thus reducing system performance.

PREVIOUS RESEARCH:

Most previous pilot performance studies involved short exposure times (measured in minutes), and high stress levels. In vibration studies where degradation was found, it could be attributed to mechanical interference. The vibration was so severe that it interfered with the subject's control movements. Most of these studies (for example 2, 19 and 33) used one-degree or two-degree-of-freedom control tasks on which to test performance.

During the late 1950s and early 1960s several studies examined low altitude high speed penetrations of fixed-wing aircraft. These studies involved long exposure times (up to 5 hours) but used vibration levels consisting of random gust inputs of a very high level (up to 3g). Fixed wing control tasks were used that are simpler than those involved in helicopter control. These studies (38, 59, 68, etc.) usually found no measurable performance degradation.

Most noise studies (1, 28, 43, etc.) found no effects on performance unless the noise stimuli were intermittent and/or unexpected.

The present study differs from those reported in the literature in that it combines a realistic long term environment with a complex control task (six degrees of freedom). Environmental stimuli are much lower in amplitude than those of previous studies, but they are applied over a much longer time period. Exposure is measured in hours rather than in minutes. The data, therefore, will extend the limits of what is currently known about human performance under stress in any aircraft environment.

Pg 8

Figure 1. - Simulation Facility.

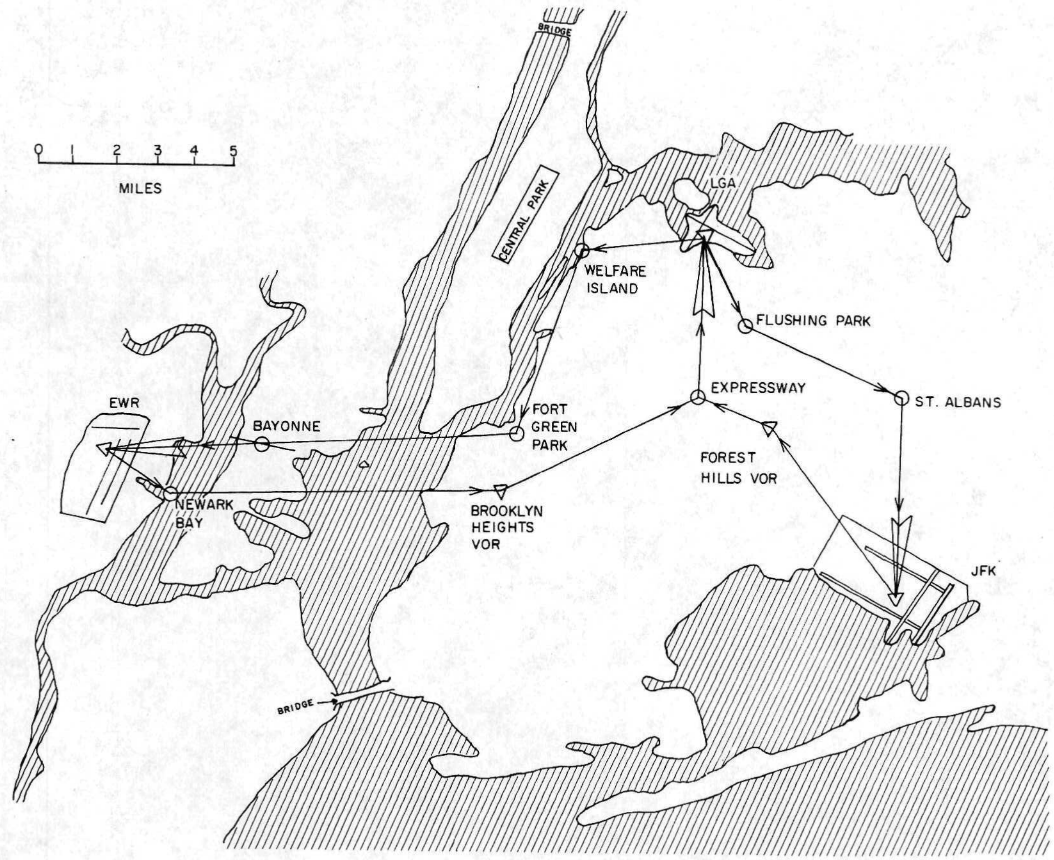


Figure 2. - Airline Route Used in Simulation.

DESCRIPTION OF THE STUDY

Data on the effects of noise, vibration, and fatigue were collected while pilots flew a helicopter simulator, and accomplished instrument flight tasks typically required of commercial VTOL aviators. Performance was measured in terms of flight path and altitude deviations from desired values. The simulator used for the study, Figure (1), is a fixed base device which makes use of both analog and digital computers. Appendix III provides a technical description of the equipment used.

Control/Navigation Task

A realisitc piloting task was defined by visiting New York Airways (NYA) and riding with the helicopter airline pilots to determine work loads, tasks accomplished, and work/rest schedules.

Based on this experience, the airline route shown in Figure 2 was set up to represent an IFR route structure within the three airports of the New York metropolitan area.

The helicopter airway routes are located to avoid existing fixed wing approach pathways. Altitudes flown were kept below 2,000 feet and at least 500 feet above ground obstacles. Helicopter landing areas 400 feet square were assumed along with special ILS approach facilities. Two facilities were assumed to provide navigational information. These facilities (VOR/DME) provide information on the distance, in miles, and the relative bearing of the aircraft from the station.

One of the goals was to provide data directly applicable to present operations, therefore, the route set up was exactly the same as is presently flown (JFK to LGA to EWR and back). The work/rest schedules were initially set up to simulate those flown by NYA. Four-minute rest periods were given at each stop but Kennedy, where an 8-minute rest period was permitted. Subjects were not allowed out of the simulator except at the 8-minute Kennedy stop. A lap around the route required one hour to accomplish with this schedule.

Several variables were considered in determining the length of the experimental period. The first consideration was the length of the present daily work period - eight hours - and the expected length of exposure in the future. Another variable considered involved the duration of IFR conditions. A short study of this (Figure 3) indicated that IFR conditions present a skewed distribution. The data examined in our study have a mean of 4.5 hours, a mode of less than one hour, and a median of 2 hours. 85% of instrument weather conditions last less than 8 hours. The third major variable involved the practical considerations of experimental schedule and cost. For this study, the initial test period

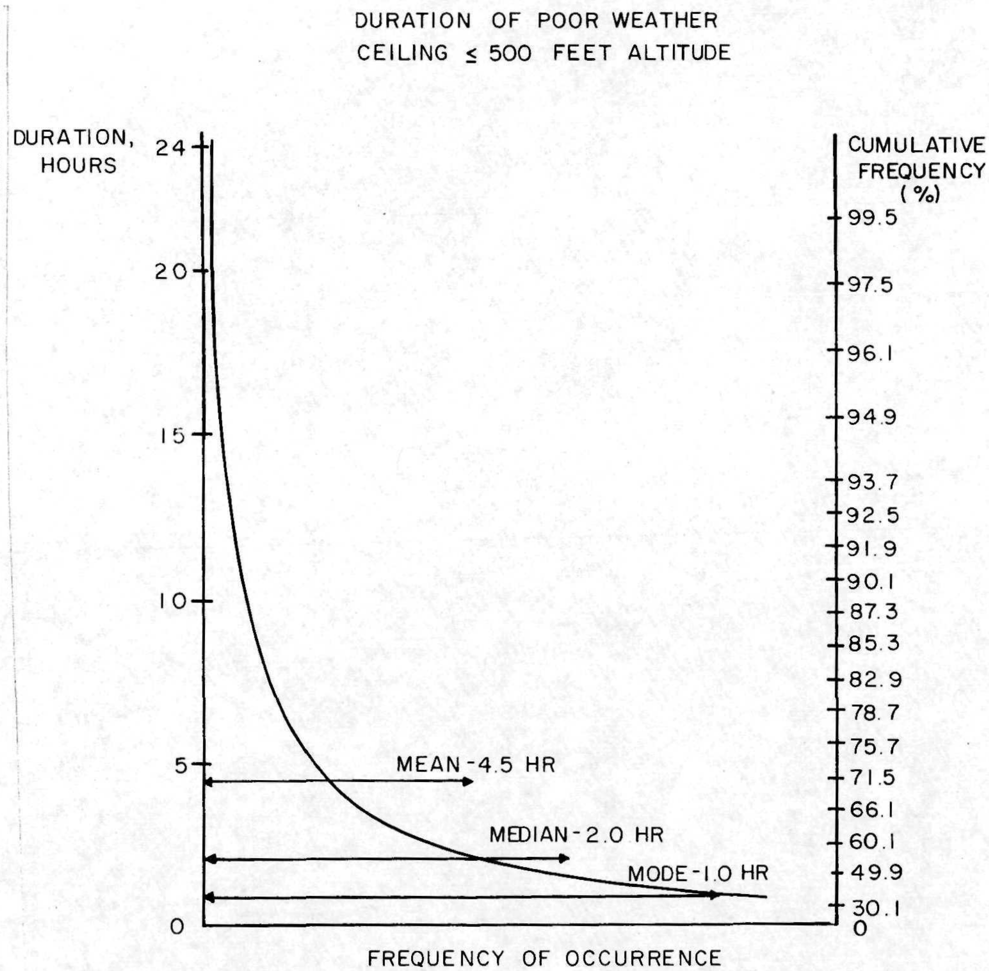


Figure 3. - Duration of Poor Weather (Ceiling At Or Below 500 Ft.).

was set at 4 hours. During the course of the study, this was changed first to a 3-hour period without rest stops and then to 6-hour and 8-hour periods to be described later.

To carry out the flights, the Sikorsky simulator was programmed to provide a complete flight simulation of an S-61 transport helicopter in all speed regimes and flight conditions. The flight instruments provided (Figure 4) correspond exactly with those in the standard S-61 cockpit. The pilot subjects were given a 6-degree-of-freedom tracking task closely simulating the real aircraft.

A special ILS type approach facility was created. Its beam had a 6° glide slope, which is much steeper than current fixed wing approach facilities. A steep approach beam is necessary if helicopters are to operate in metropolitan areas and make approaches to small helipads. The cross needles on the VOR indicator were used as a display when flying the ILS. Standard ILS displays have a 3° sensitivity on either side of the center line. Early experimentation in the simulator showed that this was too sensitive for use on a 6° glide slope. Accordingly, the sensitivity was changed to provide a full-scale reading of 6° on either side of the center line. Various types of quickening were also tried, but it was found that a simple position display was easiest to use. Vertical sensitivity remained the same as in standard ILS indicators.

The aircraft was flown with the help of four navigational aids: visual omni range (VOR) bearing information, shown on the VOR indicator; distance from the VOR stations, shown on the distance measuring equipment (DME) read-out; ADF (automatic direction finding) bearing from the VOR stations; and the instrument landing system (ILS) beam.

When the VOR was tuned to one of the ILS stations (located at each of the landing sites), the cross needles on the indicator provided glide slope and localizer information. When flying an ILS approach, the start of the glide slope was shown by means of a marker beacon light on the VOR indicator.

Data runs were conducted as though the subjects were making a series of commercial transport flights around NYA routes. IFR procedures were simulated; subjects were required to request and copy clearance, make position reports over navigational fixes, and maintain specific climb, cruise, and approach airspeeds and altitudes. Details of the procedures are contained in Appendix I, which is a copy of the training material supplied to each subject.

In the material to follow, data runs have been broken up into three units as follows:

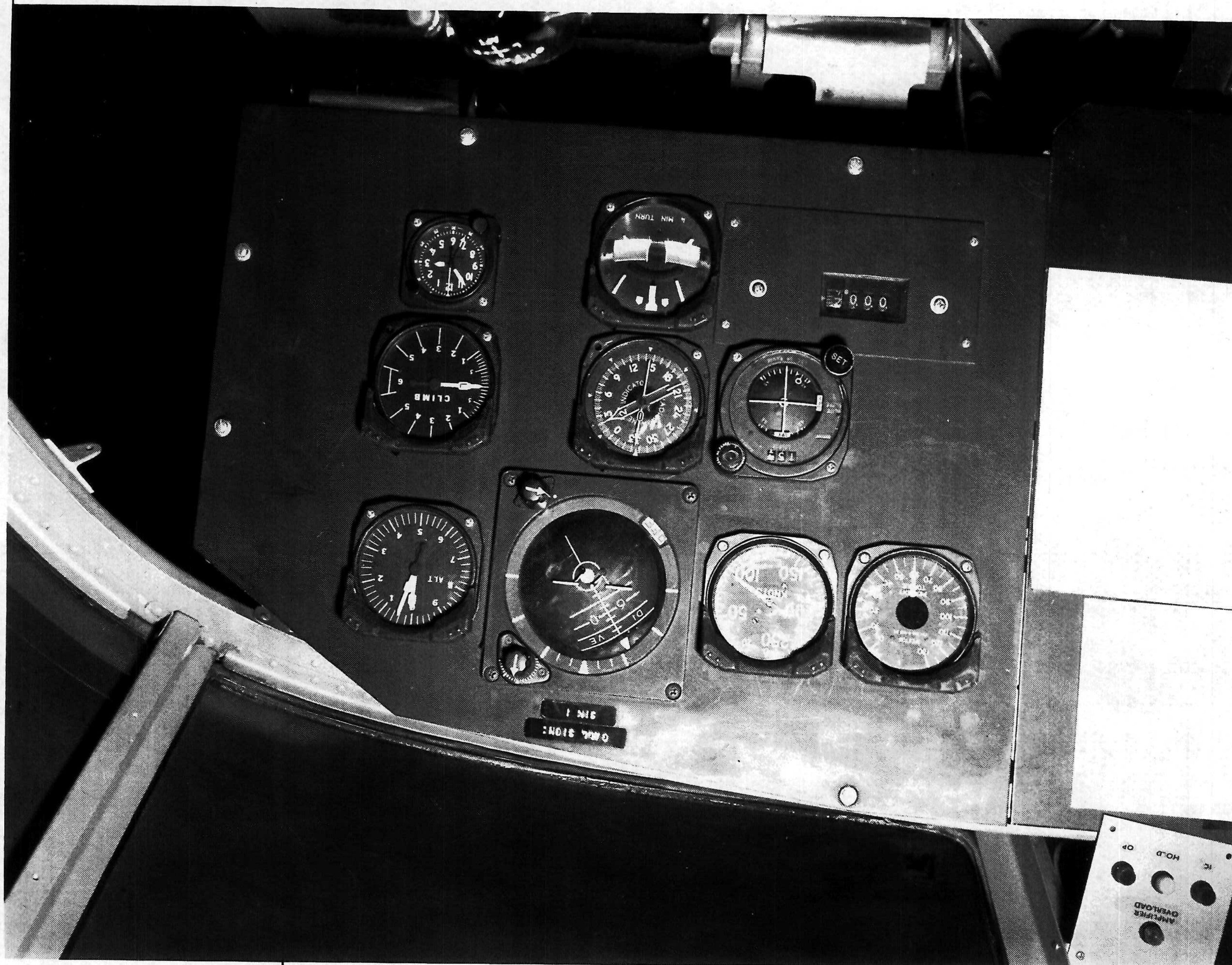


Figure 4. - Flight Simulator Instrument Panel.

Leg: That part of a data run lasting from takeoff at one heliport to landing at another (e.g., Kennedy to LaGuardia).

Round: That part of a data run consisting of 4 legs or one circuit of the route (e.g., Kennedy to LaGuardia, to Newark, to LaGuardia, to Kennedy).

Run: All of the data collected from one subject in one session. The data consist of 4 or 8 rounds.

Five subjects were selected from a group of former helicopter aviators who held instrument ratings. The final group used in the study averaged more than 1000 helicopter flight hours. Subjects were paid at a fixed hourly rate and given a small bonus if they flew well. (Since all of the subjects maintained a high level of motivation during the 11 month data collection period the bonus was always paid.

Data runs took place during the evening hours (5 p.m. to 1 a.m.). This was done because all of the subjects worked during the day. Thus subjects began data runs after 8 hours of normal daily work.

<u>Data Collection</u>

During the time the subjects were flying, both objective and subjective data were collected.

Objective data were recorded in three forms:

1. An X - Y plotter provided a continuous record of helicopter location with regard to the various heliports and navigational fixes (Figure 5).

2. A brush recorder provided 8 channels of analog data consisting of the following parameters recorded during each ILS approach:

   Rudder pedal motion
   Longitudinal cyclic stick motion
   Lateral cyclic stick motion
   Collective motion
   Airspeed
   Altitude
   Altitude error (with respect to the ILS beam)
   Heading error (with respect to the ILS beam)

3. The computer teletype printed out data at the end of each ILS run (Figure 9). Data were recorded as follows:

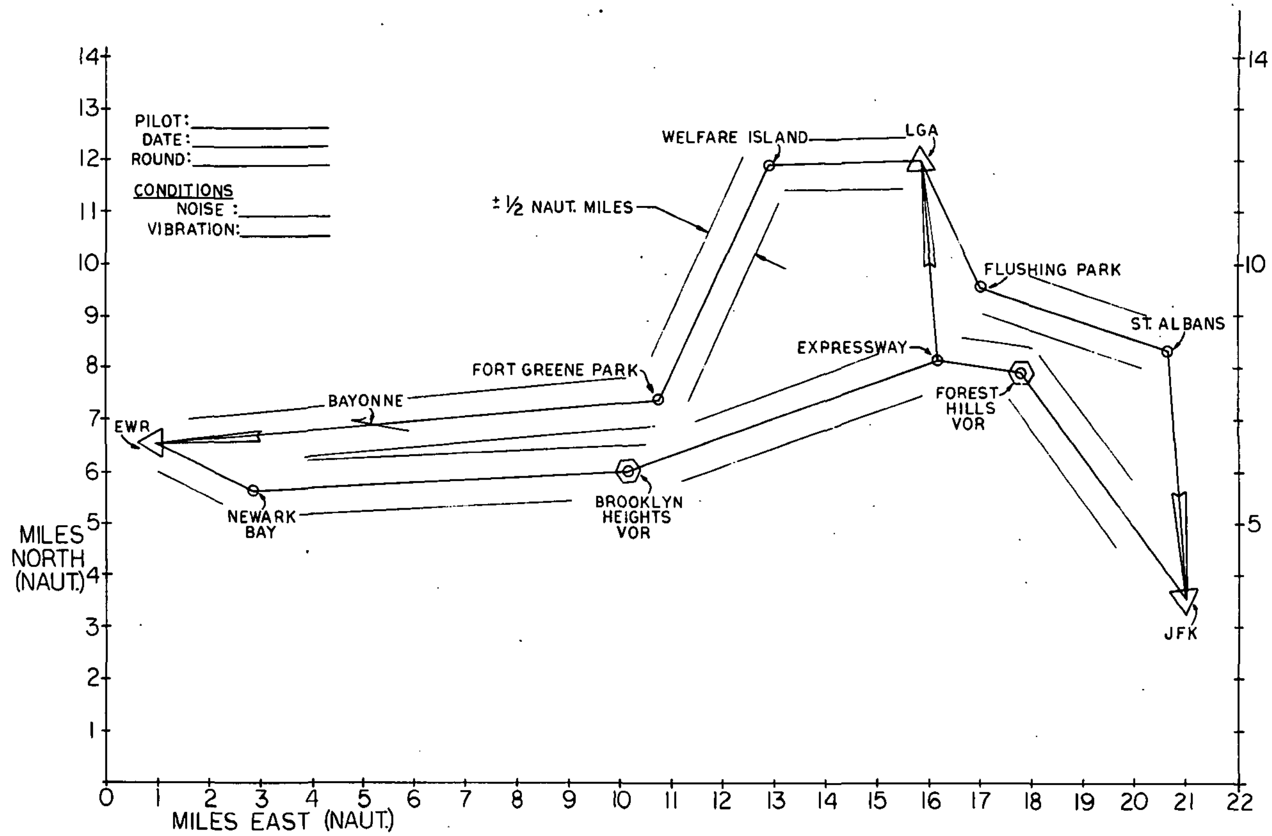


Figure 5. - Position Recording Chart (X-Y Plotter).

- Navigational error computed as root mean square (RMS) distance off course (in yards).

- Horizontal deviations from the glide slope computed as RMS degrees off course.

- Vertical deviations from the glide slope computed as RMS degrees above or below the glide slope.

- Total ILS score, which was the sum of vertical and lateral scores.

- Vehicle airspeed at each 100 feet of altitude while on the glide slope.

Degrees off course was used to score ILS performance, because it weights the final seconds more heavily than the initial part of the glide path. This corresponds to the real world situation in which final position at breakout is much more important than positioning during approach. Subjects began the ILS run at 1,000 feet and ended it at 75 feet when the problem was automatically terminated. Since the scoring system records errors, high scores mean poor performance and low scores mean good performance, i.e., less error.

Subjective data were obtained from subjects on the rating sheet shown in Figure 6. This sheet was filled out at the end of each leg. It contains two types of information: self-ratings of performance and a self-rating of fatigue.

During the initial training period, each subject's rating of his own performance was calibrated against the objective performance measures by providing immediate feedback to the subject on his scores at the end of each run. During data collection, no feedback was given.

The investigator also collected subjective data in terms of his own observations, hypotheses and an informal open end interview at the end of each data run or during rest periods. These were recorded in a log of each run and filed with the rest of the records for that run.

Name: ______________________

RATING SHEET FOR PERFORMANCE ON EACH LEG

This form is to be filled out after completion of each leg. Please answer the questions according to your judgement of your own performance. Use the word descriptions in the scoring Key below to guide you in assigning your ratings. Each rating should be a number from one to ten with the lower numbers representing better performance.

Scoring Key

1. -- *Best I have flown so far!*
2. --
3. -- Better than average precision.
4. --
5. -- Average performance.
6. --
7. -- Below average precision (still satisfactory).
8. --
9. -- Unsatisfactory.
10. -- Crash!!

PLEASE RATE THE FOLLOWING STATEMENTS

	Destination: LGA	EWR	LGA	JFK
1. How well did you hold desired airspeeds?	___	___	___	___
2. How well did you hold desired altitudes?	___	___	___	___
3. How well did you hold requested headings?	___	___	___	___
4. How well did you fly the ILS approach?	___	___	___	___
5. How would you rate your overall performance?	___	___	___	___
6. Rate your energy level according to the below key	___	___	___	___

1. Rested and eager to continue.
2. Not tired.
3. Tired but OK.
4. Looking forward to the rest periods.
5. Just hanging on till *end of period*.

Figure 6. - Pilot Rating Sheet.

Experimental Conditions

At the start of this study, it was assumed that pilot performance would slowly degrade as a function of noise, vibration, and time in the simulator. Consequently, specific data collection points were set up and a structured investigation was planned to bracket the point of degradation. As data collection proceeded, it became apparent that performance was not degrading in the expected manner. Performance did not seem to degrade regardless of the severity of the noise and vibration conditions. The experimenter began to suspect that the 4-minute rest periods were permitting the subjects to recover from the effects of the stress. This was reinforced by results in the Sussman study (75). In that study, subjects drove an automobile simulator for 4 hours without rest. Driver performance decrement was clearly seen during the test. At the end of the 4-hour period, subjects were given a 4-minute rest, and another performance record was taken. After the rest period, performance recovered almost completely.

It was decided therefore, to modify the planned schedule of noise and vibration conditions to include an investigation of the effects of rest periods on performance.

The first step was to examine the results of a series of zero-rest runs. If performance degraded with no rest, we could then vary rest periods to determine the shortest rest period required to prevent degradation. Accordingly, four conditions were set up: control (no noise, no vibration), an extreme condition (100dB and .2g), and two intermediate combinations (100dB, no vibration; 0dB, .2g).

The three-hour no-rest runs were similar to the previous four-hour runs, except that the 4-minute and 8-minute rest periods were not permitted. Subjects still accomplished four round trips, but after each landing the subject filled out the rating sheet and immediately requested takeoff clearance for the next leg. Ground time at each station averaged about 60 seconds.

During the no-rest runs, the investigator observed that the control run, which should have shown the best scores, seemed to be having the most "bombs" and the worst scores. Questions to subjects indicated that the noise and vibration added an element of realism to the problem. In light of this, another condition was added to represent a middle ground (95dB, .1g). By the time the 3-hour series was completed, it was obvious that degraded performance was not occurring. As a result, it was decided to experiment with longer runs, an 8-hour run that extended the normal 4-hour runs and had identical rest periods, and a 6-hour no-rest run.

TABLE I. - TABLE OF EXPERIMENTAL CONDITIONS

17 CPS				12 CPS
4 HR WITH REST	NO REST RUNS		8 HR WITH REST	3 HR NO REST
	3 HR	6 HR		
O/O CONTROL	O/O CONTROL	95 dB .2G	95dB .2G	90 dB .1G
100 dB .2 G	100 dB .2G	90dB .1G		
100dB .4G	95 dB .1G	95dB .3G		
OdB .2G	OdB .2G			
100dB OG	100dB OG			
95dB .1G				

When the first set of 8-hour data was complete it was obvious that performance was not degrading. In fact, it appeared to be doing the opposite! On the basis of this, no further 8-hour runs were accomplished.

Two other sets of 6-hour data were run, a low stress condition (90dB, .1g) and a high stress condition (95dB, .3g). The noise level could not go beyond 95dB since this would have exceeded the hearing damage curves in the literature (48).

A final 3-hour data point was taken at a vibration frequency of 12 Hertz. (This provided a calibration point for a future study that will investigate effects of varying vibration frequency). The present study was limited to a vibration frequency of 17 Hertz. Table 1 shows the data points collected in the present study.

The order of presentation of noise and vibration conditions to each subject was randomized as much as possible within the constraints of the study.

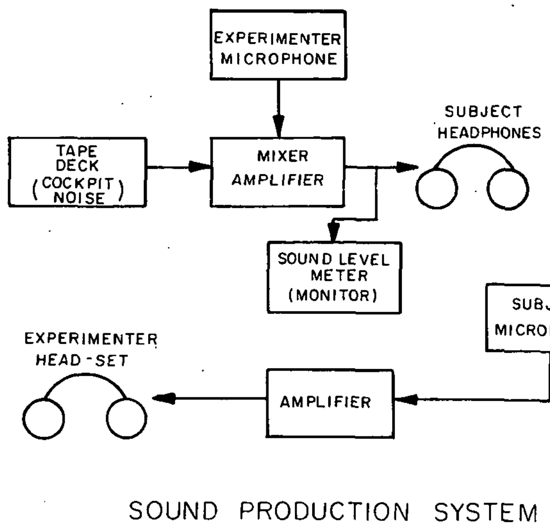
Noise and Vibration Stimuli

This section will describe the noise and vibration stimuli used in this study. The apparatus used to generate the stimuli is described further in Appendix III.

Vibration

Vibration was imparted to the subjects by means of a hydraulic ram attached to the pilot's seat. This device provided vertical sinusoidal motion at 17 Hertz. The motion of the seat was sensed by an accelerometer on the base of the seat. The sensed vibration was read out on a meter located near the experimenter. During runs the investigator set the desired vibration level and maintained it by adjusting a control on a servo controller that regulated vibration amplitude. Figure 7 shows a schematic of the vibration system.

The literature on human reactions to vibration reveals conflicting results. In various studies, some subjects were seated on hard surfaces such as metal plates, boards, or uncushioned seats. Other subjects were seated on standard pilot or passenger seats. Since standard seats and seat cushions provide a good deal of vibration attenuation it seems evident that subjects exposed to equal floor vibration levels are not subject to equal vibration levels at the base of the spine. This may explain the discrepancies between studies. Accordingly, it was decided to measure seat vibration attenuation (transmissibility) in the flight simulator, which uses a standard pilot seat found in the Sikorsky S-61 commercial transport. Knowledge of the seat transmissibility would permit accurate comparison of our results with those of other investigators.



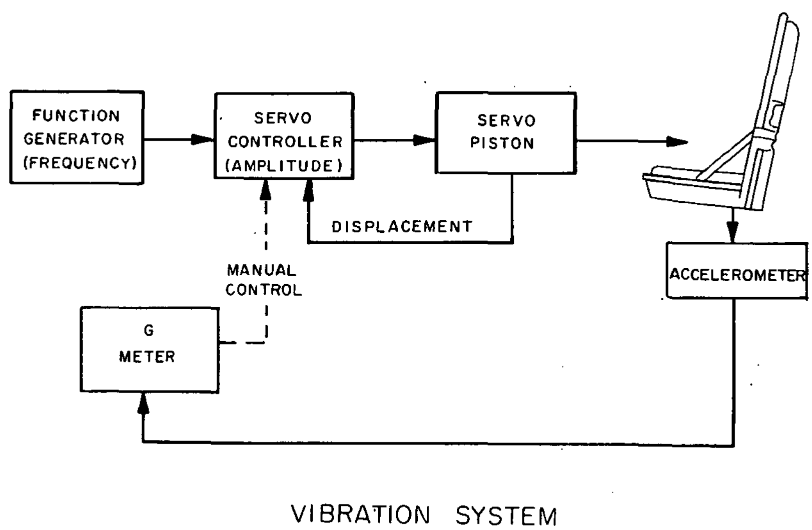


Figure 7. - Sound Production System and Vibration System.

Apparatus was set up to permit simultaneous measurement of vibration levels from the base of the simulator seat and from the top of the seat cushion with the pilot in the seat. The following is a comparison between floor and spine levels for each vibration condition used in this study:

	Frequency: 17 Hertz			Frequency: 12 Hertz
Floor level:	0.3g	0.2g	0.1g	0.1g
Spine level:	0.11g	0.06g	0.02g	0.08g

Measurements of S-61 cockpit floor vibration levels have shown that a level of 0.1g at 17 cps is typical of most vehicles. Pilots said that this vibration level in the simulator felt the same as that experienced in the aircraft. We have concluded, therefore, that if the floor vibration level in the simulator is equal to that of the floor in an aircraft, simulator pilots are receiving the same vibration as aircraft pilots.

Noise

Noise stimuli provided to subjects consisted of a tape recording of S-61 cockpit noise played through high quality headphones. A schematic of the sound system is shown in Figure 7. The tape used to convey noise to the subjects underwent modifications because noise experienced by pilots is attenuated by the headsets normally worn in flight. It was also recognized that headphones attenuate some of the signal fed into them. For these two reasons, the final tape used in the study was a product of the following activities:

1. A plot was made of the sound-attenuating properties of the normal headset used in commercial helicopters.

2. The original tape of cockpit noise was attenuated to match the attenuating properties of the pilot's headset.

3. The frequency response of the headphones used in the simulator was determined.

4. The tape resulting from step 2 above was boosted so that, when heard through the headphones in the simulator, it would accurately represent the noise spectrum heard by pilots in the field.

Figure 8 shows a frequency spectrum of the resulting tape used to present noise stimuli to subjects. We were also concerned that the noise level heard by subjects might change depending on how each subject placed the headset on his head. A test was run to determine the differences in noise level when the headphones were removed and replaced on the head. The results show that no

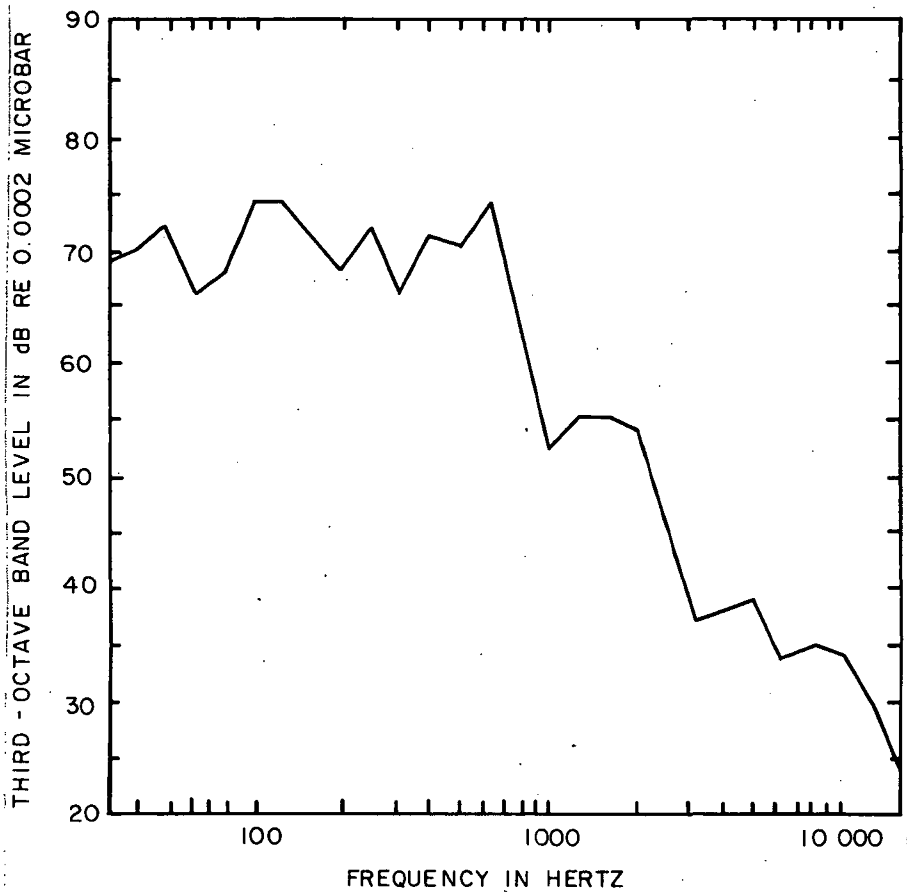


Figure 8. - Frequency Content of Noise Stimuli.

more than 3 or 4 dB differences in extreme frequencies are involved. It was felt that these differences were small enough to ignore. Noise levels were measured in terms of overall sound pressure level, i.e., no corrective weighting was used.

Subject Instructions

A mission script was prepared to assure that all subjects were treated alike and faced simular experimental situations. This script provided verbatim instructions to be transmitted to each pilot as he reached each reporting point in his run. This script was followed closely throughout all of the data runs. A copy is included in Appendix II.

To avoid influencing the results by improvements in pilot skill, a training program was carried out before data collection. Each subject was given explanatory material and navigation charts prepared especially for the study. Appendix I contains a copy of this material. (The navigational charts were also provided for use in the simulator cockpit.) Subjects flew the simulator for three-hour periods during which frequent 10-minute rest periods were permitted. Records were kept of ILS and navigation scores, and a plot was made of each subject's progress. When his curve leveled off and no progress was observed for two consecutive sessions, data runs were started. Time required for training varied from three to eight sessions depending on individual skill levels.

Results

Observed Phenomena

During data collection two unique phenomena were observed. The first was a sudden lapse in performance which was termed a "bombed" run. The second was the strong influence of very short rest periods. The following material describes these occurrences.

"Bombed" Runs

In the early stages of the program, it was observed that a subject would suddenly perform quite poorly in the midst of otherwise normal data. Figure 9 is a copy of a teletype record showing a bombed ILS run on the approach to LaGuardia. When asked about what happened on these occasions, subjects usually had no explanation. At the beginning of the study, the experimenter assumed that "bombed" runs were a training problem that would disappear when the subjects became thoroughly familiar with the simulator and the techniques required to carry out runs. This did not happen. In fact the example in Figure 9 is taken from the last data run accomplished by one of the subjects. The subject had been flying data runs for over 11 months!

It was also thought that "bombs" occurred only on the ILS parts of the various data runs. During data reduction, however, it was discovered that "bombs" also occurred during enroute navigation.

It was decided that scores obtained in "bombed" runs would not be included in the data analysis, since a single run could have a large effect on the average of the runs for that round. Accordingly, any run that exceeded three standard deviations from the mean of rest of the scores for that round was classified as a "bomb" and removed from the data for that round.

Influence of Short Rest Periods

As stated previously, the reason for shifting to the 3-hour no-rest run was that the investigator suspected that rest periods were a significant variable in determining subject performance. An oppertunity to check this directly came during one of the early 3-hour no-rest runs. The subject started off doing poorly. By the end of the second hour, his performance was all but unsatisfactory. At this point, the subject began asking for a few moments rest. He indicated that he was falling asleep and wanted to wake himself up. The experimenter felt that the run would have to be repeated anyhow. Since he was curious to see what happened as a result of a short rest period, he permitted a 4 minute rest. The subject then threw water on his face and came back into the simulator. The results are shown in Figure 10. The average ILS score prior to the test is 4.192. His average score just after the rest period is 1.295.

RTV WATSON

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R        185 07018
1  .
DESTI NATION: LGA                      WI ND: 00KNTS AT 000DEGS
A LT            VX                     RMS SAE                    RMS VAE
922.14147       42.025947              P.76727058         P.88011141
399 . 9354      39 158926
299 77635       41 245959
199 95895       43 .1 21345
99 .794858      43 .194140
.4. 04759       43 .253952
          TOTAL RMS ERROR = 1 6471820

R        158.96277
14.
DESTI NATION: EWR                      WI ND: 00KNTS AT 000DEGS
A LT            VX                     RMS SAE                    RMS VAE
990.04511       48.1 69063             1 5399958          P.20984875
399 . 764       49 .190637
299 . 6407      50.044363
199 85090       49 .031134
99 89 6055      48.572880
.4.775866       48.353393
          TOTAL RMS ERROR = 1 6098426

R        383 .24339
15 .
DESTI NATION: LGA                      WI ND: 00KNTS AT 000DEGS
A LT            VX                     RMS SAE                    RMS VAE
911 80274       57.495375              4.1392930          1 6961035
399 . 6328      45 025773
299 22561       42.878875
199 95414       37.686219
99 5 8661       28.890579
.4.5 27173      24.567764
          TOTAL RMS ERROR = 5 8353965      BOMB

R        112.27980
1 6.
DESTI NATION: JFK                      WI ND: 00KNTS AT 000DEGS
A LT            VX                     RMS SAE                    RMS VAE
587. 5739       42.846867              1 4467300          P.52928277
399 9 6019      40.660405
299 95196       40.742212
199 70246       40.791913
99 .37914       40.503148
.4.678491       40.174919
          TOTAL RMS ERROR = 1 976012 8
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Figure 9. - Typical Teletype Record (Showing "bombed" Leg).

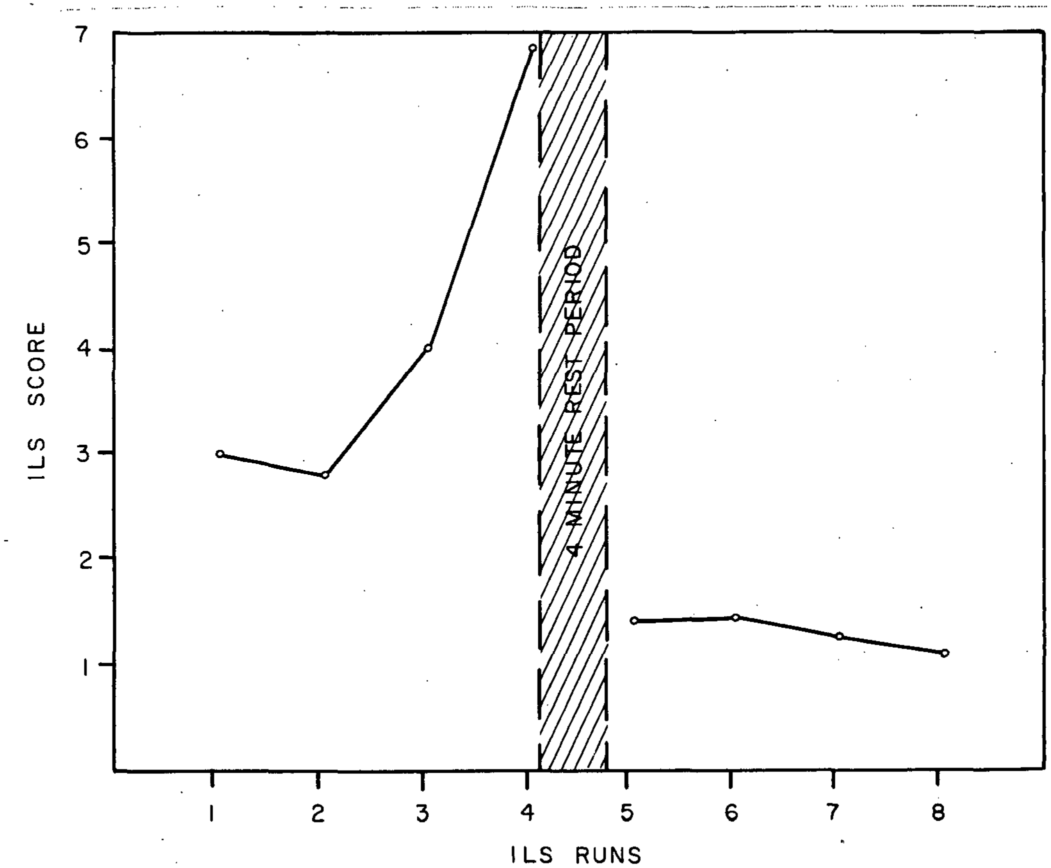

Figure 10. - Effects of Short Rest Periods.

Before treating the data statistically, it was adjusted to eliminate the effects of differences in pilot skill. A stress rating scheme was also worked out to permit comparison of performance with stress exposure.

Skill Adjustment

Since the effects of pilot skill on performance are well known, and since this study is not concerned with skill differences, it was decided to improve the precision with which predictions could be made by adjusting the data to remove skill variability. All of the obtained scores from each subject were taken and average scores for both ILS and navigation performance were calculated. These were compared and, as expected, differences were found. These average score differences can be considered differences in pilot skill. To adjust the data for these differences, therefore, a constant amount was added or subtracted from each raw score so that the average for all subjects then became the same.

The adjustment factors were applied to the scores as follows:

ILS Scores

Subject	Raw Average	Adjustment Factor	Final Average
S	0.9854	+0.5548	1.5402
B	1.8215	-0.2813	"
G	1.5402	0.0	"
W	1.8690	-0.3288	"
K	1.4186	+0.1216	"

Navigation Scores

Subject	Raw Average	Adjustment Factor	Final Average
S	215.73	-6.17	209.56
B	209.56	0.0	"
G	275.16	-65.60	"
W	176.63	+32.93	"
K	173.71	+35.83	"

Stress Rating

To analyze the results of the study effectively, a method was needed for relating all of the variables. The method selected was to order the conditions in terms of stress experienced by the subjects.

Stress was broken down into three categories; noise, vibration, and time (fatigue). Each of the three stresses was broken down further into those conditions used in the study, and each condition was given a rating as shown in Figure 11.

The noise conditions included a no-noise condition, in which the helicopter noise tape was not used. After completion of the data runs, several sound level meter readings were taken of the ambient noise level in the cockpit. The average of these readings, 74dB, was used as the control noise level. All of the dB levels were converted into Sones, so that they could be rated on a subjectively equal interval scale. The Sone levels were then divided by ten to make the final ratings more manageable.

Time stress was quantified by asking each subject to rate his reaction to each of the time intervals shown in Figure 11. Each subject's rating was then combined and averaged, as shown in Figure 11.

The subjective intensity of the vibration exposures was quantified through use of Shoenberger's equal subjective intensity curves (71). The subjective intensities were modified to provide ratings more compatible with the ratings of the other parameters. After all of the ratings were tabulated for each condition, a method was needed for combining them into a total stress rating for each individual condition. It was decided to do this by simple addition. This was based on Grether's findings (31).

VIBRATION STRESS

G LEVEL	SUBJECTIVE INTENSITY	$\frac{S}{10}$	RATING
0	0	0	1
.1 G	8	0.8	1.8
.1 G 12 CPS	9	0.9	1.9
.2 G	20	2.0	3
.3 G	30	3.0	4

TIME STRESS

TIME	RATING
4 HR	1
3 HR (NO REST)	2
8 HR (1^{st} HALF)	3.5
6 HR (NO REST) (1^{st} HALF)	3.5
8 HR (2^{nd} HALF)	5
6 HR (NO REST) (2^{nd} HALF)	6

NOISE STRESS

Db	SONES	$\frac{SONES}{10}$	RATING
AMBIENT 74	10.6	1.06	1
90	32.0	3.2	3.2
95	45.3	4.53	4.5
100	64.0	6.4	6.4

Figure 11. - Stress Rating Scheme.

RESULTS

STATISTICAL ANALYSES

STATISTICAL ANALYSIS

Four basic types of statistical treatment were undertaken in analyzing the data. The first was an analysis of variance on the 3-hour data. The next were comparisons of scores, bombs, and fatigue ratings with stress ratings. The third type of analysis involved comparisons of the data with the ratings of fatigue provided by the subjects. The final analysis involved tracing the history of the navigation and ILS scores against time in the simulator. Appendix IV explains the various statistical concepts used in this study. The following material describes the outcomes of the above analyses.

Analysis of Variance

An analysis of variance (Appendix IV) was performed on the ILS scores for four cases of the 3-hour data, 100 dB/.2g, 100 dB/0g, 0 dB/.2g, and 0 dB/0 vib. (control condition). The results of this analysis, Table II and Figure 25, show that only the 4-way interaction is significant. This reinforces the casual observation that there was no effect on performance due to the experimental conditions. The meaning of the 4-way interaction is difficult to interpret but one conclusion that can be drawn is that performance within a one hour period(a round) is significantly more consistant than performance from hour to hour. Another intrepretation might be that each subject was affected differently by the complex experimental conditions facing him each night. One night he might do well and another night poorly.

Stress Analyses

Several analyses were made of the effects of stress on performance. For this analysis and all subsequent analyses, all of the data were used. As described previously three types of stress were rated and then combined to give each data point a total stress rating. Table III compares these stress ratings with conditions and the various performance statistics. Table IV shows a matrix of Pearson product-moment correlations of the data in Table III (see Appendix IV). As shown in the table, almost all the relationships are inverse, i.e., the higher the stress, the better (lower) the score or the smaller the percentage of "bombs". In observing the subjects, it was noted that the navigation task seemed easier and less demanding than the ILS task. This observation is supported by the correlations in Table IV. None of the relationships between stress and navigation scores was significant.

The broad picture of the influence of noise on performance shows no significant relationships. This is not unexpected since research by others has shown that steady state noise does not seem to affect performance (47, 27). Conversations with subjects indicated that noise added a note of realism rather than stress.

TABLE II. - ANALYSIS OF VARIANCE

EFFECTS	SOURCE	SS	DF	VARIANCE	F	SIGNIFICANCE
MAIN	NOISE	0.0499	1	0.0499	0.0294	NS
	VIBRATION	1.2243	1	1.2243	1.7125	NS
	ROUNDS	2.7966	3	0.9322	1.2487	NS
	SUBJECTS	1.9591	4	0.4897	—	NS
PAIRS	N×V	0.7708	1	0.7708	—	NS
	N×R	2.8863	3	0.9621	1.3803	NS
	N×S	6.7826	4	1.6956	2.4425	NS
	V×R	0.8670	3	0.289	—	NS
	V×S	2.8597	4	0.7149	1.029	NS
	R×S	8.9584	12	0.7465	1.075	NS
TRIPLE	N×V×R	2.4938	3	0.8312	1.1973	NS
	N×V×S	4.4735	4	1.1183	1.6108	NS
	N×R×S	8.3643	12	0.697	1.004	NS
	V×R×S	6.3704	12	0.5308	—	NS
4th	N×V×R×S	8.3313	12	0.6942	2.0011	*SIG
	RESIDUAL	77.7277	224	0.3469		
	TOTAL	136.9157	303			

TABLE III. - COMPARISON OF STRESS RATINGS, SCORES, AND "BOMBS" WITH CONDITIONS

	CONDITION		STRESS RATING				% BOMBS			SCORE				NO. LEGS
			VIB.	NOISE	TIME	TOTAL	NAV	ILS	TOTAL	ILS	NAV	NAV/200	TOTAL	
3 HR. RUN , NO REST	100/0G		1	6.4	2	9.4	6.2	2.5	8.7	1.749	185.9	0.929	2.678	80
	100/.2		3	6.4	2	11.4	11.2	7.5	18.7	1.652	218.5	1.092	2.744	80
	0/0		1	1	2	4	7.5	7.5	15.0	1.729	215.8	1.079	2.808	80
	0/.2G		3	1	2	6	7.5	2.5	10	1.572	231.1	1.155	2.727	80
	95/.1		1.8	4.5	2	8.3	2.5	5	7.5	1.668	197.5	0.987	2.655	80
	90/.1 *		1.9	3.2	2	7.1	5	6.2	11.2	1.455	204.1	1.02	2.475	80
4 HR. RUN WITH REST	0/0		1	1	1	3	4.7	10.9	15.6	1.515	197.7	0.988	2.503	64
6 HR. RUN , NO REST	95/.2	F	3	4.5	3.5	11	4.7	4.7	9.3	1.585	211.2	1.055	2.641	64
		L	3	4.5	6	13.5	0	1.5	1.5	1.409	196.8	0.984	2.393	64
	90/.1	F	1.8	3.2	3.5	8.5	1.2	2.5	3.7	1.426	204	1.02	2.446	80
		L	1.8	3.2	6	11	3.7	3.7	6	1.492	204.8	1.024	2.516	80
	95/.3	F	4.1	4.5	3.5	13.1	4.7	0	4.7	1.349	202	1.01	2.359	64
		L	4.1	4.5	6	14.6	6.2	4.7	10.9	1.370	212.1	1.06	2.430	64
8 HR. RUN WITH REST	95/.2	F	3	4.5	3.5	11.0	7.8	3.1	10.9	1.505	198.7	0.993	2.498	64
		L	3	4.5	5	12.5	1.5	3.1	4.7	1.395	197.0	0.985	2.380	64
TOTAL														1088

* 12 CPS

TABLE IV. - TABLE OF CORRELATION COEFFICIENTS

		STRESS			
		TIME	NOISE	VIBRATION	TOTAL
SCORE	ILS	-0.466 SIGNIFICANT AT 0.05	0.038 NOT SIGNIFICANT	-0.603 SIGNIFICANT AT 0.02	-0.506 SIGNIFICANT AT 0.05
	NAV	-0.117 NOT SIGNIFICANT	-0.411 NOT SIGNIFICANT	0.299 NOT SIGNIFICANT	-0.178 NOT SIGNIFICANT
	TOTAL	-0.605 SIGNIFICANT AT 0.01	-0.252 NOT SIGNIFICANT	-0.422 NOT SIGNIFICANT	-0.517 SIGNIFICANT AT 0.05

		STRESS			
		TIME	NOISE	VIBRATION	TOTAL
BOMBS	ILS	-0.512 SIGNIFICANT AT 0.05	-0.359 NOT SIGNIFICANT	-0.491 SIGNIFICANT AT 0.05	-0.611 SIGNIFICANT AT 0.01
	NAV	-0.460 SIGNIFICANT AT 0.05	0.054 NOT SIGNIFICANT	0.069 NOT SIGNIFICANT	-0.180 NOT SIGNIFICANT
	TOTAL	-0.613 SIGNIFICANT AT 0.01	-0.169 NOT SIGNIFICANT	-0.230 NOT SIGNIFICANT	-0.474 SIGNIFICANT AT 0.05

The "bomb" analysis shows that the major relationship is time in the simulator. The longer the subject is exposed to the simulator environment, the less "bomb" behavior manifests itself. Another point to note from Table III is that there is no clear-cut pattern of "bomb" occurrence in the first or last part of the long data runs. One would think that if "bombs" are inversely related to time stress when all the runs are considered that they would also occur more frequently in the early parts of the long data runs. This did not happen.

Fatigue Analyses

Fatigue vs. Time: The fatigue ratings given by subjects on their rating sheets (Figure 6) were combined for each hour in the simulator. Figure 12 is a plot of the fatigue ratings against time in the simulator. As one would suspect fatigue ratings increased with exposure to the simulator environment. The subjects seemed to adapt their feelings of fatigue as a function of the length of time they knew they would have to spend in the simulator. The highest ratings reached in the 8-hour, 4-hour, and 3-hour missions are approximately the same (about 3.5). The results of the 6-hour mission, however, are different. Subjects fatigued initially at the same rate as in the 3-hour mission but the curve levels off at three hours and falls slightly for about two hours. During the last 90 minutes, the curve rises sharply to a rating in excess of four at the end of six hours.

These data are presented to illustrate the large subjective element in feelings of fatigue. In effect, subjective preception of fatigue was influenced by the length of time a subject had left in the simulator. In many individual cases, the fatigue ratings seemed to reach a plateau at the 3 rating (tired but OK), until the subjects realized that the session was almost over. At that time, the ratings would climb rapidly to the 4 or 5 level. The normal rate of increase for fatigue ratings was on the order of a change in rating every hour or so (every four approaches). In the 6 hour no-rest runs, it was not unusual for the rating to change from 3 to 5 within the space of a few legs (30 minutes).

Noise vs. Fatigue: Figure 13 is a plot of fatigue ratings by noise conditions. None of the differences shown is significant, although one might note that the fatigue ratings for 90 and 95 dB conditions are in inverse order. That is, 90 dB conditions are rated more fatiguing than 95 dB conditions. It is possible the 90 dB condition was less stressful, therefore less challenging to the pilots. They become bored, therefore fatigued.

g Level vs. Fatigue: Figure 14 is a plot of fatigue ratings against g level. These curves show little systematic differences due to vibration and thus indicate that the vibration levels used in this study have not influenced fatigue ratings.

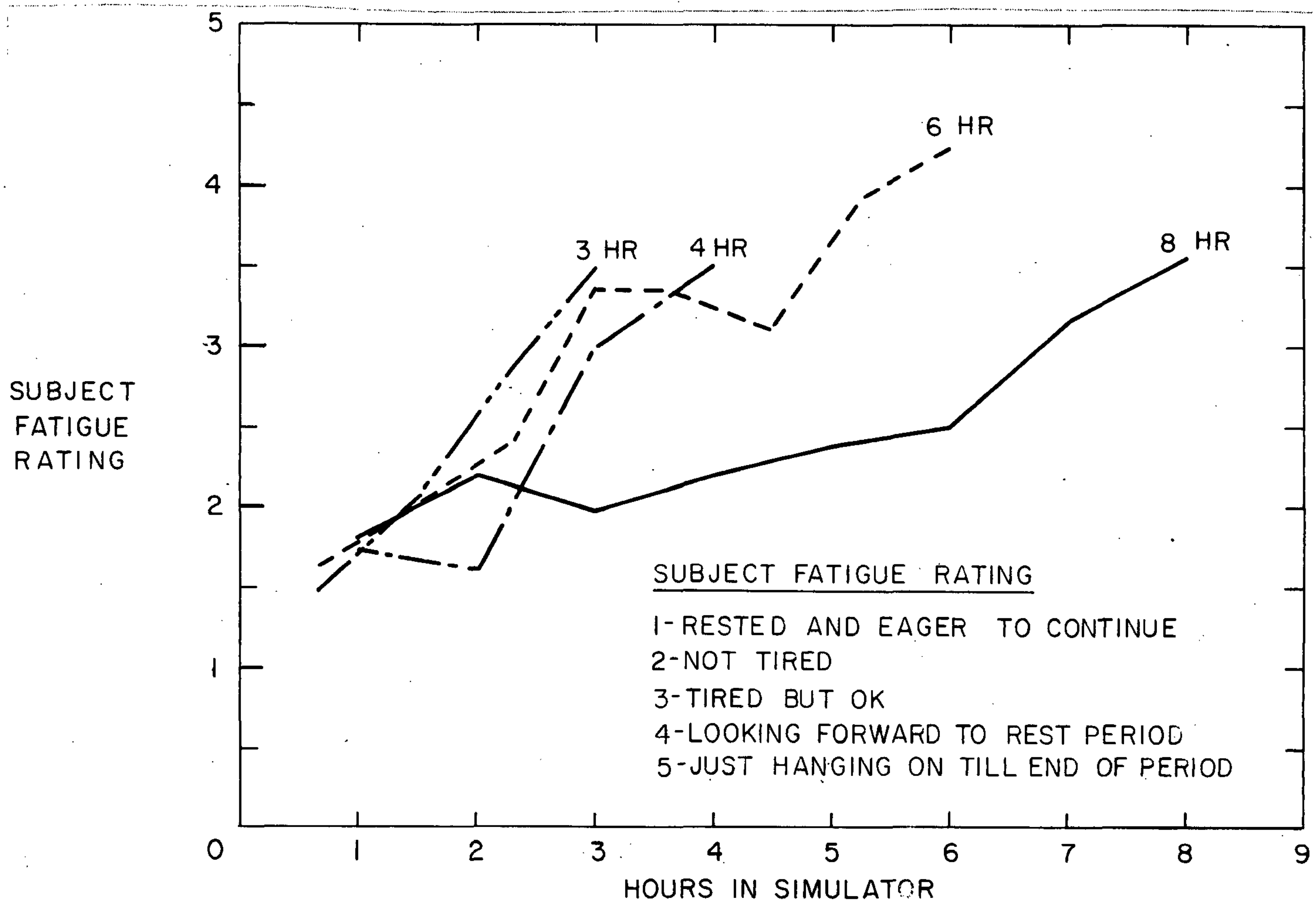

Figure 12. - Fatigue Rating vs. Exposure Time.

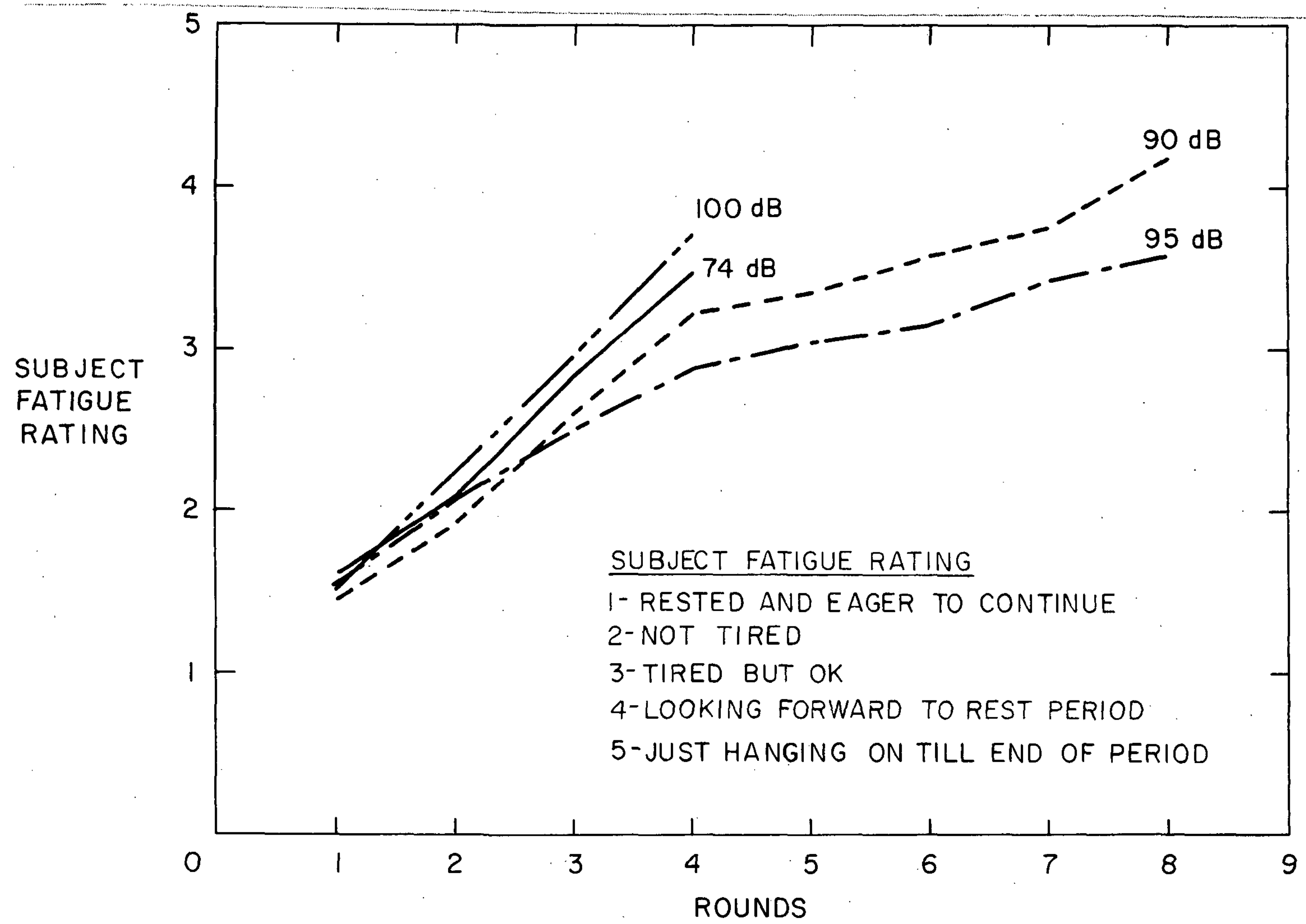

Figure 13. - Fatigue Rating vs. Noise Conditions.

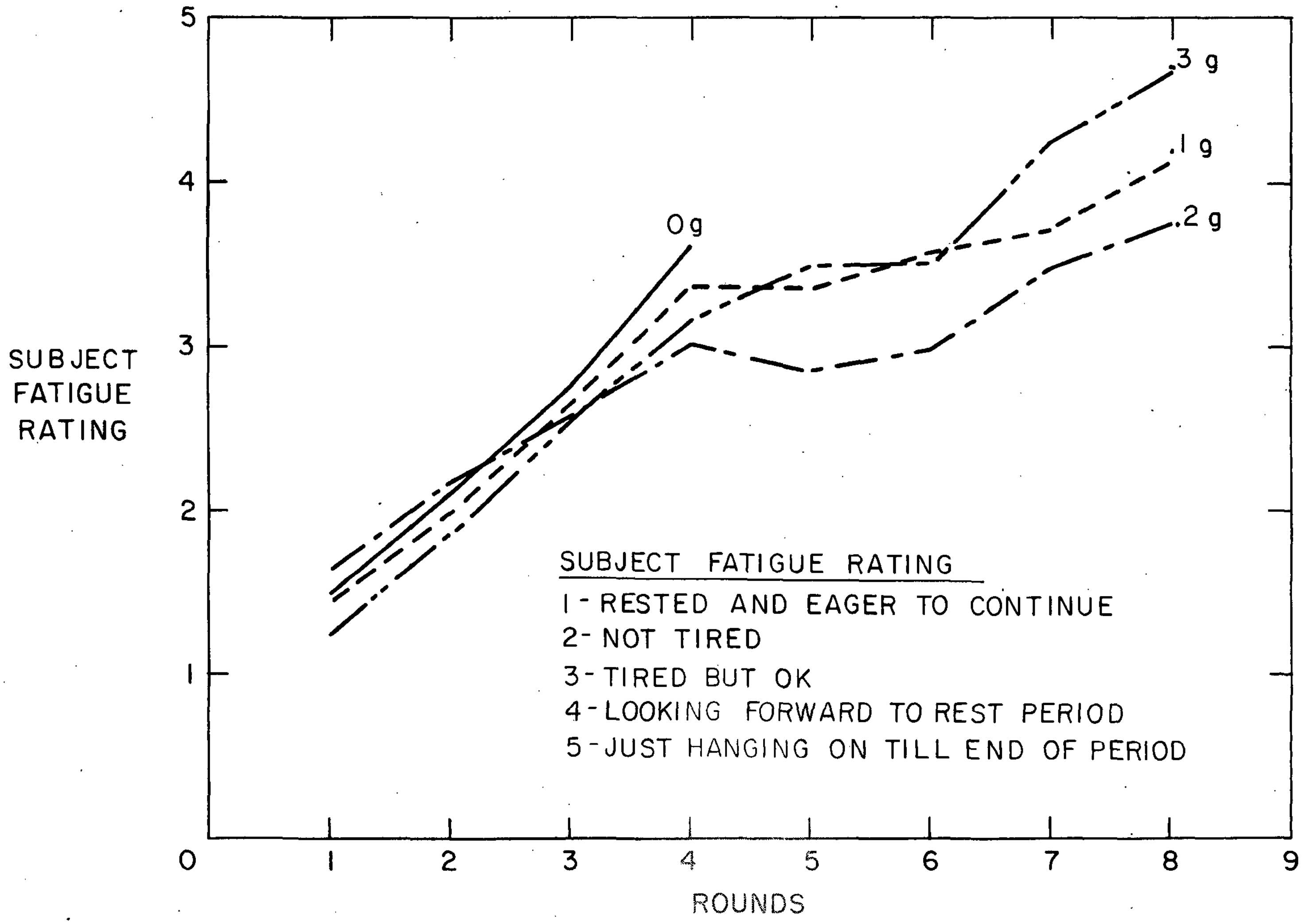

Figure 14. - Fatigue Rating vs. g Level.

ILS Score vs. Fatigue Rating: Figure 15 shows a plot of ILS error scores against fatigue ratings. The plot shows that as subjects felt more and more tired their ILS scores tended to improve, i.e., an inverse relationship. Statistical analysis of the data yielded a correlation coefficient of -.557 which is statistically significant.

When the percentage of "bomb" occurrences is plotted against fatigue ratings the results show, Figure 16, a positive relationship. This means that whatever is causing "bombs" is related in some way with an increase in fatigue.

The following table is a matrix of Pearson product-moment correlations showing the above relationships; a "t" test shows all relationships to be statistically significant except for that between fatigue ratings and navigation scores.

Scores	R
Fatigue vs. ILS	-.557
Fatigue vs. Nav.	-.123 ns
Fatigue vs. Total	-.666
"Bombs"	
Fatigue vs. Nav.	+.831
Fatigue vs. ILS	+.692
Fatigue vs. Total	+.875

Relationships of Scores To Time

The relationship of performance scores to time is shown in Figures 17, 18, and 19. Figure 17 combines all conditions and plots the resulting ILS error scores against time or rounds in the simulator. The results show a general improvement with time with the best scores in round 5 (during the third hour), and a rise during the remainder of the run.

Figure 18 is a similar plot of navigation scores. There is much less of an improvement in performance during the third hour but a small relationship can be seen.

The saw-tooth pattern in scores is an artifact of the navigation task. The second and last leg of each round are more difficult to fly than the first and third and thus result in

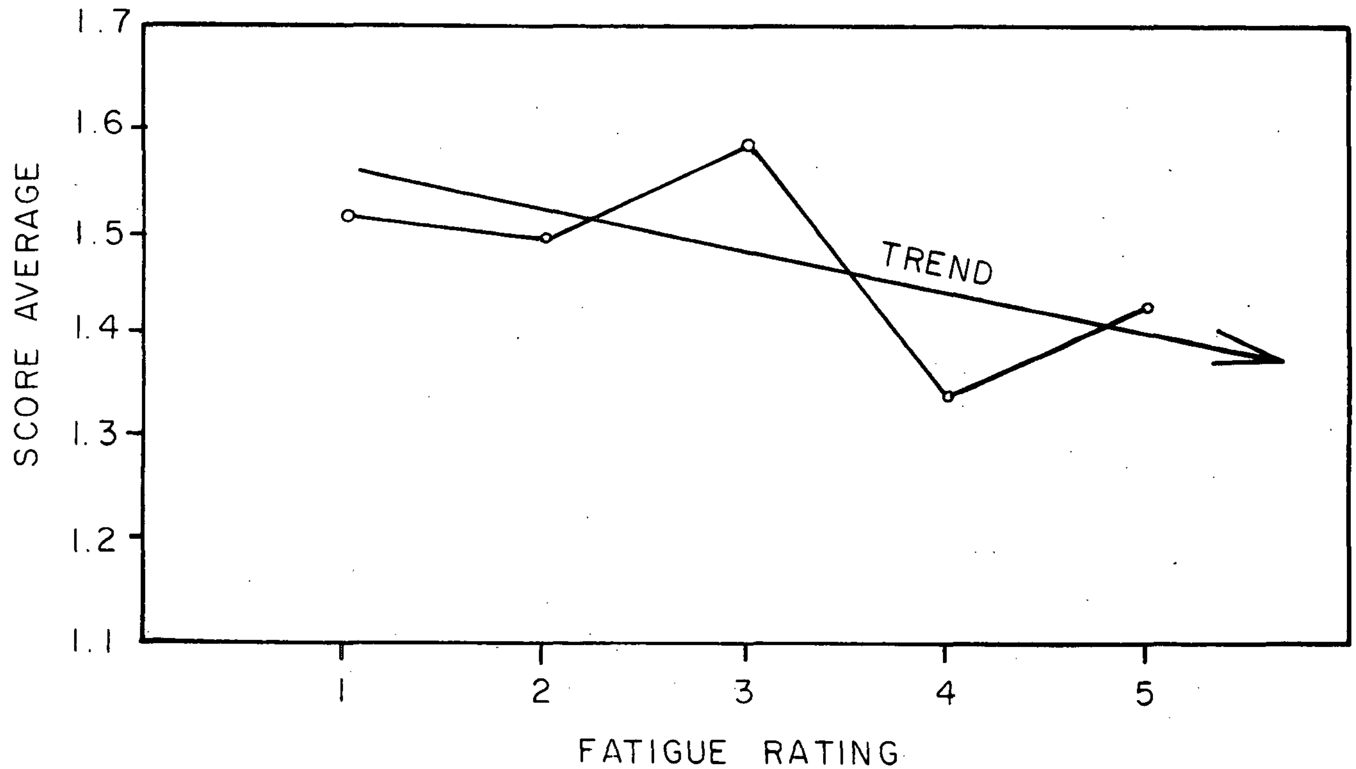

Figure 15. - Fatigue Rating vs. ILS Error Score.

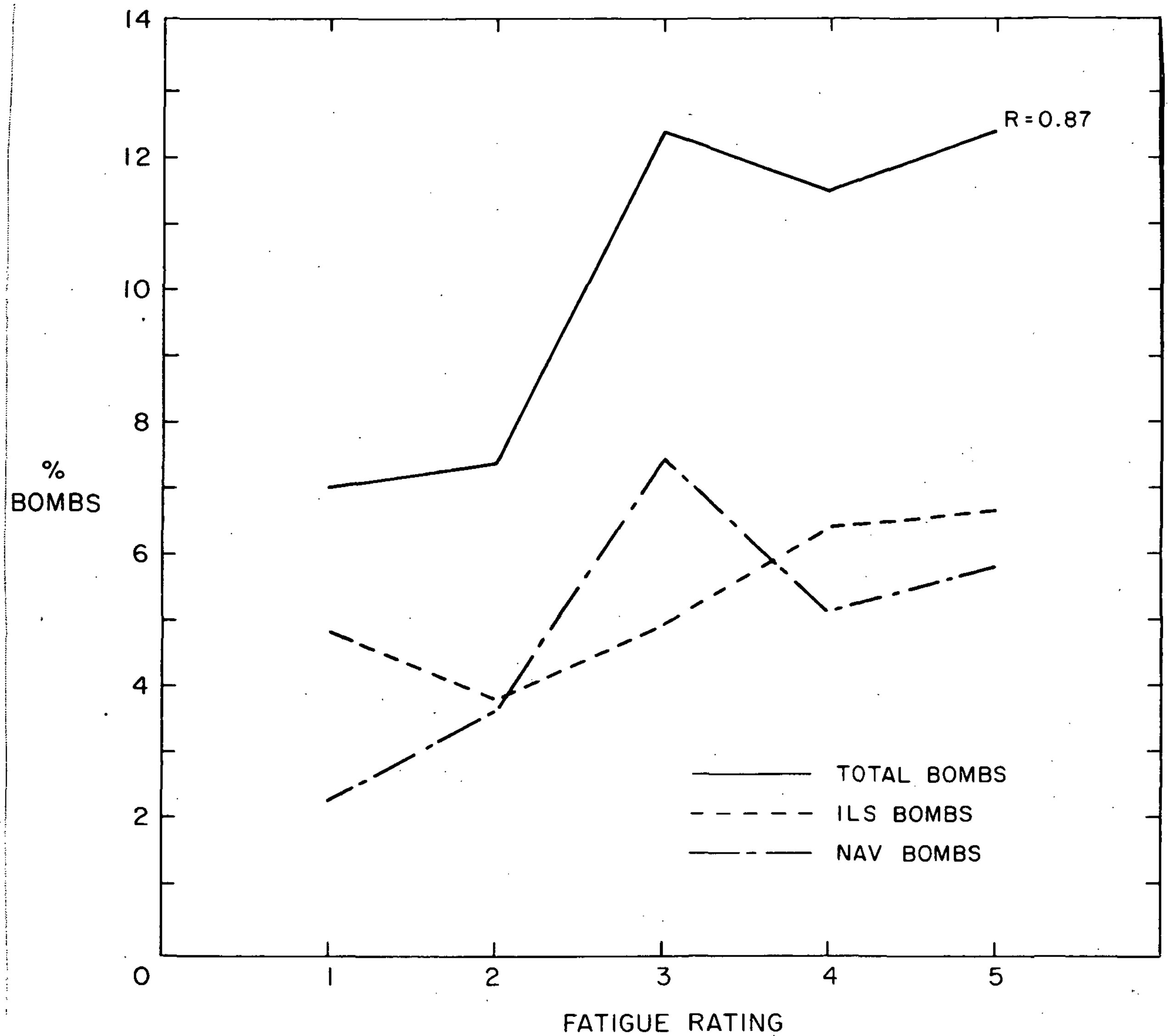

Figure 16. - Fatigue Rating vs. Percent "bombs".

higher navigation errors.

In Figure 19, the ILS scores are combined with navigation scores to show total performance changes over time. Navigation scores had to be modified (divided by 200) so that both scores contribute evenly to the final result. The combined scores show the low point during the third hour and a rise beginning in the 4th hour. These data are similar to the findings of Jones (44). In his study, radio operator performance was measured during long missions in actual aircraft. He found a slow improvement in performance for three hours and then a degradation. His data were taken over a series of 5-hour watches on flights that lasted up to 16 hours. Thus we have two independent studies both showing that tasks requiring constant alertness result in slow improvement in performance for a period of 2-4 hours and then degradation.

Differences Between First and Last Halves

While running the subjects, the experimentor observed that the consistency of navigation scores seemed to improve with time. Subjects appeared to exhibit less variability in their performance as time went on. The more fatigued they became the more predictable their navigation seemed to be. Statistical examination of the data showed that the average navigation scores for the first half of the 6-hour set of data runs were no different from those for the second half (204 vs. 203).

However, during these three 6-hour data runs (52 data points) there was an average standard deviation of 63.3 for the first half scores, as opposed to 52.9 for the second half scores. This indicates that there were fewer extreme scores in the second half and that subject performance became more predictible during the last three hours of a 6-hour data run.

A "t" test was run and the difference between the two was found to be statistically significant at the .05 confidence level.

This is interpreted as evidence for the hypothesis that as subjects get tired, they compensate by trying harder and as a result, their average performance improves.

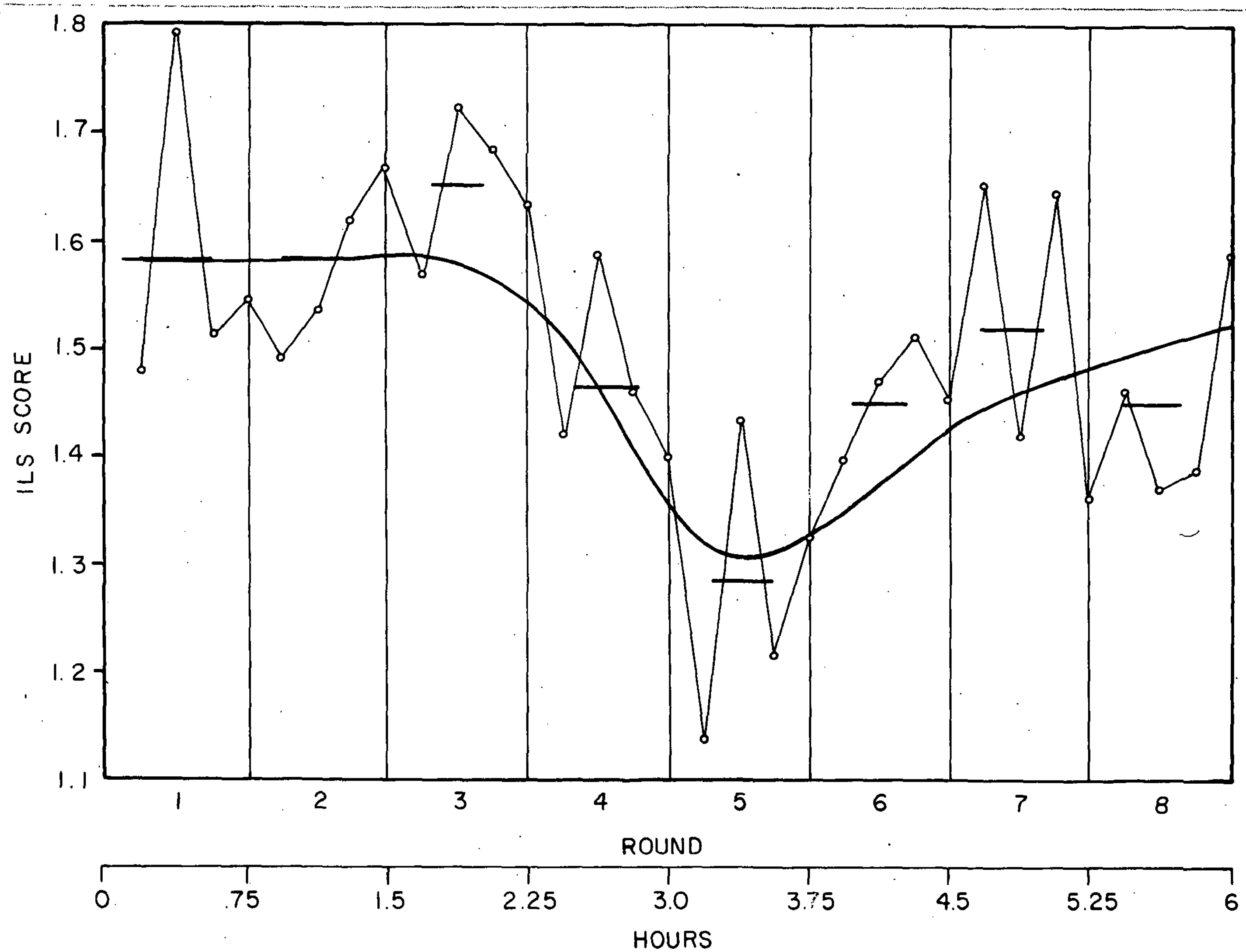

Figure 17. - ILS Score vs. Simulator Time.

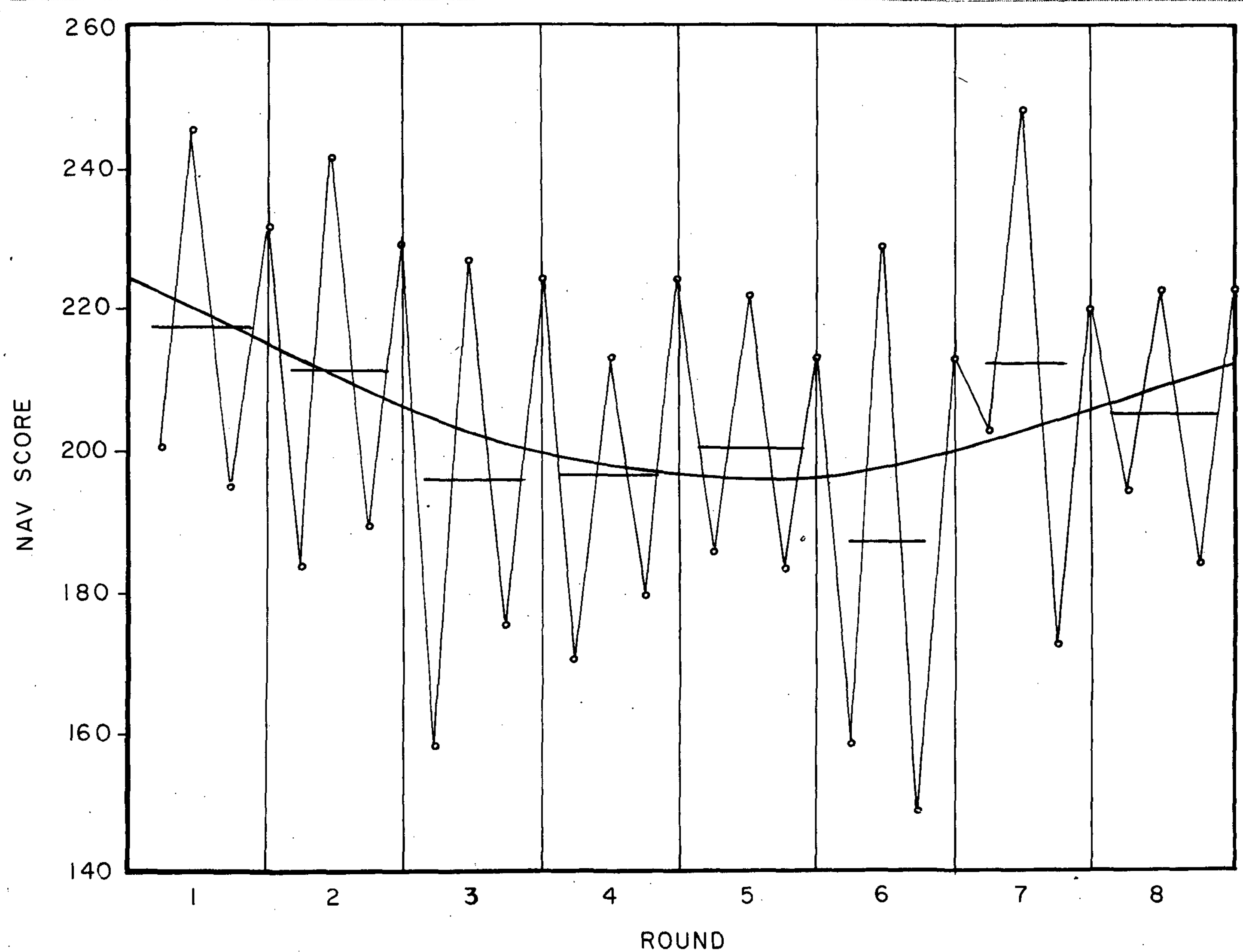

Figure 18. - Navigation Score vs. Simulator Time.

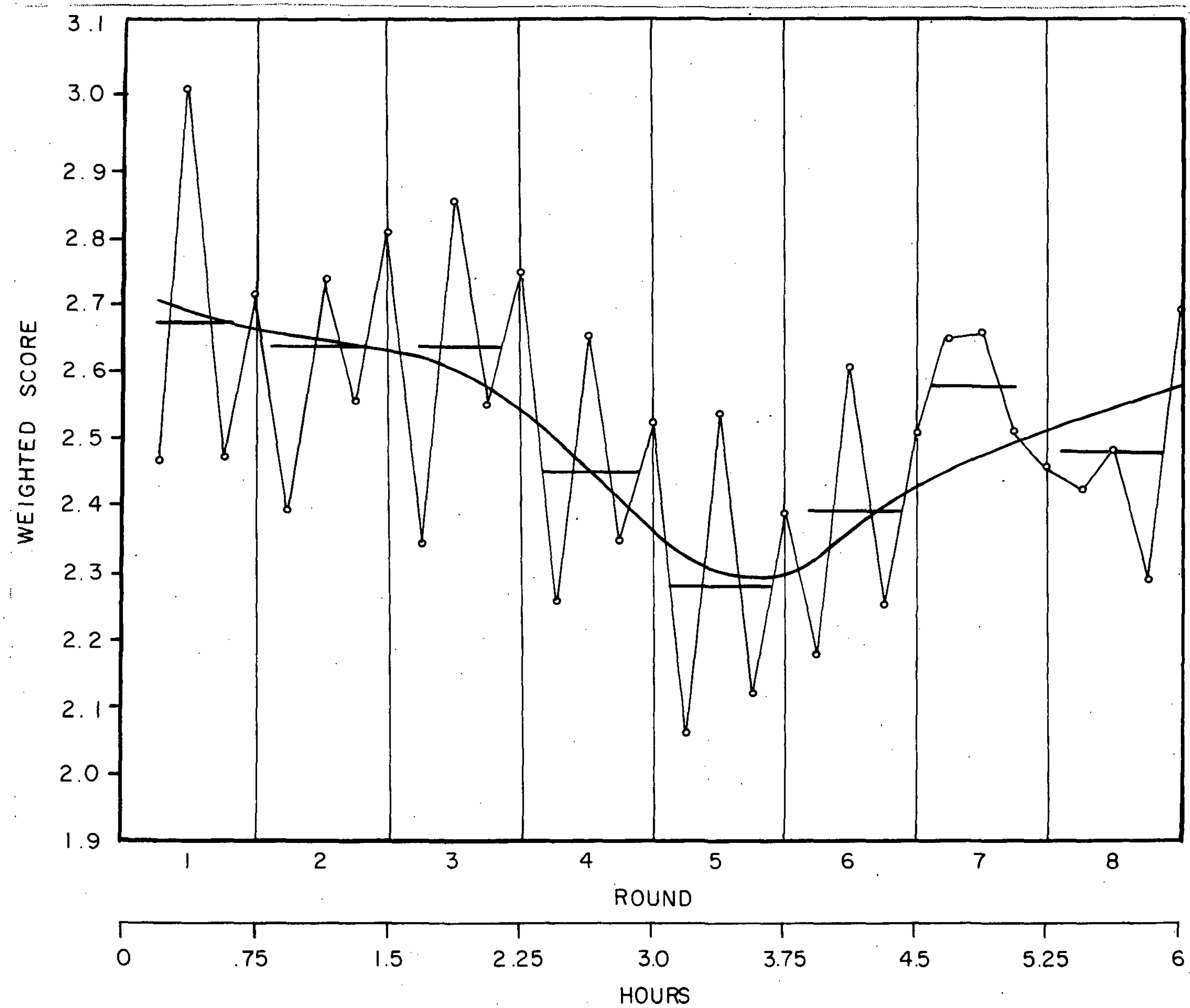

Figure 19. - Combined Scores vs. Simulator Time.

DISCUSSION

This study has many complex implications. Perhaps the most important is that performance and fatigue are independent. This conclusuion is quite obvious especially when one watches subjects coping with the problem of working continuously for six hours. Subjects usually start a session talking with the experimentor, making long involved position reports, singing to themselves, whistling under their breath, etc. In general, there is a relaxed atmoshpere. As time goes on, this slowly changes to occasional muttered swear words during ILS approaches, shorter and shorter position reports, and finally into a grim silence interrupted only by brief position reports. This pattern in essentially the same for all subjects. It differs only in its rate of onset. Despite the onset of fatigue, performance not only did not degrade, but it actually improved with time. This was apparent to the investigator during data collection and was amply backed up by the statistical analyses performed afterward.

The literature is rich in studies of the complex effects of fatigue. An excellent overall view of the problem is found in an article by an anonymous author writing in the British Medical publication "Lancet" of March 1966.

> "Not much is known about the cause of fatigue even in its simplest form, and one reason is that fatigue is hard to measure. When repeated muscular work is done and recorded, a time comes when there is a decrement in the work performed, and this is said to be due to fatigue of the motor system. But even at this stage an adequate stimulus may restore the strength of the muscular contraction, at least for a time. Thus, the decline in work done, though it may be a measure of fatigue in certain defined circumstances, does not provide information about all the factors involved. A hard-worked muscle can produce a feeling of tiredness, but this sensation is rarely disagreeable and may even be pleasant, in contrast to other types of tiredness. Pain and stiffness following unaccustomed exercise are a different matter. That tiredness following exercise can be pleasant may depend on the fact that the cause is known and contains no element of frustration, anxiety, or fear. These three emotions are potent causes of tiredness, leaving aside obvious or concealed ill health, or over-stimulation of one of the senses as by prolonged loud noise or dazzling or flickering light. On the other hand, the continuous gloom of dull weather makes for depression and tiredness. Thus tiredness has two sources: one related to physical and the other to mental

events. Tiredness felt at the end of a day's work may partially depend on boredom, sense of hunger, and the accumulating physical discomfort of circulatory stagnation due to prolonged standing or sitting. Tiredness may be a warning or an escape according to individuals and circumstances."

One of the more interesting findings of the present study was the effect of extremely short rest periods. Results reported by others agree with this finding. Bergum and Lehr (11) found that vigilance performance could be maintained effectively if subjects were granted short rest pauses (10 minutes). Coloquhoun (20) in examining inspection tasks found that men given short rest pauses of 5 minutes maintained undegraded effort for periods of one hour. Subjects working without rest could not maintain performance.

Sussman (75), as described earlier, exposed subjects to four hours of continuous driving in a simulator and found large degradations in performance. When given only four minutes rest at the end of the four hours, these subjects recovered almost completely. Kraft (47) found that the optimum rest pause for physical work on a dynamometer was one minute. As subjects became fatigued, rest pauses should be given at shorter intervals but the optimum length of pause remained at one minute. Wilkinson (81) in testing subjects on a task performed after 30 hours of sleep deprivation found that rest pauses of 30 seconds duration every 5 minutes could not prevent degradation in a task of 25 minutes duration.

The above studies have been cited in descending order of rest period duration to illustrate that rest periods ranging from 10 minutes down to only one minute have all been effective in preventing performance degradation. Wilkinson's study shows that there is a lower limit to the effectiveness of short rest pauses. Thus, the effectiveness of the 4-minute rest in preventing performance degradation, Figure 10, as accidentally demonstrated in this study is a characteristic of human performance that should be taken into account in all studies of this kind. Explanation of why such short rest pauses should be effective must necessarily be tentative, but the writer agrees with W. R. Pierson (62) who, after measuring reaction time and movement time on a simple stimulus response task, reached three conclusions as follows:

"1. Subjective experience of fatigue is not a valid criterion of ability to perform speed or endurance type (muscular) work.

2. Fatigue and endurance cannot be measured by work decrement.

3. Fatigue, endurance, and work decrement are independent variables."

Although the tasks performed in the present study were a much more complex mixture of psychomotor elements, the findings can be summarized in almost the same way.

Perhaps the key parameter in performance is subject motivation. Where motivation is high, performance does not degrade. Since motivation was not measured directly in this study, the only evidence for this is the daily observation of subject behavior while data were collected.

One of the indicators of the high subject motivation level was the fact that only one of the 6-hour no-rest data runs was aborted due to subject inability to continue. The run was aborted in the fourth hour after the subject had exhibited very poor performance. During the run, the subject showed a great deal of irritability, impatience, and anger. In discussing the situation with him immediately after the abort, it was learned that the subject had had a particularly trying day and was facing a complex and demanding schedule of activities in the next few weeks. About three weeks later, the subject completed another six hour data run without problems.

The abort could be better explained by mental rather than by physical fatigue. The subject was preoccupied with other problems, and the additional mental load imposed by the flight task may have saturated his already overloaded system.

Some support for this explanation can be found in the literature where several systems have been developed for classifying subjective fatigue reactions. Bartlett (8) distinguished between fatigue resulting from physical exertion and "skill fatigue", which resulted from continuous concentration in performing highly skilled tasks. The task of flying a helicopter is clearly in the "skill fatigue" category. Ryan (67) used the same line of thinking when he distinguished between sedentary and non-sedentary tasks which correspond closely to Bartlett's concepts. Duffy (25) then introduced motivation into the scheme by categorizing "simple fatigue" as a condition following a period of highly motivated physical exertion and "nervous fatigue" as a reaction to a prolonged period of high arousal in a mental task. A condition of low motivation is not classified as fatigue since the operator shows only a disinclination to work without evidence of exhaustion from previous exertion. Wolf (82) used a factor analysis technique to identify three types of fatigue: nervous fatigue, drowsy fatigue, and exhaustion fatigue. Drowsy fatigue is caused by low motivation while working on a sedentary task. Exhaustion fatigue is caused by working with high motivation on a non-sedentary task. Nervous fatigue is the result of working under conditions of high motivation on a sedentary task and has as its main symptom increased irritability.

The aborted flight fits into the "nervous fatigue" category. The subject was working on a sedentary task with high motivation and exhibited irritable behavior during the run.

At the start of the study, it was assumed that performance would slowly degrade as the subjects became tired. This did not happen. Most reported research in this area has also failed to find any convincing relationship (7, 59, 64 and others). Pearson (63) points out that laboratory tasks of longer duration (20 or 30 hours) may be needed to demonstrate greater agreement between performance degradation and fatigue. The author feels that once performance begins to degrade, it will do so quite rapidly, that is, once the subject loses motivation, performance will drop drastically.

The question remains, however, as to why performance improved as stress increased. The author feels that the hypothetical curve of performance shown in Figure 20 might be used to explain the initial improvement in performance. As pilots feel the onset of fatigue, they put forth increased effort to compensate. This increased effort results initially in improved performance, which then degrades as the products of fatigue build up and cause a reduction in motivation. The plot of ILS scores for 8-rounds provides factual evidence for the hypothetical curve. As a practical matter, however, subjects indicate that they would not fly a real vehicle under IFR conditions if they considered themselves to be as tired as indicated by a fatigue rating of 4. One might assume, therefore, that no pilot would fly an actual aircraft beyond the center portion of the hypothetical curve, that is, they would not fly beyond the point where motivation can sustain normal performance.

The focus of this study was to test performance under stress conditions comparable to those that could occur in a real world commercial VTOL environment. The results show that pilot performance is not degraded by the noise, vibration, and duration conditions tested.

In military and commercial environments, pilots are often required to fly long hours for several consecutive days. This study did not look at this aspect of the problem. The average interval between flights by individual subjects was about one week. At this interval no carry over fatigue effects were seen in the data. Subjects did report that they felt irritable for a day or so after completing one of the six hour flights. Thus, there may be a cumulative fatigue effect on performance which has not been examined by this study.

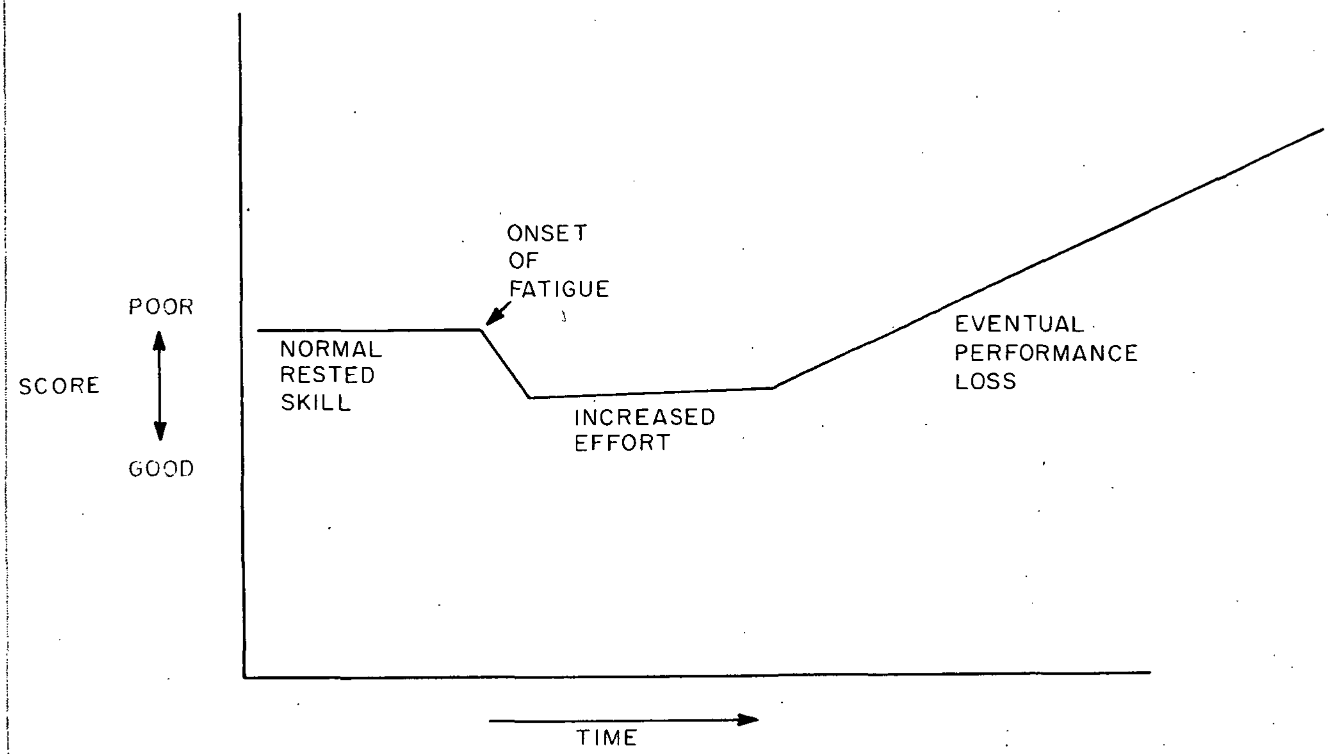

Figure 20. - Hypothetical Curve of Performance.

If one views broadly the results of this study, probably the most important finding has to do with the phenomenon of "bombs".

The phenomenon, as manifested in our study, was not a function of training since "bombs" continued to occur throughout the data collection period (about one year). Approximately 5% of the ILS runs resulted in "bombs". From the data in the results section, the occurrence of "bombs" appears related to feelings of fatigue. Correlation with the fatigue rating is high and positive, but "bombs" are also inversely related to stress, i.e., the more stress, fewer "bombs".

Casual observation of pilot's reactions during data runs leads to the inference that "bombs" are caused by a lapse in attention lasting for a short period of time (seconds in length). Such a lapse would cause the subject not to correct position errors and thus allow error buildup. The ILS pathway was quite difficult to fly and the larger the error buildup, the more difficult it was to recover.

A lapse of short duration would not, however, explain navigation "bombs". One possibility is that several lapses might occur during a short period of time. This would explain the "bombs" occurring during navigation part of the various runs.

A.G. Bills (12, 13, 14, 15) describes a phenomena similar to "bombs" which he calls "blocking". This manifests itself in extra long reaction times of subjects working on a long series of relatively simple tasks. As a result of his extensive studies Bills (13) felt that "blocks" are;

> "the tendency, shown by practically all persons, on continuous mental work, to show periodic gaps or pauses in their responses, which they are unable to prevent, no matter how hard they try. These breaks were found to occur about three times a minute on the average and to have a duration of from 2 to 6 average response times: though practice decreases and fatigue increases their length and frequency, and individuals differ from one another widely."

Bills felt that blocking is the body's reaction to fatigue products in the nervous system. The effect of the block is to rest the brain cells and permit the continuance of mental work without degradation in performance. In a later study (15) he found that a reduction in the amount of Oxygen in the air breathed by subjects both increased the number of blocks and prolonged their duration. He reasoned that a momentary lack of Oxygen in the brain will cause a block.

It is felt that "blocks" and "bombs" are manifestations of the same phenomena and that "bomb" behavior is not peculiar to the conditions of this study.

If it can be shown that this phenomenon occurs in actual flight, then a possible causative mechanism for "pilot error" accidents has been identified. Further investigation is required for clarification and possibly corrective procedures.

CONCLUSIONS

1. Under conditions of continuous work, for 8 hours or less, pilot performance does not degrade, it may improve for periods up to 4 hours under operational levels of noise and vibration stress.

2. For the stress levels and time durations studied, pilot performance improves with increasing levels of noise, vibration, and time stress.

3. While continuously performing in a simulated VTOL commercial airline environment for long periods of time, pilot subjects suffered from lapses in ability that occur at unexpected times and are probably of short duration (seconds in length).

4. Rest periods as short as 4 minutes are extremely effective in maintaining effective performance for at least 8 hours.

5. Many of the apparent discrepancies in the findings of vibration studies can be resolved through use of measurements made at the subject's spine rather than measurements from the floor. The vibration transmissibility of the pilot's seat can have a significant effect on the level of vibration actually experienced by the subject.

6. Pilot performance is independent of fatigue. Performance apparently depends on subject motivation rather than on feelings of fatigue.

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APPENDIX I

TRAINING MATERIAL

INTRODUCTION:

You have been selected as subjects for study on the effects of noise and vibration on pilot performance. A simulated S-61 has been set up in which you will fly simulated airline schedules for 4 hour periods. We are simulating the routes of New York Airways and we will give you only those rest periods afforded to NYA pilots.

We hope to give each of you about two hours familiarization with the simulator, the route structure, and the 6° ILS beam we have set up. After the training periods you will be asked to fly several four hour flights, on the average, one flight each week.

The following material should be carefully examined. It gives you an idea of the route structure and IFR procedures you will be using.

AIRLINE SET UP:

SAI (Simulated Airlines Inc.) routes are flown between Kennedy (JFK), Laguardia (LGA), and Newark (EWR) heliports. They are flown over an airway structure which is separate from fixed wing traffic. All landings are accomplished with the help of a 6° ILS system. You are to fly the aircraft down the beam until the problem automatically turns off at 75 feet.

The problem has two VOR navigation aids (Brooklyn Heights, and Forest Hills) and three ILS stations. You have a VOR receiver that can be used to navigate between stations or can be tuned to any one of the three ILS beams located at the heliports. Tuning to ILS or VOR stations is automatic and accomplished by simply moving a selector switch to the proper location. The simulator is also equipped with a single ADF receiver which can be tuned to either of the VOR stations. Tuning is again automatic through movement of a selector switch.

COMMUNICATIONS:

You will be flying with a 4 channel VHF system. Channel #1 contacts the Helicopter Route Controller who handles enroute traffic. The other channels are for each of the heliport towers on the route. (Channel 2 is for JFK, 3 for LGA, and channel 4 for EWR).

Use standard radio procedure when flying the SAI vehicle.

AIRWAY PROCEDURE

All SAI flights are IFR. Flight Plans are filed for you but you must call the tower and request final clearance prior to take off. Cruise speed will be 120 knots, climb speed 70 knots and approach speed 60 knots.

The SAI route structure begins and ends its flights at JFK. The route for a flight is from JFK to LGA to EWR, back to LGS, and finally to JFK. (see route map). Each flight requires one hour to complete and you will fly four flights per day. You are allowed 4 minutes at each stop and 8 minutes at the point or origin (JFK). Engines will not be stopped at any heliport except JFK and therefore, you will remain in the cockpit at all stops except JFK. Please maintain the schedule insofar as possible. i.e. take off on the schedule time for each leg of the four flights.

During your time at each heliport there will be a certain amount of paperwork required, much the same as is required to New York Airways pilots. This will take the form of a sheet on which you rate your performance on the past leg.

The major factor governing the procedures outlined above is the current practice of New York Airways. Thus for brief periods each week you will become to all intents and purposes a commercial airline pilot for SAI.

Recommended Enroute Procedures for

HA-1

JFK to LGA — Call Sign "Sim - 1"

Before Take off

1. Tune in Forest Hills VOR (select 144° radial)
2. Set clock to read on the hour
3. Request Clearance to LGA heliport Via HA #1

After Take off

1. Track Inbound to Forest Hills (mag hdg about 324°)
2. Climb on course
3. Report reaching altitude (to JFK tower) increase to 120 K estimate Forest Hills 3 min after take off
4. When directed switch to Route control (chan #1)
5. Report over Forest Hills (ETA Expressway 1 min later) (slow to 100 knots)
6. Track outbound on 277° radial (turn a little before reaching FH)
7. When 1.6 miles out of FH report over Expressway
8. Turn Inbound to LGA ILS 335° mag (turn a little early to ILS hdg)
9. Switch to LGA tower and reduce to approach airspeed (60K)
10. Maintain Altitude until crossing the beam (1,000 ft)
11. Make approach and report on the deck

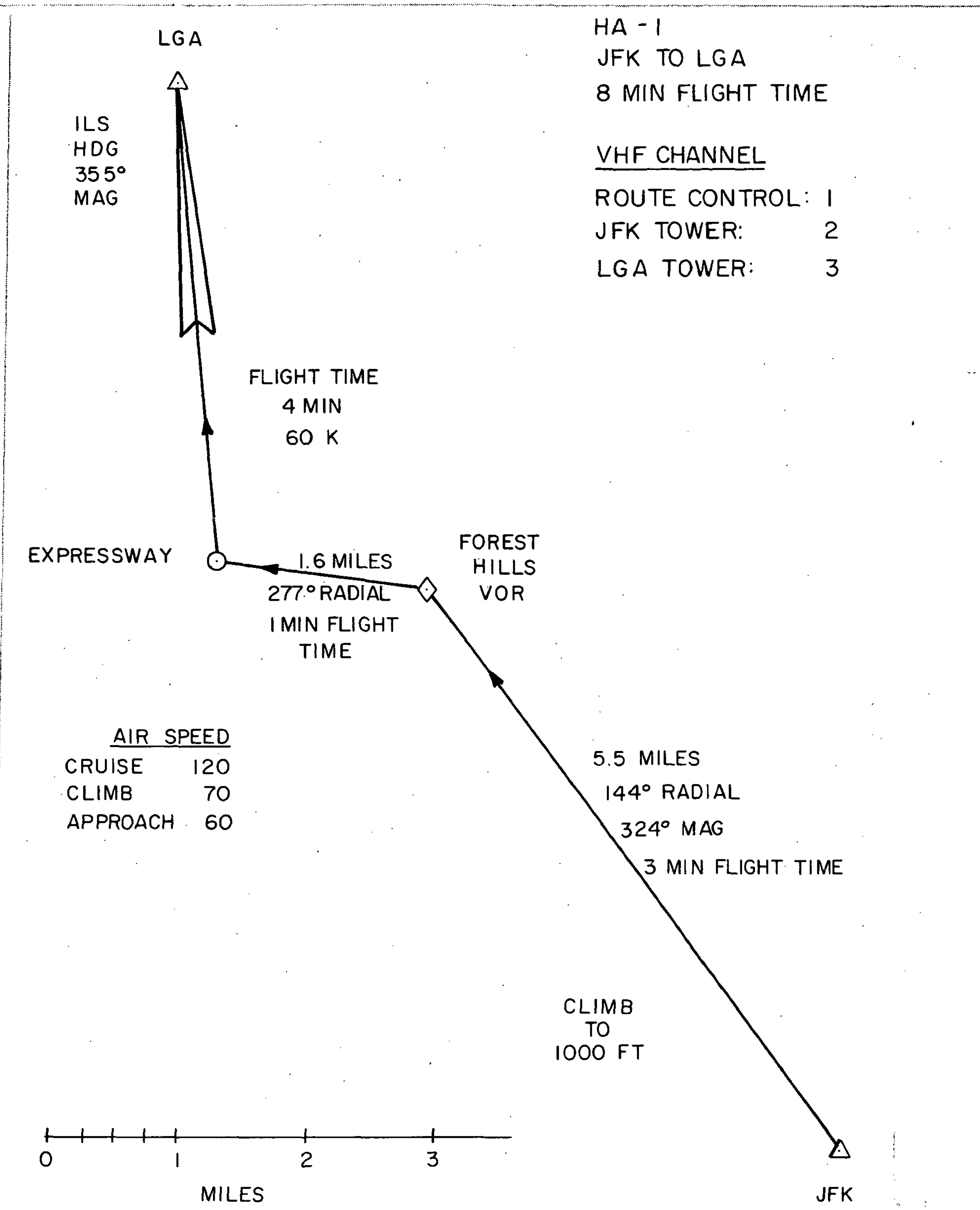

Figure 21. - Helicopter Airway One.

HA-#2

LGA - EWR

I. On the Ground

1. Tune to Brooklyn Heights VOR (025° radial)

2. Tune ADF to BH also

3. Call tower request clearance to EWR via HA #2

II. After Take off

1. Climb to 1,500 ft on course

2. You should not get more than 8.5 miles from BH during first leg, not closer than 6.2 miles

3. When ADF bearing is 235° you should be 7.2 miles away (half way point)

4. Report reaching 1,500 ft and switch to Route control (chan 1) when directed

5. Report when inbound to BH on 025° radial (when DME is 6.5 mi you are 2 min from Fort Green Park)

6. Track BH 025° radial inbound

7. When DME reads 1.5 mi report over Fort Green Park

8. Track inbound to EWR ILS (mag hdg 266°)(also 266° radial of FH)

9. Descend to 1,000 feet when cleared

10. Put ADF on BH, when BH bears 280° report over Bayonne (Also 12.5 miles from FH VOR)

11. Switch to EWR tower and reduce airspeed to 60 knots

12. If not already on EWR ILS tune it in, maintain altitude till crossing the glide slope.

13. Make approach

14. Report on the ground

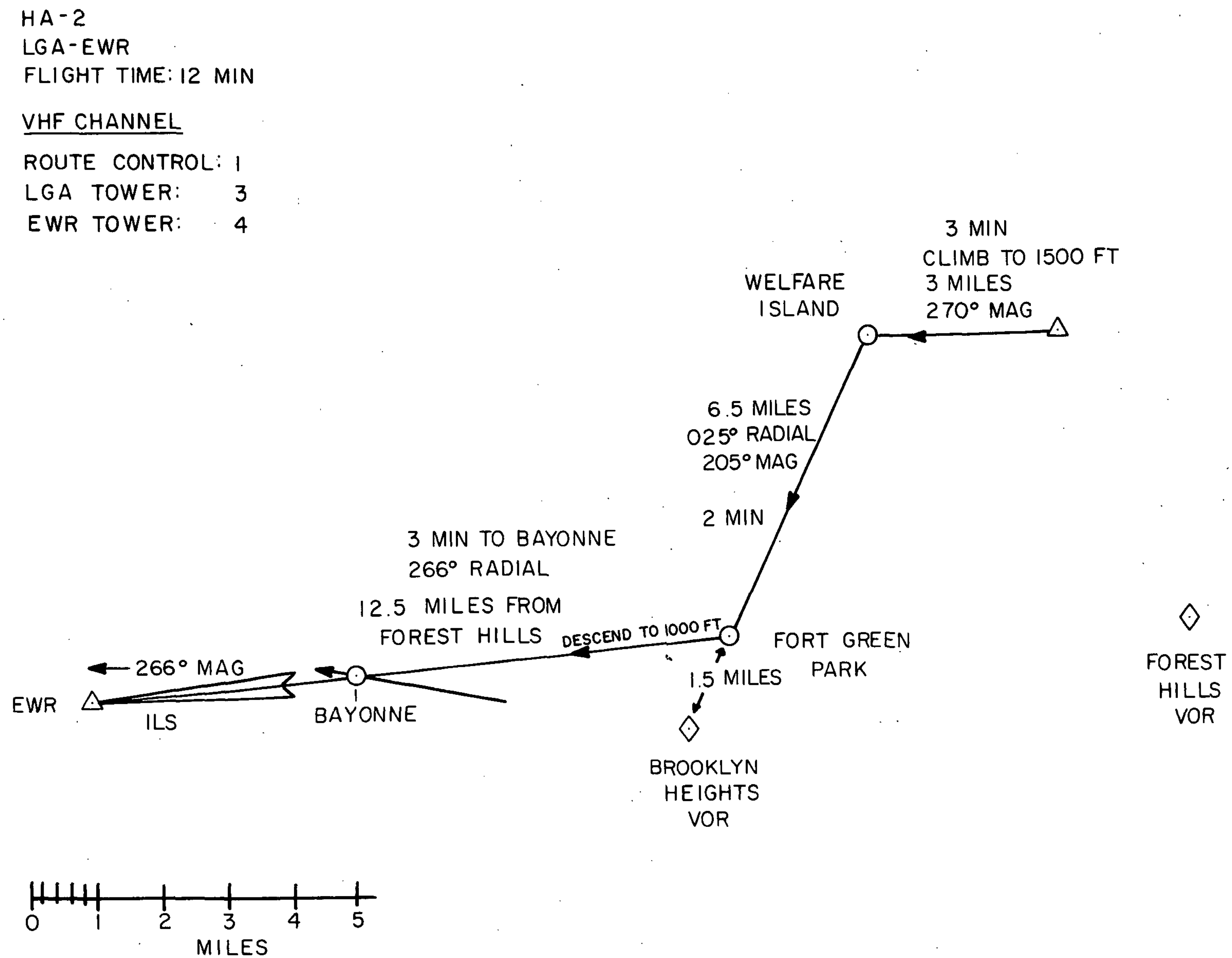

Figure 22. - Helicopter Airway Two.

HA - #3

EWR to LGA

On Ground:

1. Tune in Brooklyn Heights VOR (267° radial)

2. Request clearance from tower to LGA via HA 3# (channel 4)

Take off:

1. Climb on a heading of 115 Mag.

2. Intercept the BH 267° radial (report over Newark Bay)

3. Report reaching 1,000 feet switch to route control

4. Inbound heading to BH 087° (ETA BH 6 min from EWR & 4 min from Newark Bay)

5. Report over Brooklyn Heights and track out bound radial 070° (eta expressway 3 min from BH)

6. When 6.4 miles out of BH report over expressway

7. Turn inbound to LGA ILS (355° mag) Reduce airspeed to 60 K

8. Contact LGA tower channel #3

9. Maintain altitude, 1,000 ft, till crossing glide slope

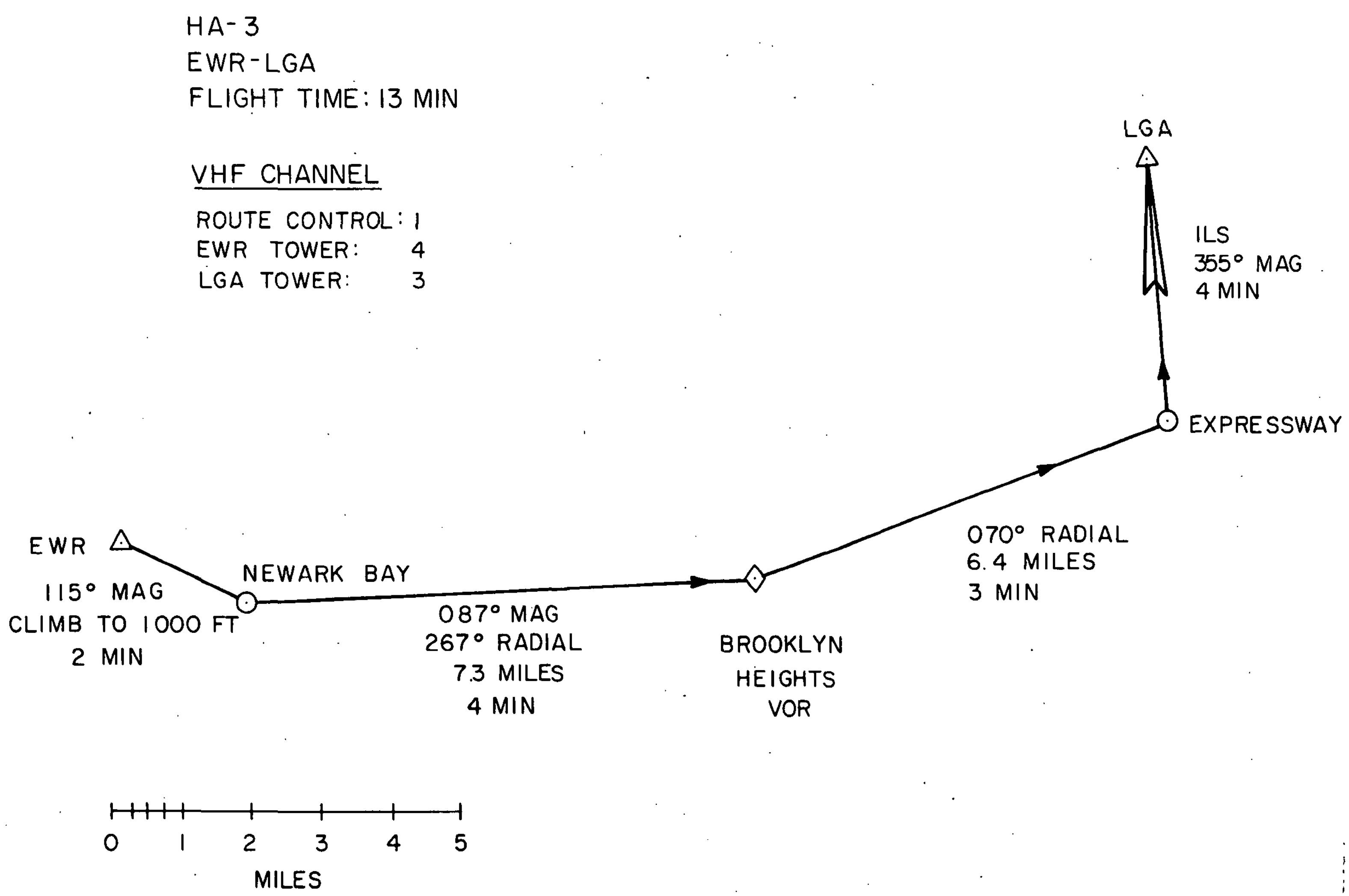

Figure 23. - Helicopter Airway Three.

HA #4

LGA to JFK

<u>On Ground</u>:

1. Tune to Forest Hills VOR (334 radial)
2. Tune ADF to FH also

<u>In Air</u>:

1. Climb to 1,000 ft on 154° mag hdg
2. Report reaching 1,000 feet switch to route control
3. Track inbound to Forest Hills
4. Turn to mag heading of about 108° when FH DME is a little over 2 miles
5. Report over Flushing Park keep Forest Hills DME between 1.25 miles and 3.0 miles
6. Tune to FH radial 080° (as you approach 080 radial the distance slowly approaches 3 miles)
7. Tune to JFK about 1.5 min after leaving Flushing Park and just prior to 3 mi DME on FH
8. When on the JFK ILS turn inbound and call over St Albans
9. Track inbound and contact JFK tower
10. When FH bears 283° on the ADF you are 4 min out, reduce to approach airspeed
11. When on glide slope make approach

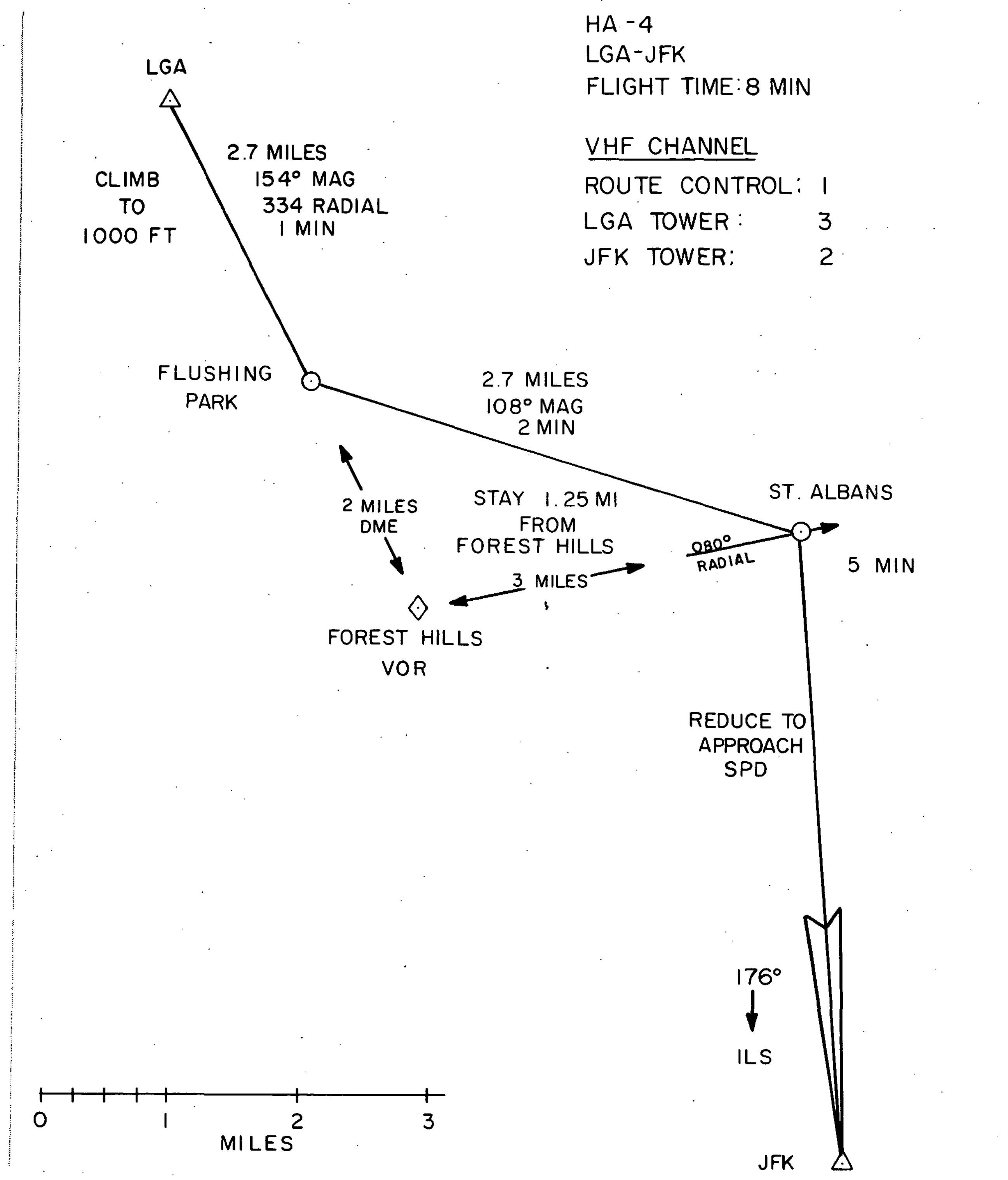

Figure 24. - Helicopter Airway Four.

APPENDIX II

MISSION SCRIPT

Helicopter Airway #1 Script

JFK to LGA

1. Pilot requests clearance via HA #1 to LGA (on channel 2)

   "Sim. One is cleared to the LGA Helipad via Helicopter Airway 1. Climb to and maintain 1,000 ft. on course and report reaching altitude. Over."

   Pilot reads back clearance.

   "Roger, Sim I, cleared for immediate takeoff at (read off time)."

2. Pilot reports at altitude.

   "Roger, Sim I, have you at 1,000 ft. at (time) Contact Route Control Channel 1"

3. Pilot calls Route Control

   "Roger, Sim I, have you at 1,000 ft. IFR to LGA via HA1. Cleared to continue flight, report reaching Forest Hills"

4. Pilot calls over Forest Hills

   "Roger, Sim I, copy you over Forest Hills at (time) at 1,000 ft. Contact LGA tower on channel 3 reaching Expressway"

5. Pilot calls LGA Tower over Expressway

   "Roger, Sim I, have you inbound for approach at 1,000 ft. Cleared #1 at this time, reduce to approach airspeed and give us a call on the deck"

6. Pilot calls on the ground

   "Roger, Sim I, have you with us at (time) cleared to taxi"

Helicopter Airway #2 (Script)

LGA to EWR

1. Pilot requests clearance to EWR via HA #2 (channel 3)

   "Roger, Sim I, you are cleared to the Newark Helipad via HA #2. Climb to and maintain 1,500 ft. on course. Call reaching altitude"

   Pilot reads back clearance

   "That is correct, Sim I, cleared for immediate takeoff at (time)"

2. Pilot reports at altitude

   "Roger, Sim I, have you at 1,500 ft. Contact Route Control Channel 1 reaching Welfare Island"

3. Pilot calls at Welfare Island

   "Roger, Sim I, have you at 1,500 ft. enroute EWR via HA #2. Cleared to continue flight, report over Fort Green"

4. Pilot calls over Fort Green

   "Roger, Sim I, have you at Fort Green at (time). At this time descent to 1,000 ft. and report reaching altitude. Over"

5. Pilot reports at 1,000 ft.

   "Roger, Sim I, contact Newark Tower Channel 4 at Bayonne"

6. Pilot calls EWR Tower over Bayonne

   "Roger, Sim I, have you inbound for an approach to Newark. Cleared #1 at this time. Reduce to approach airspeed and report on the ground"

7. Pilot reports on the ground

   "Roger, Sim I, have you with us at (time), cleared to taxi"

Helicopter Airway #3 Script

EWR to LGA

1. Pilot requests clearance (channel 4)

   "Sim I is cleared to the LaGuardia Helipad Via HA #3 as filed. Climb to and maintain 1,000 ft. on course and call reaching altitude"

   Pilot reads back clearance

   "Roger, Sim I, that is correct, cleared for immediate takeoff"

2. Pilot reports at altitude

   "Roger, Sim I, have you at altitude, contact Route Control Channel 1 for further instructions, over Newark Bay"

3. Pilot calls Route Control at Newark Bay

   "Roger, Sim I, have you at Newark Bay, 1,000 ft. IFR to LaGuardia. Cleared to continue flight, give us a call over Brooklyn"

4. Pilot calls over Brooklyn Heights VOR

   "Roger, Sim I, copy you over Brooklyn VOR at (time). Call 5.5 miles northeast of the station"

5. Pilot calls 5.5 miles out of Brooklyn VOR

   "Roger, Sim I, contact LGA tower Channel 3 reaching Expressway"

6. Pilot calls LGA tower over Expressway

   "Good evening, Sim I, have you over expressway for ILS approach. You are cleared #1 at this time, reduce to approach airspeed and give us a call when you are with us"

7. Pilot calls on the ground

   "Roger, Sim I, have you in at (time), cleared to taxi"

Helicopter Airway #4 Script

LGA to JFK

1. Pilot requests clearance to JFK (Channel #3)

"Roger, Sim I, Sim I is cleared to the Kennedy Helipad via Airway 4. Climb to and maintain 1,000 ft. Report reaching altitude. Over"

Pilot reads back clearance

"Roger, Sim I, that is correct, cleared for immediate takeoff at (time)"

2. Pilot reports at altitude

"Roger, Sim I, have you at 1,000 ft. Contact Route Control Channel 1 at this time"

3. Pilot calls Route Control

"Roger, Sim I, have you HA #4 to Kennedy at 1,000 ft. Cleared to continue flight, report over Flushing"

4. Pilot reports over Flushing Park

"Roger, Sim I, have you at Flushing at (time), give us a call over St. Albans"

5. Pilot calls over St. Albans

"Roger, Sim I, contact JFK Tower when inbound for ILS Channel 2. Good day"

6. Pilot calls JFK Tower

"Roger, Sim I, have you inbound for ILS approach to Kennedy Helipad cleared number 1 at this time, give us a call on the deck"

7. Pilot calls on the ground

"Roger, Sim I, have you on the ground at (time), cleared to taxi"

APPENDIX III

APPARATUS DESCRIPTION

Noise, Vibration, Simulator, Recording Devices

SIMULATION FACILITY

The Sikorsky Aircraft Hybrid Facility is a modern integrated computer system engineered to operate as an entity. The system consists of two Applied Dynamics Model AD/4 analog computers, a Digital Equipment Corporation Model PDP-10 digital computer, a helicopter flight simulator, a hybrid interface unit, and input/output peripherals.

The AD/3 analog computers consist of the following equipment:

	Console I	Console II
Integrator Amplifiers	32	32
Summer Amplifiers	24	24
Inverter Amplifiers	56	56
Track/Store Networks	10	10
Potentiometers	140	140
Electronic Multipliers	10	20
Function Generators	0	10
Electronic Switches	10	10
Variable Hard Limiters	8	8
Patchable Logic Set	1	1
X-Y Plotter	8	6
Chart Recorder, Channels	8	6
Digital Voltmeter	1	1
Oscilloscope, Traces	1	4

Analog peripheral devices include a plotter/digital interface unit, an extensive patchable simulator drive/interface, numerous digital and analog voltmeters, and a single-axis tilt table.

The Sikorsky PDP-10 digital computer is a third generation, solid state, asynchronous general purpose digital computer with 32,000 words of core memory. The machine uses a 35-bit word and operates with a 1-microsecond core memory cycle time. The time-shared arithmetic processor uses sixteen high-speed hardware registers, hardware floating point, byte manipulation, memory protection and relocation, multistep indirect addressing, and sevel levels of programmable priority interrupts. Digital peripheral devices include a magnetic tape controller, three low-speed magnetic tape drives, a high-speed paper tape punch and reader, local and remote teletypes, and remote low-speed paper tape equipment.

The high-speed data and control interface consists of 32 analog-to-digital channels and 32 digital-to-analog channels. In addition, the interface provides mode control, potentiometer setting, interrupt, and discrete control between the digital program and the analog consoles.

Sound Apparatus

To control sound reaching the subject's ears, noise is presented by a magnetic tape loop feeding into a high quality Pickering headset. The earphone has good external noise attenuation and an excellent acoustic seal. The headphones are adjusted to absolute level by use of a Bruel & Kjaer artificial ear, calibrated microphone, and sound-level meter. The voltage across the headphones is measured during calibration while the sound under consideration is being fed into the system. The cockpit noise stimulus is placed on magnetic tape, and the desired level is obtained by adjusting the output of the mixer amplifer.

Radio communication with the subject is provided through an intercommunications system feeding through the mixer amplifier into the subject's headset. The headset used in the study has undergone extensive testing to provide accurate presentation of noise to the subject's ears. The major concern was to assure that the level of noise heard by the subject was independent of the position of the headset over the subject's ears. Less carefully designed headsets have variations of up to 20 dB, depending on how the subject wears the headset. Tests have shown that variation for the headset to be used is never more than 5 dB. We are, therefore, safe in assuming equal noise exposure for each subject on each experimental data run.

Vibration Apparatus

The equipment used to vibrate the pilot's seat was constructed for this study. It consists of a function generator to control the frequency of vibration, a servo controller to control the amplitude of vibration, a servo piston to move the seat, and an accelerometer/g meter combination to provide feedback on actual g level imparted to the seat. The system can provide any frequency of vibration and up to 1 g amplitude at any frequency up to 20 cps.

PERIPHERAL EQUIPMENT UTILIZED DURING STUDY

Equipment	Model	Manufacturer
Load controller	620	Scientific Corp.
Electronic voltmeter	2409	Bruel and Kjoer
Oscillator	200CD	Hewlett Packard
Tape recorder	IIIN	Nagra
Audio amplifier	AU13455	Acoustics Research, Inc.
Audio amplifier	MC30	McIntosh Lab. Inc.
XYY' recorder	480	Electro Instr. Co.
8 channel recorder	200-2222	Brush Instr. Div.
Teletype	ASR 37	Teletype Inc.
Minute/second timer	S-10	Standard Co.
Power supplies	6200A	Hewlett Packard
Power supplies	6200B	Hewlett Packard
*Digital-to-synchro converter		

* Sikorsky packaged, Darlington complementary silicon pairs wired to computer amplifiers being fed by computer multiplying ditital-to-analog converters (MDACS) using 26 VAC 400 Hz as the multiplier.

APPENDIX IV

EXPLANATION OF STATISTICAL CONCEPTS

APPENDIX IV

Statistical Evaluation

The material to follow is intended to give the reader a brief idea of how and why the various statistical techniques used in this study were applied.

Significant Difference

In human research one can be sure that no two experimental results will ever be exactly the same. Even if one were to perform two experiments exactly duplicating each other, the second set or results would be different from the first. The difference between two experimental outcomes is sometimes the result of luck or chance variations. Sometimes, however, the difference in outcomes is the result of a real difference. The problem in dealing with human data is in telling the difference between that which is random and that which is real.

The concept of statistical significance is used to help in distinguishing between the real and the accidental. The question that must be answered in this: Could random variability or chance account for an effect as large as the one obtained? The answer to this question is important because there is no point in worrying about results that can be explained by the variability inherent in the data.

Tests of statistical significance involve three basic quantities, i.e., (1) the size of the difference (the bigger the difference the more confidence one can have that it is a real difference), (2) the number of observations used for the data (we have more confidence if a difference is based on 100 people rather than only 10), (3) the amount of variability in the measurements (the more precise the measures the greater the confidence that a small difference is a true difference). Combination of the above quantities yields a measure of the probability that one would get a given difference if in fact there were no real difference. This is the task of most statistical formulae, i.e., ways of combining size difference with number of observations and precision of measurement into a single index of probability that can be used to express the credibility of experimental outcomes.

This is a weakness of statistical techniques. That is, statistics do not make decisions, its answers are always in terms of probability. It is up to the investigator to decide what level of probability he is willing to accept. If one is experimenting with human lives, you might not be satisfied unless the risk of fatality were less than 1 in 10,000. If, on the other hand, one is concerned with a manufacturing process, one might be satisfied with probabilities on the order of 1 in 10. The point is that the level of significance is an arbitrary value which must be selected by the investigator. There is a general concensus, however, that differences can be considered significant if they occur by chance only 5 times out of a hundred opportunities. A difference is generally considered to be highly significant if it could occur only once in a hundred times. These are the levels that have been used in the current study. This is also what is meant by the words "siginificant at the .05 level" or "at the .01 level".

Correlation Coefficient

A correlation coefficient is a measure that describes the degree to which we can safely predict the behavior of one variable when we know the behavior of another. A good example of two correlated variables is height and weight. By looking at people, one can tell that there is a relationship between height and weight. As a general rule, taller people weigh more than shorter people. You can also tell that the relationship is not perfect. Some people who are 5 feet tall weigh more than others who are 6 feet tall. How good is the relationship between height and weight? That is what a correlation measures -- the closeness of the relationship between variables.

Correlation coefficients range in value from plus 1 through 0 to minus 1. Positive and negative coefficients of the same numerical value are equally good. The sign of the correlation coefficient indicates the direction of the relationship: with a positive correlation, the two variables vary together like height and weight. With a negative correlation, the two variables vary inversely, as one becomes larger, the other becomes smaller. A coefficient of 0 indicates no relationship, i.e., the two variables are independent of each other.

In addition to providing a measure of the degree of association, correlational techniques allow an estimate of the probability of a particular correlation coefficient (level of association) occurring by chance. Thus, to be of use in interpreting data, a correlation coefficient must be significant; that is, the possibility of its chance occurrence must be rejected.

Analysis of Variance

The analysis of variance is a statistical method for analyzing the effects of several variables all acting at once. This is done by dividing the observations made in the experiment up into cells that can then be recombined into various units to show the effects of any desired combination of variables. Figure 25 shows the way in which the data for this study were broken into cells that were then recombined for the analysis of variance.

		ROUND I		ROUND II		ROUND III		ROUND IV	
		ZERO g	0.2g	ZERO g	0.2g	ZERO g	0.2g	ZERO g	0.2g
SUBJECT 1	100 dB								
	0 dB								
SUBJECT 2	100 dB								
	0 dB								
SUBJECT 3	100 dB								
	0 dB								
SUBJECT 4	100 dB								
	0 dB								
SUBJECT 5	100 dB								
	0 dB								

Figure 25. - Data Cells for the Analysis of Variance.

The basic unit used in analysis of variance is the sum of squares. This is simply the sum of all the deviations of a group from its mean or average. An analysis of variance begins with a calculation of the total sum-of-squares for all of the measurements taken in the study combined.

The total sum-of-squares can be divided into two independent components. The first, the between groups sum-of-squares, measures the variation of the group means around the overall mean. The second, called the within groups sum-of-squares, measures the variation of the scores within each group around their own group means. Thus the within groups sum-of-squares measures the random variability in the data. When each of these sums-of-squares is divided by its appropriate number of degrees of freedom, we obtain two independent estimates of the same population variance. The ratio of these two estimates is the F-ratio. If there is no significant difference between the groups, we should have merely two independent estimates of random variability so that, on the average, the F-ratio should be 1.00. If the group means really differ because of the influence of experimental variables, there will be an extra source of variability in the numerator of the F-ratio so that it should be larger than 1.00. Tables of the F-distribution enable us to determine the probability that F values of various sizes could have occurred by chance.

This technique is not limited to examination of independent variables. It can also investigate the interaction between variables. An interaction measures discrepancies between patterns of measurements in one variable when these patterns are computed for different values of a second variable. For example, in a study of the effects of variable A and B, variable A may produce an effect by itself and B may also produce an effect by itself. However, when we expose subjects to both variables at once, subject performance may be different with each combination of A and B. That is, A will have a different effect on performance because of the presence of B.

The technique of analysis if variance allows the separation of the effects due to many variables all acting on the subject at the same time. It permits us to separate out those that effect performance and those that do not. It also shows us the interdependence of variables. In the present study we examined the effects of time, subjects, noise, and vibration on the pilot's ability to fly the simulator.

The specific computational techniques used for computing sums of squares, variance and F-ratios in this study are shown in Figure 26. The method for calculating the sums of squares and variances was obtained from M. J. Moroney (56), page 395. The method of combining variances to form F ratios was obtained from E. F. Lindquist (51), page 237. The standard method of using the residual variance as a divisor for all of the F tests could not be used because the 4-way interaction was significant.

SOURCE	DF	SUM OF SQUARES	VARIANCE	F RATIO
NOISE	$(2-1) = DF_N$	$\left(\frac{\sum X_N^2}{N_N} - \frac{\sum X_T^2}{N_T}\right) = SS_N$	$\frac{SS_N}{DF_N} = V_N$	$\frac{V_N}{V_{N\times S}}$
VIBRATION	$(2-1) = DF_V$	$\left(\frac{\sum X_V^2}{N_V} - \frac{\sum X_T^2}{N_T}\right) = SS_V$	$\frac{SS_V}{DF_N} = V_V$	$\frac{V_V}{V_{V\times S}}$
ROUNDS	$(4-1) = DF_R$	$\left(\frac{\sum X_R^2}{N_R} - \frac{\sum X_T^2}{N_T}\right) = SS_R$	$\frac{SS_R}{DF_R} = V_R$	$\frac{V_R}{V_{R\times S}}$
SUBJECTS	$(5-1) = DF_S$	$\left(\frac{\sum X_S^2}{N_S} - \frac{\sum X_T^2}{N_T}\right) = SS_S$	$\frac{SS_S}{DF_S} = V_S$	$\frac{V_S}{V_{N\times V\times R\times S}}$
N × V	$(2-1)(2-1) = DF_{N\times V}$	$\left(\frac{\sum X_{N\times V}^2}{N_{N\times V}} - \frac{\sum X_T^2}{N_T} - SS_N - SS_V\right) = SS_{N\times V}$	$\frac{SS_{N\times V}}{DF_{N\times V}} = V_{N\times V}$	$\frac{V_{N\times V}}{V_{N\times V\times S}}$
N × R	$(2-1)(4-1) = DF_{N\times R}$	$\left(\frac{\sum X_{N\times R}^2}{N_{N\times R}} - \frac{\sum X_T^2}{N_T} - SS_N - SS_R\right) = SS_{N\times R}$	$\frac{SS_{N\times R}}{DF_{N\times R}} = V_{N\times R}$	$\frac{V_{N\times R}}{V_{N\times R\times S}}$
N × S	$(2-1)(5-1) = DF_{N\times S}$	$\left(\frac{\sum X_{N\times S}^2}{N_{N\times S}} - \frac{\sum X_T^2}{N_T} - SS_N - SS_S\right) = SS_{N\times S}$	$\frac{SS_{N\times S}}{DF_{N\times S}} = V_{N\times S}$	$\frac{V_{N\times S}}{V_{N\times V\times R\times S}}$
V × R	$(2-1)(4-1) = DF_{V\times R}$	$\left(\frac{\sum X_{V\times R}^2}{N_{V\times R}} - \frac{\sum X_T^2}{N_T} - SS_V - SS_R\right) = SS_{V\times R}$	$\frac{SS_{V\times R}}{DF_{V\times R}} = V_{V\times R}$	$\frac{V_{V\times R}}{V_{V\times R\times S}}$
V × S	$(2-1)(5-1) = DF_{V\times S}$	$\left(\frac{\sum X_{V\times S}^2}{N_{V\times S}} - \frac{\sum X_T^2}{N_T} - SS_V - SS_S\right) = SS_{V\times S}$	$\frac{SS_{V\times S}}{DF_{V\times S}} = V_{V\times S}$	$\frac{V_{V\times S}}{V_{N\times V\times R\times S}}$
R × S	$(4-1)(5-1) = DF_{R\times S}$	$\left(\frac{\sum X_{R\times S}^2}{N_{R\times S}} - \frac{\sum X_T^2}{N_T} - SS_R - SS_S\right) = SS_{R\times S}$	$\frac{SS_{R\times S}}{DF_{R\times S}} = V_{R\times S}$	$\frac{V_{R\times S}}{V_{N\times V\times R\times S}}$
N × V × R	$(2-1)(2-1)(4-1) = DF_{NVR}$	$\left(\frac{\sum X_{NVR}^2}{N_{NVR}} - \frac{\sum X_T^2}{N_T} - SS_N - SS_V - SS_R - SS_{NV} - SS_{VR} - SS_{NR}\right) = SS_{NVR}$	$\frac{SS_{NVR}}{DF_{NVR}} = V_{NVR}$	$\frac{V_{NVR}}{V_{NVRS}}$
N × V × S	$(2-1)(2-1)(5-1) = DF_{NVS}$	$\left(\frac{\sum X_{NVS}^2}{N_{NVS}} - \frac{\sum X_T^2}{N_T} - SS_N - SS_V - SS_S - SS_{NV} - SS_{VS} - SS_{NS}\right) = SS_{NVS}$	$\frac{SS_{NVS}}{DF_{NVS}} = V_{NVS}$	$\frac{V_{NVS}}{V_{NVSR}}$
N × R × S	$(2-1)(4-1)(5-1) = DF_{NRS}$	$\left(\frac{\sum X_{NRS}^2}{N_{NRS}} - \frac{\sum X_T^2}{N_T} - SS_N - SS_R - SS_S - SS_{NR} - SS_{RS} - SS_{NS}\right) = SS_{NRS}$	$\frac{SS_{NRS}}{DF_{NRS}} = V_{NRS}$	$\frac{V_{NRS}}{V_{NRSV}}$
V × R × S	$(2-1)(4-1)(5-1) = DF_{VRS}$	$\left(\frac{\sum X_{VRS}^2}{N_{VRS}} - \frac{\sum X_T^2}{N_T} - SS_V - SS_R - SS_S - SS_{VR} - SS_{RS} - SS_{VS}\right) = SS_{VRS}$	$\frac{SS_{VRS}}{DF_{VRS}} = V_{VRS}$	$\frac{V_{VRS}}{V_{VRSN}}$
N × V × R × S	$(2-1)(2-1)(4-1)(5-1) = DF_{NVRS}$	$\left(\frac{\sum X_{NVRS}^2}{N_{NVRS}} - \frac{\sum X_T^2}{N_T} - SS_N - SS_V - SS_R - SS_S - SS_{NV} - SS_{NR} - SS_{NS} - SS_{VR} - SS_{VRS} - SS_{VS} - SS_{RS} - SS_{NVR} - SS_{NVS} - SS_{NRS}\right) = SS_{NVRS}$	$\frac{SS_{NVRS}}{DF_{NVRS}} = V_{NVRS}$	$\frac{V_{NVRS}}{RESIDUAL}$
RESIDUAL	$(N-1) = DF_{RES}$	$\left(SS_T - SS_N - SS_V - SS_R - SS_S - SS_{NV} - SS_{NR} - SS_{NS} - SS_{VR} - SS_{VS} - SS_{RS} - SS_{VRS} - SS_{NVR} - SS_{NVS} - SS_{NRS}\right) = SS_{RES}$	$\frac{SS_{RES}}{DF_{RES}} = V_{RES}$	
TOTAL		$\left(\sum X_T^2 - \frac{\sum X_T^2}{N_T}\right) = SS_T$		

Figure 26.- Analysis of Variance Calculation.