EVALUATION OF A SUPPLEMENTARY AUDITORY DISPLAY IN A DUAL AXIS COMPENSATORY TRACKING TASK

by

PITU BHAGWANDAS MIRCHANDANI

B.S., University of California, Los Angeles, 1966

M.S., University of California, Los Angeles, 1967

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Signature of Author ....
Department of Aeronautics and Astronautics

Certified by ....
Thesis Supervisor

Accepted by ....
Chairman, Departmental Committee on Graduate Students

just as a scientist will work wonders out of various applications of the law of nature, even so a man who applies the law of love with scientific precision can work greater wonders.

-- Gandhi

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ABSTRACT

This study was concerned with the evaluation of an auditory display technique in a dual axis compensatory tracking task. The auditory display was used as a supplement to a visual display.

Subjects were presented with two control tasks. The primary task was the control of an inertia plant (with dynamics represented by $1/s^2$). The secondary task was velocity control (dynamics represented by $1/s$). The errors for both the tasks were shown on separate visual displays. The object of the experiment was to investigate the effects on performance when the secondary task was supplemented with an auditory display. The auditory display consisted of a frequency-volume regulator: a positive error increased the volume and the pitch, and a negative error increased the volume but decreased the pitch. Two performance measures were obtained, the integral square errors (ISE) and the describing functions of the human operators.

Statistical analysis on the ISE performance measures indicated that when the secondary task was supplemented with the auditory display, there was an improvement in the performance of the secondary task at a .001 level of significance. The improvement in performance of the primary task was at a significance level of 0.1. The variance of the ISE performance measures, for both the tasks, decreased; this indicated a more consistent behavior with the auditory display.

The describing function analysis showed that supplementing the secondary task with an auditory display increased the gain of the human operator for this task. The describing functions for the primary task did not show any apparent changes.

Thesis Supervisor: Laurence R. Young

Title: Professor of Aeronautics and Astronautics

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CHAPTER 1

INTRODUCTION

1.1 Motivation and Background

This study is concerned with the evaluation and application of auditory display techniques in manual control. The study was undertaken to investigate whether the use of the auditory sensory modality could enhance a system which conventionally makes use of only the visual sensory modality of the human operator. Both the Human Engineering and Display Engineering aspects were considered in this study. The Display Engineering aspect was the consideration of the concept of the auditory display and the design of the particular display chosen. The Human Engineering aspect was its evaluation; that is, an investigation of how it effects the performance of the human operator.

It is apparent that for a single-axis task a visual display would be superior since the visual system gives better qualitative and quantitative knowledge of the state of the system in a tracking task. In fact, a recent study by Vinje and Pitkin[22*] showed that the performance

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* Superscripts refer to references listed at the end of the report.

on a single-axis single task is not improved when the visual display is replaced by an aural display or a combined visual-aural display. However, for multi-axis or multi-task situations this argument does not necessarily hold. Hence, a dual-task situation was considered. It is conceivable that in a dual-task situation using a different sensory modality for each task may give a superior performance than when the same modality is used for both the tasks.

One could think of several reasons why supplementing existing displays in multi-control tasks with an auditory mode would improve the system performance. Some of these are:

(1) The eyes have too many visual displays to handle. The cycle of switching attention from one visual display to another, focussing, reading and performing the appropriate control may take one to two seconds in a simple control task.[14] Consider the case of two displays in a dual-task situation, for example, in an aircraft, the artificial horizon for pitch and the heading indicator for yaw control. Once the operator transfers his gaze from one display to the other, it could take several seconds before he could update the control for the first display. This substantial amount of time may be critical in some situations.

(2) Visual displays could sometimes compete for the attention of the operator and this could lead to a reduction of effectiveness. For example, in VFR flying conditions,

visual displays in the aircraft are used to compliment direct visual contact. However, if the pilot pays too much attention to any one instrument, he would deteriorate his performance.

(3) In certain situations one is unable to get a quantitative measurement using a visual display, while a significant quantitative measurement may be helpful for smoother operation. For example, when the eyes already have many visual signals to handle, a warning light (an on/off light, which conveys only binary information) is sometimes used to display a certain state of the system. If the operator would like to have a somewhat quantitative, though not necessarily precise, knowledge of the state, without major interference with concurrent visual displays, a non-visual display may prove more helpful.

(4) Sometimes the visual processes of the operator are hampered due to physiological factors and visual displays lose their effectiveness in such cases. For instance, in a high g or vibration environment the visual system is effected and hence, non-visual displays could be more effective.

(5) Since auditory cues provide another sensory dimension[14] the information retrieval rate obtainable from a combined audio-visual display may exceed that obtainable from a visual display. Even if the human operator is considered as a single-channel information processor,[7,18] aural cues could increase the information transmission rate provided the channel capacity is not already filled.[24]

There have been a number of investigations carried out on human performance in multi-display situations and in response to multiple stimuli, specifically to audio-visual stimuli.

It has been observed that human information processing rates are additive upon addition of other displays until a limit of total information rate is reached.[24] It has also been observed that information retrieval can be increased by using many separate stimulus dimensions (for example, in visual stimulus some of the dimensions could be color, intensity and position) with relevant information grossly quantitized along each dimension.[14,25] Hence there is reason to believe that by using another sensory modality more dimensions could be included in the total display system. Using two sensory modalities which apparently complement each other and do not interfere with each others' usefulness for information retrieval would probably improve system performance.

A study by Wargo, Kelly, Prosin and Mitchell[23] indicated that both the muscle action potential (from the arm) and the hand/switch disjunctive reaction times were faster with combined visual-auditory displays than with visual or auditory displays only. They also noted that responses to the auditory display were not, as expected, faster than the responses to the visual display.

Auditory stimulus has one advantage over visual stimulus, in that it gives the human operator a greater capacity to retrieve peripheral information. By this it is meant that visual stimulus requires the stimulation to be in the field of view of the operator, while the auditory stimulus can be located anywhere in the proximity of the operator. Hence a distinct possibility exists for the utilization of the peripheral information transmission quality of the auditory stimuli in manual control tasks where minimum attention display techniques are essential. Also in connection with this property of auditory stimulus, aural displays provide an approach to fulfill the need for head-up displays, a need that is clearly recognized.

Previous attempts have been made for utilization of auditory stimulus in manual control situations. DeFlorez[4] (1936) and later Forbes[8] (1945) investigated auditory signals for instrument flying and designed auditory displays to replace visual ones. Although auditory displays could be followed, the performance was generally inferior to that when visual displays were used.

A more complete study on auditory displays was reported by Katz et al (1966).[11] They studied aural displays for two types of tasks, target detection tasks and tracking tasks. In the experiments on target detection, subjects, while concurrently involved in visual tracking, showed significant improvement in detection performance when the target was displayed by an auditory or an auditory-visual display, as compared to that when the target was displayed by a visual display. In their experiment on aural cues for tracking, performance using visual displays was compared with performance using auditory displays. They were not able to show significant changes. Their comparison was based mainly on various error scores and no attempt was made to evaluate the changes in human operator dynamics for the two conditions. They also did not examine the possibility of using auditory displays to complement the visual displays rather than replace them.

The above discussion suggests that a good possibility exists in multi-task situations, for an appropriate auditory display that could complement (not replace) the existing display systems and make present systems more efficient.

1.2 Scope of Research

This study is concerned with the evaluation of a combined auditory-visual display technique in dual-axis compensatory control tasks. It is applicable in a typical situation where the human operator has two independent control tasks and two displays indicating the state of the two control systems. Preliminary experiments showed that if only an auditory display was used for the secondary task the performance was inferior to the performance when a visual display was used. However, when the secondary task employed a combined auditory-visual display, an improvement in performance was apparent.

This study attempts to quantify this improvement in performance and to investigate the confidence with which one could expect an improvement. It also attempts to examine the change in the dynamical characteristics of the human operator which produces this improvement.

The experiments were performed at the Man-Vehicle Laboratory at M.I.T.. Chapter 2 presents the description of all the facets of the experiments. The analysis of the experimental data and the results are included in Chapter 3. The conclusions from this research effort and areas of further research are presented in Chapter 4.

CHAPTER 2

EXPERIMENT

2.1 Apparatus

The equipment consisted of a general purpose hybrid computer facility, two oscilloscopes which were used as displays, a tape recorder, a chart recorder for recording data, and two joy sticks.

The digital computer of the hybrid computing facility is a PDP-8 computer, built by Digital Equipment Corporation.[5] The analog portion of the hybrid computer consists of a general purpose 290T analog computer built by GPS Instrument Company.[9] A more detailed description of the hybrid computing facility can be obtained from reference 21.

The two oscilloscopes used were the Tektronix Type 531 (for the secondary task) and the Dumont Type 304 (for the primary task). The tape recorder on which the random inputs were recorded was an FM magnetic recorder/reproducer (a Precision Instrument tape recorder PS-207A with 7 channels). The chart recorder was a Brush Mark 240 Recorder with four channels.

2.2 Experimental Set-up

The subjects were presented with two concurrent compensatory manual control tasks. The primary task was the control of a second order plant (an inertia plant with dynamics represented by $1/s^2$ in

Laplacian notation). A fixed initial condition on the state of the system (both in velocity and in position) was presented to all the operators. Their task was to bring the state of the system to zero and keep it there. The position of the plant was represented by a vertical line on the screen of the oscilloscope. The oscilloscope was placed on the right hand side of the experimental set-up. The control was a spring restrained joy-stick which moved about a horizontal axis and in a direction compatible with the display. Moving the joy-stick to the left increased the acceleration to the left and moving the joy-stick to the right increased the acceleration to the right. The plant was continuously disturbed by a random input and the operator had to continuously control the system in order to keep it at null position. The random input was previously recorded on a tape recorder. It consisted of a sum of sixteen sinusoids. This was not a true random input, because for a finite number of sinusoids there is a finite period of oscillation in the resulting function. However, it could be considered as a pseudo-random input due to the fact the operator cannot predict the input. References 10 and 20 discuss the use of sinusoids to simulate random-appearing signals having Gaussian amplitude distributions. Appendix A gives a description of the random input.

The secondary task was the control of a first order plant (velocity control with dynamics represented by $1/s$) also being disturbed by a similar pseudo-random input. The inputs for the two tasks were separate and not in phase. The subjects had to keep the state of the system at zero. The display was a horizontal line on the screen of the oscilloscope.

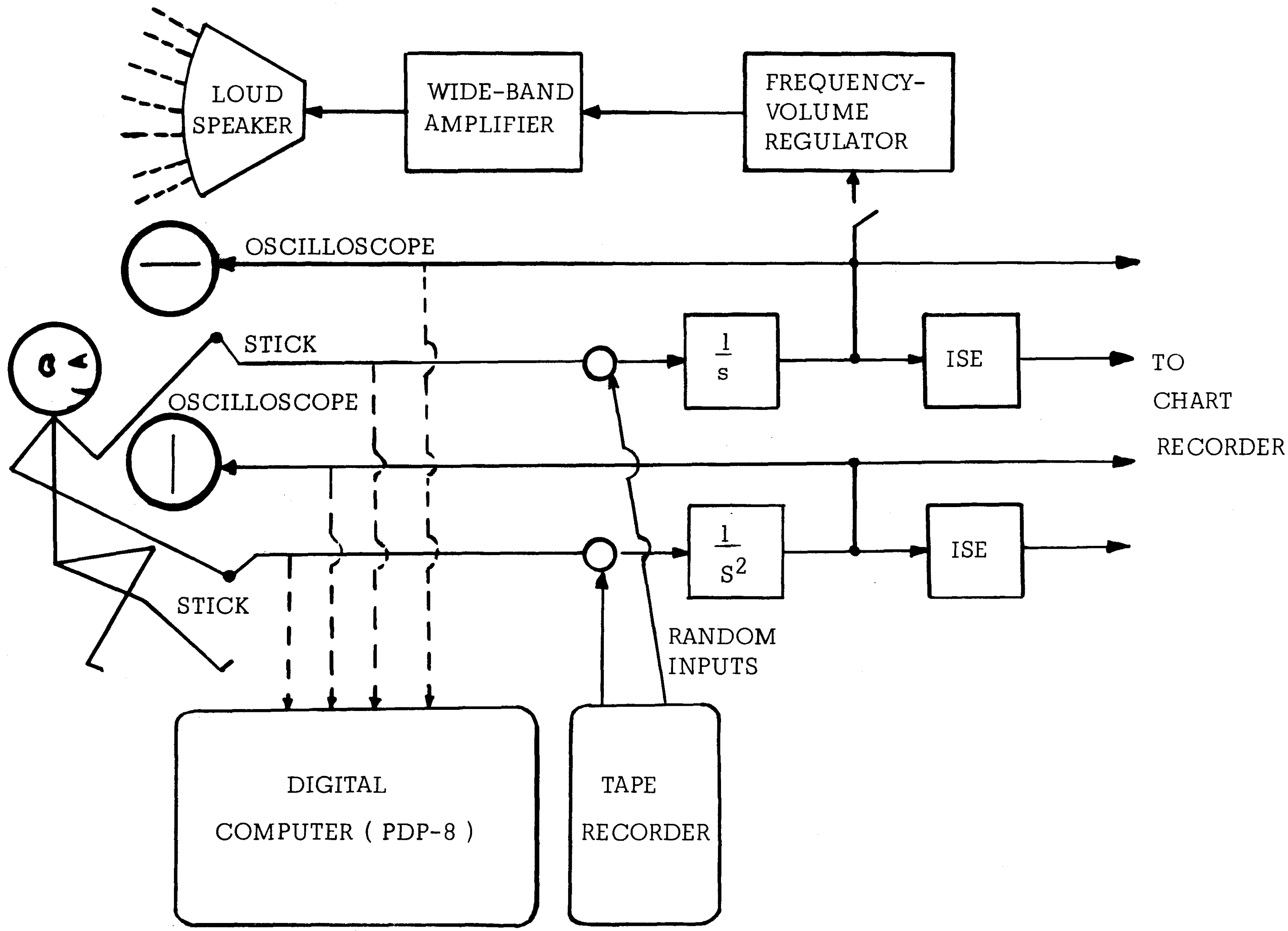


FIGURE 1. Schematic Diagram of Experimental Set-up

The oscilloscope was placed on the left hand side of the experimental set-up. The control was a joy-stick which moved about a horizontal axis in a direction compatible with the display, (i.e. similar to the primary task but in an orthoganal direction). The display was supplemented with an auditory display (which is explained later in this section), when the combined auditory-visual display was being tested.

The centers of the displays were approximately 18 inches apart and the subject's eyes were approximately 30 inches from the displays. The sensitivity of the oscilloscopes was set such that the subjects used the full screen of the oscilloscope, (approximately two inches from both sides of the center line).

A schematic diagram of the experimental set-up is shown in Figure 1. The analog programs for the simulation of the two plants are given in Appendix B.

In some preliminary experiments three types of auditory systems were evaluated in order to obtain an appropriate one for this experiment. The first type was a frequency regulating system. The null position corresponded to a reference frequency of 1000 Hz. This frequency was chosen as a compromise between getting an effect of the sound coming from a large general direction and having a high auditory sensitivity to changes in pitch.[17] A positive error increased the pitch and a negative error decreased the pitch. The second type of system that was tested was a volume regulating system. A deviation in either direction from the null position increased the volume of a fixed frequency. The fixed frequency was set at 1250 Hz because at this frequency a normal subject has a feeling of the sound coming from a large general direction rather than from a fixed direction. In other words, localization is low at this frequency. The null position corresponded to zero volume (no sound). The third type of system that was tested was a combined frequency-volume regulating system. The null position corresponded to a reference frequency of 1250 Hz. The reference volume was set a little above the threshold such that this gave the maximum volume sensitivity. A positive error increased the volume as well as the pitch. A negative error increased the volume but decreased the pitch. It was found in the preliminary experiments that the third type of display was superior. The fact that the third type of display combines the modes of information obtained from the first two types of displays could explain its superiority. The block diagrams and the analog diagrams of the auditory display system used in the experiment are also given in Appendix B.

2.3 Procedure

Four graduate students were used as subjects. They had no apparent visual or hearing defects. They were all right-handed. They all had previous training in this type of experiment, and were, in fact, well motivated and good operators. Before taking actual data, the subjects were given training sessions until they became quite skillful in these particular tasks. These training sessions lasted for approximately an hour a day per subject for a period of about a week. (Some subjects were already expert in these tasks and did not require much additional training.)

Before each test session warm-up runs were conducted. Warm-up was discontinued when the subject felt that he was performing "as best he could", and when the integral square error (ISE) performance measure (explained later) had approximately reached a plateau and was not improving much more.

Each test was run for 128 seconds. For analysis purposes, to minimize the effects due to learning, the tests for the visual display and the combined visual-auditory display were run in random order. The subjects were allowed to rest after each run. Over a period of three weeks, each subject was tested ten times, five times with visual display only, and five times with combined audio-visual display.

The instructions given to the subjects were:

> "You are given two plants to control. Your task is to keep the lines at the zero position indicated on the oscilloscopes."
>
> "The control of the plant on your right is your primary task. It is an inertia plant." (The subjects were familiar with the control system terminology.) "When you move the joy-stick on your right side to the right, the vertical line on the oscilloscope will get an acceleration towards the right, and when you move the stick to the left, the line will get an acceleration towards the left."
>
> "The control of the plant on your left is your secondary task. It is a velocity control system, with dynamics represented by $1/s$. When you move the joy-stick on your left forward, the horizontal line on the oscilloscope will get a velocity upwards, and when you move it backwards, the line will get a velocity downwards."
>
> "In some of the runs, your secondary task will be supplemented by an audio signal; you will be told ahead of time when this happens. When the horizontal line goes

above the null position, the volume and the pitch of the audio signal will increase, and when the horizontal line goes below the null position, the volume will increase and the pitch will decrease."

"Your performance will be monitored all the time so try to keep the lines as close to the null position as possible. Good luck."

2.4 Data Taking Systems

Two types of data systems were used to obtain two types of performance measures. One of the performance measures was the integral of squared error (from here on denoted as ISE); thus a lower ISE indicates a better performance. The errors in both the plants, and the time integral of the squared error on both the plants were recorded simultaneously on a chart recorder. At the end of every run the teletype of the digital computer clicked and the run was ended. From the chart recorder one was able to obtain the ISE's of both the plants for the last 128 seconds of the run. A sample of the data obtained from the chart recorder is shown in Figure 2, explaining the various factors on it.

The other type of performance measure was the measure of the describing function of the operator. The four appropriate signals, the two inputs to the operator (displayed error) and the respective operator outputs, were sampled at four times per second and stored in the memory buffer of the digital computer. At the end of every run these samples were transformed by the DECUS (Digital Equipment Computers Users Society) 8/143 Fast Fourier Transform program. This enables one to compute the frequency spectrum of a time series of a signal. A detailed explanation of Fast Fourier transforms is available in reference 2. Once

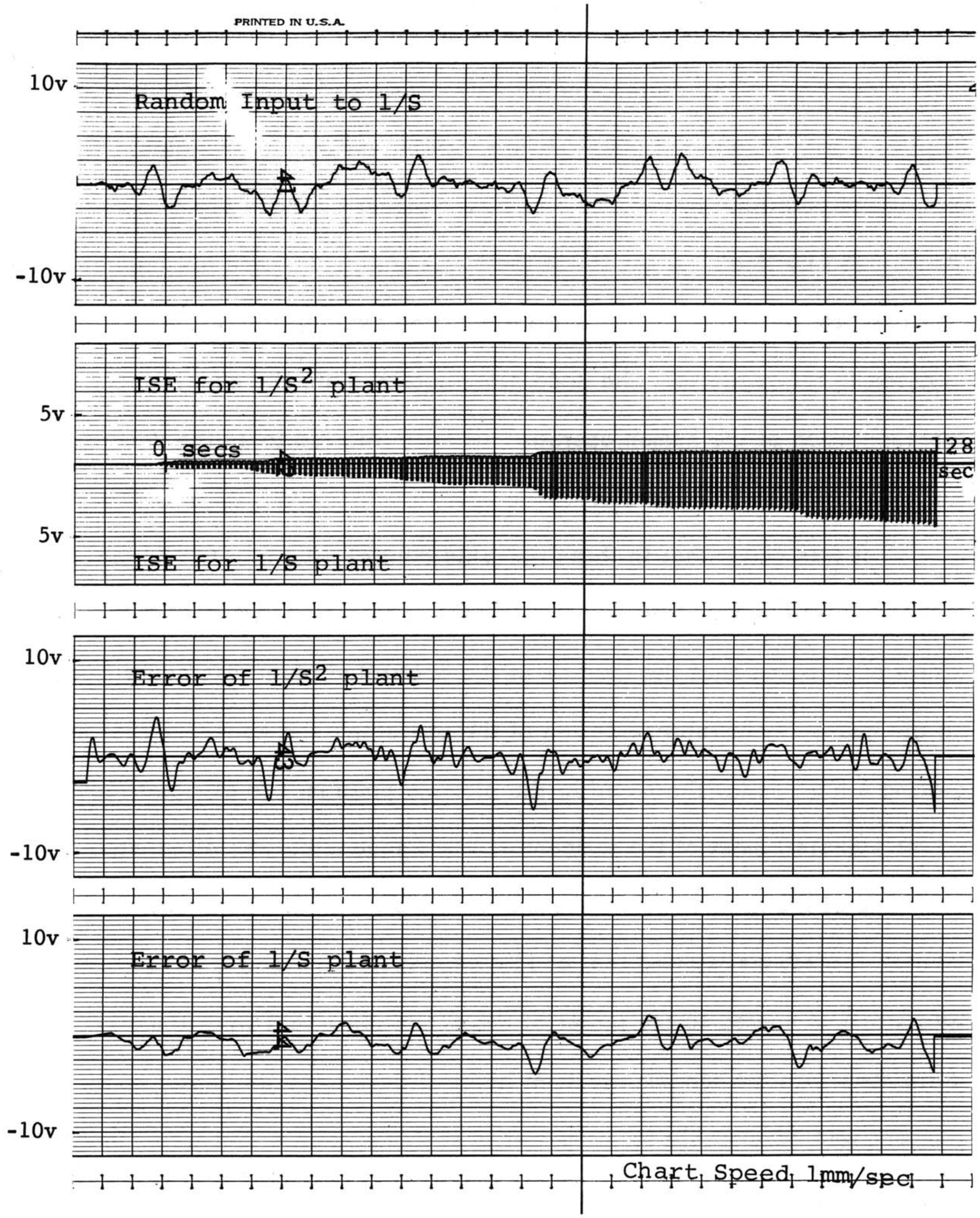


FIGURE 2. Sample of Data from Chart Recorder
(Subject NV, Run No. 2, without audio)

the frequency spectrum of the signals is obtained, one is able to obtain Bode plots for the two corresponding sets of output/input, by plotting the amplitude ratios, and the phase differences at various frequencies. This process of obtaining transforms and then plotting the Bode plots has been mechanized by Noel Van Houtte of the Man-Vehicle Lab and his program was used for the experiment. A more detailed explanation of the program is given in reference 21. The Bode plots obtained are the quasi-linear representation of the human operator, usually referred to as the describing function of the human operator.

It was noted that in this dual-axis control situation the human operator introduced a good deal of remnant at the higher frequencies. The effect of this was that the inverse of the controlled plant was superimposed on the quasi-linear representation of the operator (see Appendix D). By setting a high power threshold in the plotting program (to eliminate low power signals) most of the remnant at low frequencies was eliminated, but some of the high frequency remnant still prevailed. Print-outs of the Fourier Transforms showed that at low frequencies the power of the remnant was small compared to the power of the components that were linearly correlated with the random input; at higher frequencies the power of the remnant was comparable to the power of the components that were linearly correlated with the random input.

Because of the way in which the remnant is defined,[12] only the component of the operator's output that was linearly correlated with the random input was considered in obtaining the quasi-linear representation of the operator; that is, only the frequency components corresponding to the frequency components of the random input were considered. An example of a typical describing function thus obtained is illustrated in Figure 3. Some of the describing functions obtained were checked against those obtained using actual Fourier Transform print-outs; there were no discernible differences. Some theoretical considerations and errors due to the Fourier Transform method of obtaining describing functions are discussed in Appendix D.

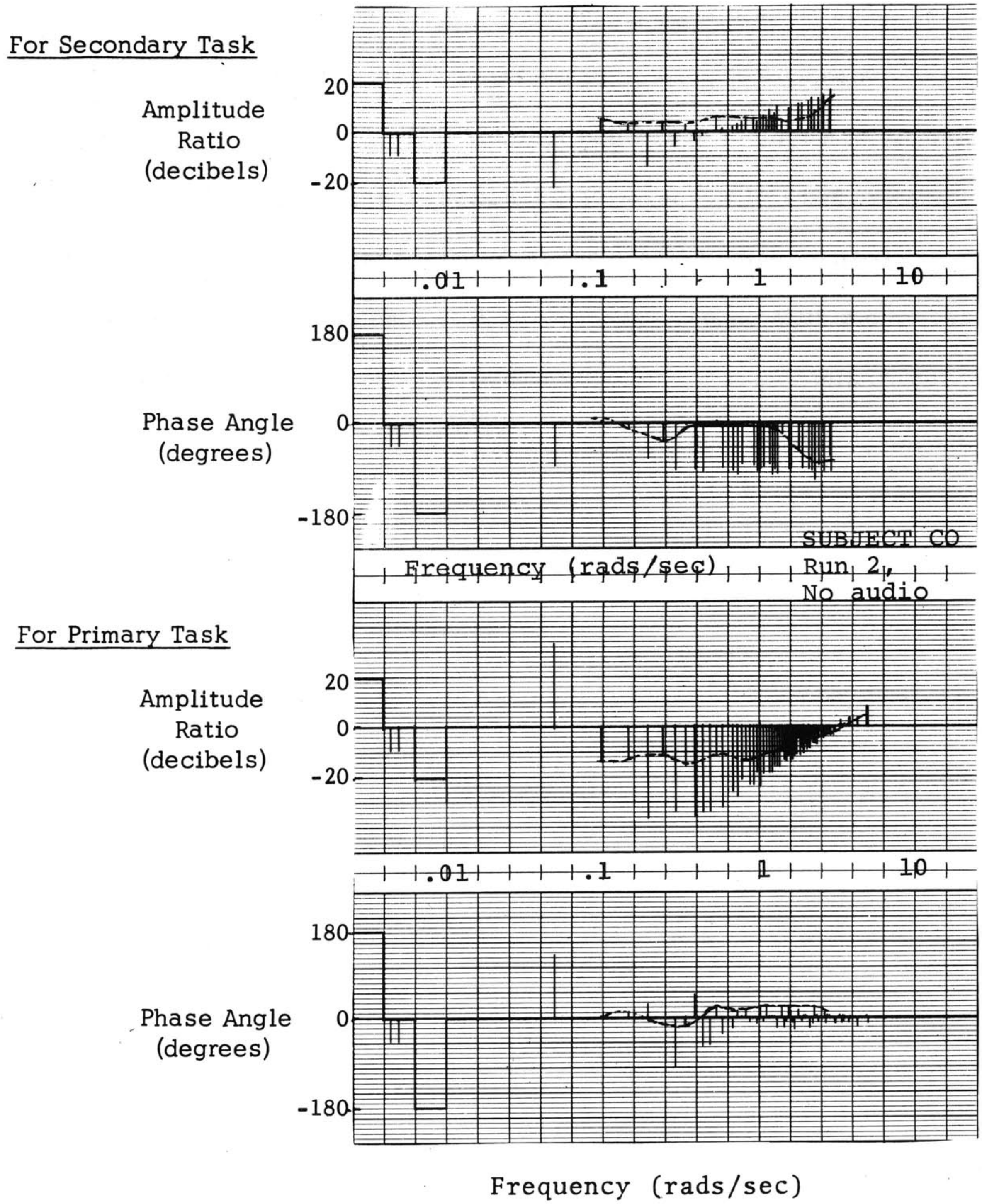


FIGURE 3. Sample of a Mechanized Bode Plot
(Subject CO, Run No. 2, without audio)
The points not used on the frequency plots are due to the remnant; i.e. they occur at frequencies other than the input frequencies.

CHAPTER 3

ANALYSIS AND RESULTS

3.1 Statistical Analysis of ISE Performance Measures

A statistical analysis was performed on the ISE scores of the subjects to examine the influence of the auditory display. Since the two conditions, one with an audio display and one without an audio display, were presented in random order, most of the effects due to the order of presentation, and the short term learning effects were eliminated. Thus a randomized block design statistical analysis was applicable. The data of the ISE scores are summarized in Appendix F.

The means and variances for each plant and for each subject were calculated for the two conditions (with audio display and without audio display). The digital program ME-VA was used for this purpose (see Appendix C for details). The results are presented in Tables 1 and 2. It can be noted that except for one subject, the mean of the ISE scores decreased (that is, the performance was improved) for both the primary task and the secondary task, when the secondary task was supplemented with an audio display.

Another interesting observation one can make from each subject's data is that in all the cases the variance of the ISE scores decreased

FOR THE PRIMARY TASK

SUBJECT	WITHOUT AUDIO MEAN	WITHOUT AUDIO VARIANCE	WITH AUDIO MEAN	WITH AUDIO VARIANCE	t	SIGNIFICANCE LEVEL
DM	13.64	6.89	14.90	4.55	-0.83	NS
CO	9.44	13.29	3.92	5.93	2.82	.05
NV	4.10	12.80	3.40	4.68	0.38	NS
MG	6.90	11.30	5.20	1.70	1.06	NS

TABLE 1. The means and the variances of the ISE scores and the t values between the means for each subject for the $1/s^2$ plant.

FOR THE SECONDARY TASK

SUBJECT	WITHOUT AUDIO MEAN	WITHOUT AUDIO VARIANCE	WITH AUDIO MEAN	WITH AUDIO VARIANCE	t	SIGNIFICANCE LEVEL
DM	13.24	52.71	3.38	1.66	2.99	.02
CO	13.90	23.30	3.54	3.48	4.48	.01
NV	8.72	34.55	5.30	2.20	1.26	NS
MG	13.00	49.00	5.20	5.70	2.36	.05

TABLE 2. The means and the variances of the ISE scores and the t values between the means for each subject for the $1/s$ plant.

when the secondary task was supplemented with an audio display. This would imply that the subjects tended to be more consistent when they continuously received audio information on the state of the secondary control system.

Three statistical tests were used for further analysis of the data in order to make as many conclusions as possible from the data, and to compare the results obtained by the various techniques. The three tests were the standard t-test, the t-test for correlated means and the analysis of variance.

Firstly, statistical t-tests were performed for each plant and each subject so that the means of the two performance measures (with audio display and without audio display) could be compared. Using the means and the variances obtained earlier, the t-values were computed by the digital program VA(T), (also in Appendix C), which calculates t values for independent samples. The significance of each of the t values was obtained from the t-tables.[3] The summary of the results for the $1/s^2$ plant is given in Table 1 and for the $1/s$ plant in Table 2.

Although there was an average improvement in performance in controlling the $1/s^2$ plant when the secondary task was supplemented with an audio display, (the average percentage decrease in the ISE value of the primary task was 23%), only one of the four subjects showed an improvement at the .05 level of significance. However, in the case of the performance on the secondary task, three of the four subjects showed significant improvement when the secondary task was supplemented with an audio display. The minimum percentage decrease in the ISE value for the secondary task was 40% (for subject NV) and the maximum decrease was 75% (for subject DM). The average percentage decrease in the ISE value for the secondary task was 62%.

Since the performance on each test depends on the subject, the samples for the analysis are not independent. In other words, for each subject, the means for the two conditions are correlated. Hence, to see whether the two tested conditions, with audio display and without audio display, differ significantly in performance on the average, the t-test for correlated means[15] was used. This test entails the comparison of the differences between the two conditions by performing the t-test on the differences between the means of the performance for the two conditions. The calculations and the results of this test are given in Tables 3 and 4.

From Table 3, it can be seen that the t-test for correlated means shows that there is no significant change in the performance on the primary task when the secondary task is supplemented with an audio display. However, the test shows that at the significance level of .02 there is an improvement in the performance of the secondary task when it is supplemented with an audio display (see Table 4).

Finally, an analysis of variance (or the F-test)[3,15] was

FOR THE PRIMARY TASK

SUBJECT	WITHOUT AUDIO	WITH AUDIO	D*	d**	d^2
DM	13.64	14.90	-1.26	-2.93	8.58
CO	9.44	3.92	5.52	3.85	14.80
NV	4.10	3.40	0.70	-0.97	0.94
MG	6.90	5.20	1.70	0.03	0.01
TOTAL			6.66		24.33

Mean of Difference, ($\overline{D}$) = 6.66/4 = 1.67
Estimated Variance of Difference = 24.33/3 = 8.11
Estimated standard error of the mean difference = $\sqrt{8.11/4}$ = 1.425
Value of t = 1.67/1.425 = 1.17 with 3 Degrees of Freedom (DF)
Therefore significance level = NS (no significance)

* D denotes the difference of the means
** d denotes the deviation from the mean difference

TABLE 3. t value for the differences between the performances on the primary task for the two conditions.

FOR THE SECONDARY TASK

SUBJECT	WITHOUT AUDIO	WITH AUDIO	D*	d**	d^2
DM	13.24	3.38	9.86	2.25	5.05
CO	13.90	3.54	9.36	1.75	3.06
NV	8.72	5.30	3.42	-4.19	17.55
MG	13.00	5.20	7.80	0.19	0.04
TOTAL			30.44		25.70

Mean of Difference, ($\overline{D}$) = 30.44/4 = 7.61
Estimated Variance of Difference = 25.70/3 = 8.57
Estimated standard error of the mean difference = $\sqrt{8.57/4}$ = 1.465
Value of t = 7.61/1.465 = 5.2 with 3 Degrees of Freedom (DF)
Therefore significance level = .02

* D denotes the difference between the means
** d denotes the deviation from the mean difference

TABLE 4. t value for the differences between the performances on the secondary task for the two conditions.

performed on the ISE scores. The analysis of variance is a more powerful standard statistical test which enables one to test whether a difference between two or more sample means is significant. The digital program ANVA was used for this purpose. Appendix C briefly discusses this statistical test and the program ANVA.

The results of the analysis are given in Tables 5 and 6. The top part of the tables gives the data on which the analysis was performed. The parameter groups for the analysis were subjects, runs and tests. In the tables DF denotes the degrees of freedom, SS denotes the sum of squares, VE denotes variance estimate of each parameter group, and VR denotes the variance ratio. The numbers given below the headings SUBJECTS, RUNS, TESTS, are the means of the quantities taken in order. For example, the first entry under SUBJECTS in Table 5 is 14.3 and this is the average ISE score subject DM had for his performance on the primary task. The numbers given at the bottom are the estimates of the standard errors of the difference between the means of any two values of the parameter given in the brackets. For example, EV(S) is the estimate of the standard error of the difference between the means of any two subjects.

From the results of the performance on the primary task (control of $1/s^2$ plant), the only parameter for which there was a significant difference was 'SUBJECTS'. The variance ratio (VR) for the subjects turned out to be 29.54, and with 31 degrees of freedom for the residuals

RUN		WITHOUT AUDIO DM	CO	NV	MG	WITH AUDIO DM	CO	NV	MG
1	=	14.50=	5.70=	1.00=	4.00=	13.00=	3.00=	1.50=	6.00
2	=	9.00=	11.00=	2.00=	3.00=	14.00=	1.60=	3.50=	5.00
3	=	14.60=	15.00=	2.00=	11.00=	18.50=	4.00=	1.00=	6.00
4	=	15.50=	7.50=	9.50=	9.00=	15.00=	8.00=	5.00=	6.00
5	=	14.60=	8.00=	6.00=	7.50=	14.00=	3.00=	6.00=	3.00

SOURCE	DF		SS		VE		VR
SUBJECTS	3	=	625.30	=	208.43	=	28.45
RUNS	4	=	78.29	=	19.57	=	2.67
TESTS	1	=	27.72	=	27.72	=	3.78
RESIDUAL	31	=	227.16	=	7.33		
TOTAL	39	=	958.47				

	SUBJECTS		RUNS		TESTS
=	14.3	=	6.1	=	8.5
=	6.7	=	6.1	=	6.9
=	3.8	=	9.0	=	0.0
=	6.1	=	9.4	=	0.0
=	0.0	=	7.8	=	0.0

EV(S)= 1.21
FV(R)= 1.35
FV(T)= 0.86
*

TABLE 5. RESULTS OF ANALYSIS OF VARIANCE FOR THE PRIMARY TASK

	WITHOUT AUDIO				WITH AUDIO			
RUN	DM	CO	NV	MG	DM	CO	NV	MG
1 =	25.00=	6.50=	6.30=	6.00=	2.80=	1.50=	5.50=	4.00
2 =	15.50=	14.00=	3.80=	5.00=	2.10=	2.20=	7.00=	2.00
3 =	9.70=	15.00=	3.50=	18.00=	3.00=	5.50=	3.00=	8.00
4 =	8.00=	14.00=	14.00=	20.00=	5.50=	5.50=	5.00=	7.00
5 =	8.00=	20.00=	16.00=	16.00=	3.50=	3.00=	6.00=	5.00

SOURCE	DF		SS		VE		VR
SUBJECTS	3	=	24.80	=	8.27	=	0.37
RUNS	4	=	72.36	=	18.09	=	0.81
TESTS	1	=	617.80	=	617.80	=	27.64
RESIDUAL	31	=	692.96	=	22.35		
TOTAL	39	=	1407.91				

	SUBJECTS		RUNS		TESTS
=	8.3	=	7.2	=	12.2
=	8.7	=	6.5	=	4.4
=	7.0	=	8.2	=	0.0
=	9.1	=	9.9	=	0.0
=	0.0	=	9.7	=	0.0

EV(S)= 2.12
EV(R)= 2.36
EV(T)= 1.50
*

TABLE 6. RESULTS OF ANALYSIS OF VARIANCE FOR THE SECONDARY TASK

and 3 degrees of freedom between the subjects, this VR corresponded to a significance level of below .001 as seen from the F-tables.[3,15] The differences between tests and the differences between runs were at a significance level of only 0.1.

Using the estimates of standard errors, one was further able to examine the differences between any two values of a parameter by using the t technique as in Tukey's procedure.[15] In this procedure the means of the elements in a parameter group are arranged in ascending order and the adjacent means are compared for significance using the t-test. When this procedure is used for SUBJECTS it can be seen that subject NV was better in his performance in the primary task at a significance level of only 0.1 (t=1.9, DF=31), while subject DM was significantly worse, at a significance level of .001 (t=6.3, DF=31). This procedure did not show a significance difference between the runs, while it showed that the significance of the difference between the two tests was only 0.1 (t=1.85, DF=31). Hence, in this analysis, both the F-test and Tukey's technique showed that at a significance level of only 0.1 could there be seen an improvement in the performance of the primary task when the secondary task was supplemented with an audio display.

Table 6 shows the results of the analysis on the performance of the secondary task. From the results one can see that there is a significant difference in the performance between the two tests, while there seems to be no significant difference between the subjects and the runs. The variance ratio of 27.64, with 31 degrees of freedom for the residuals and 1 degree of freedom between the tests, corresponds to a significance level of .001 (as seen from the F-tables). Using Tukey's procedure to compare the difference between the means of the two tests, with audio and without audio, also shows a difference at a significance level of .001 (t=5.2, DF=31). Hence, in this analysis, both the F-test and Tukey's technique showed that the supplementation of the secondary task with an audio display improved the performance of the secondary task at a level of significance of .001.

In summarizing the important results of the statistical analysis of the experimental data, it is seen that

(1) the variances of ISE performance measures were decreased for both the tasks when the secondary task was supplemented with an auditory display

(2) the t-test for correlated means and the analysis of variance showed that the improvement in performance on the secondary task, when it was supplemented with an auditory display, was highly significant

(3) the analysis of variance showed that the supplementation of the secondary task with an audio display improved the performance of the primary task at a significance level of 0.1.

3.2 Describing Function Analysis

The sets of data points which construct the describing function were plotted on a single graph for each subject. A line was faired through the points. A sample of such a composite describing function is given on Figure 4. Appendix E gives all the composite describing functions for each subject.

Differences in the describing functions for the two conditions, without audio display and with audio display, were apparent only in the describing functions of the human operator in the secondary task. The describing functions for the primary task did not seem to be different for the two conditions. Enlarged graphs for the amplitude ratio plot and the phase angle plots of the describing functions of the operators in the secondary task are presented in Figures 5 - 8. These are exactly the composite describing functions given in Appendix E.

It can be seen from the describing functions of each subject that the gain of the human operator for the secondary task is increased with the addition of the audio cue. This increase of gain is more apparent at low frequencies. The approximate gains of the describing functions for the secondary task, for frequencies less than 1 radian per second, are listed in Table 7. It can be seen that the minimum increase of gain at the low frequencies was 5 decibels (that is, 1.8 times the gain when there is no audio display) and that increase was for subject NV. It is interesting to note that subject NV was the only subject for whom the standard t-test did not show a significant improvement in ISE

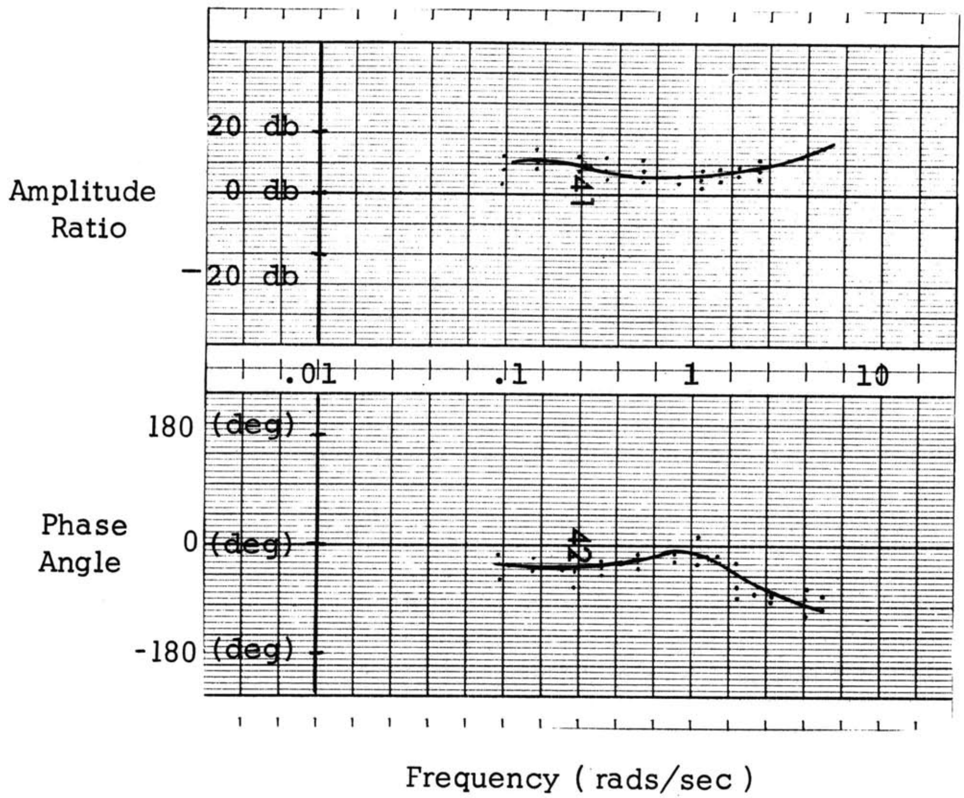


FIGURE 4. A Sample of a Composite Describing Function (The above is for subject NV in controlling the secondary task without an audio display.)

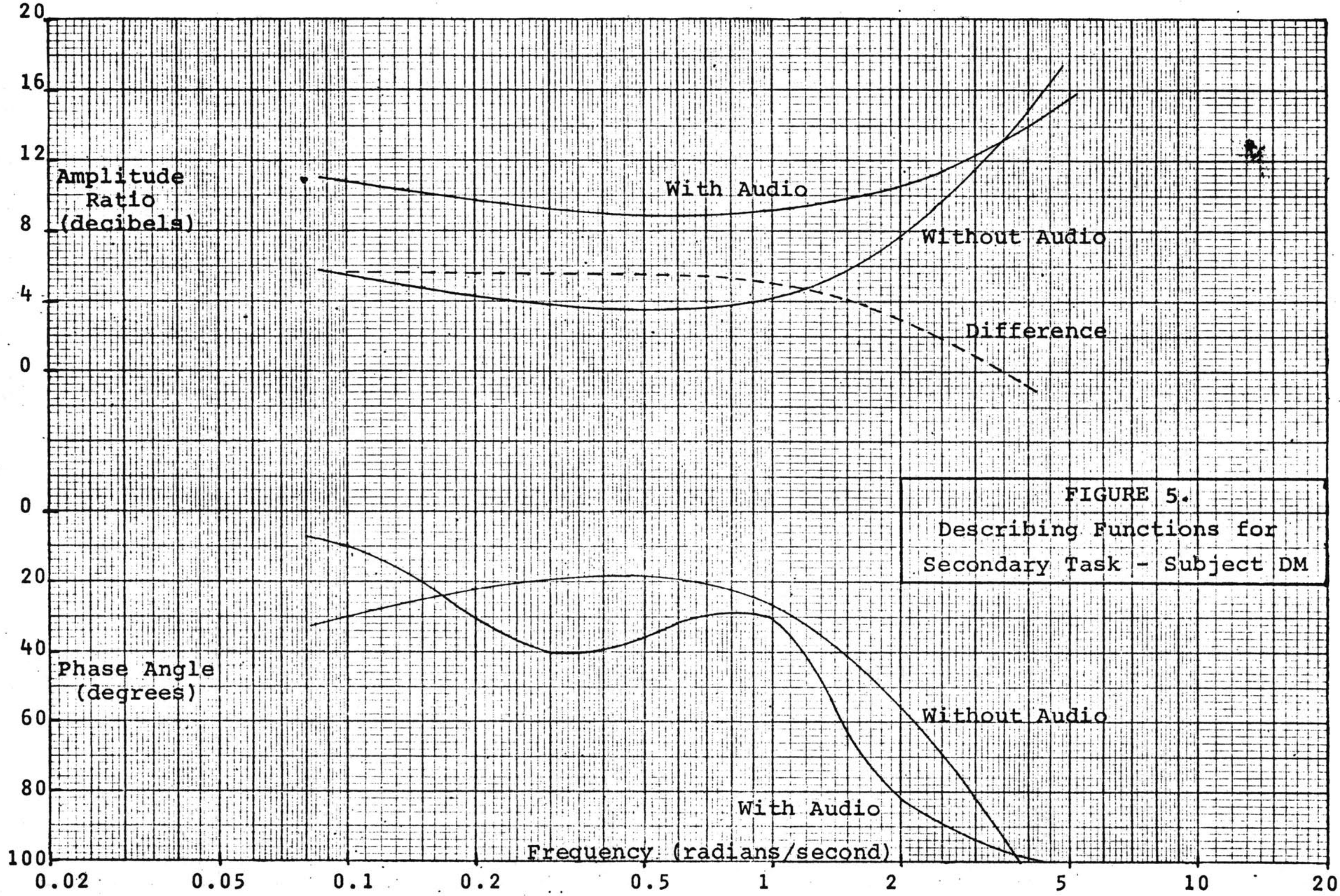


FIGURE 5.
Describing Functions for Secondary Task - Subject DM

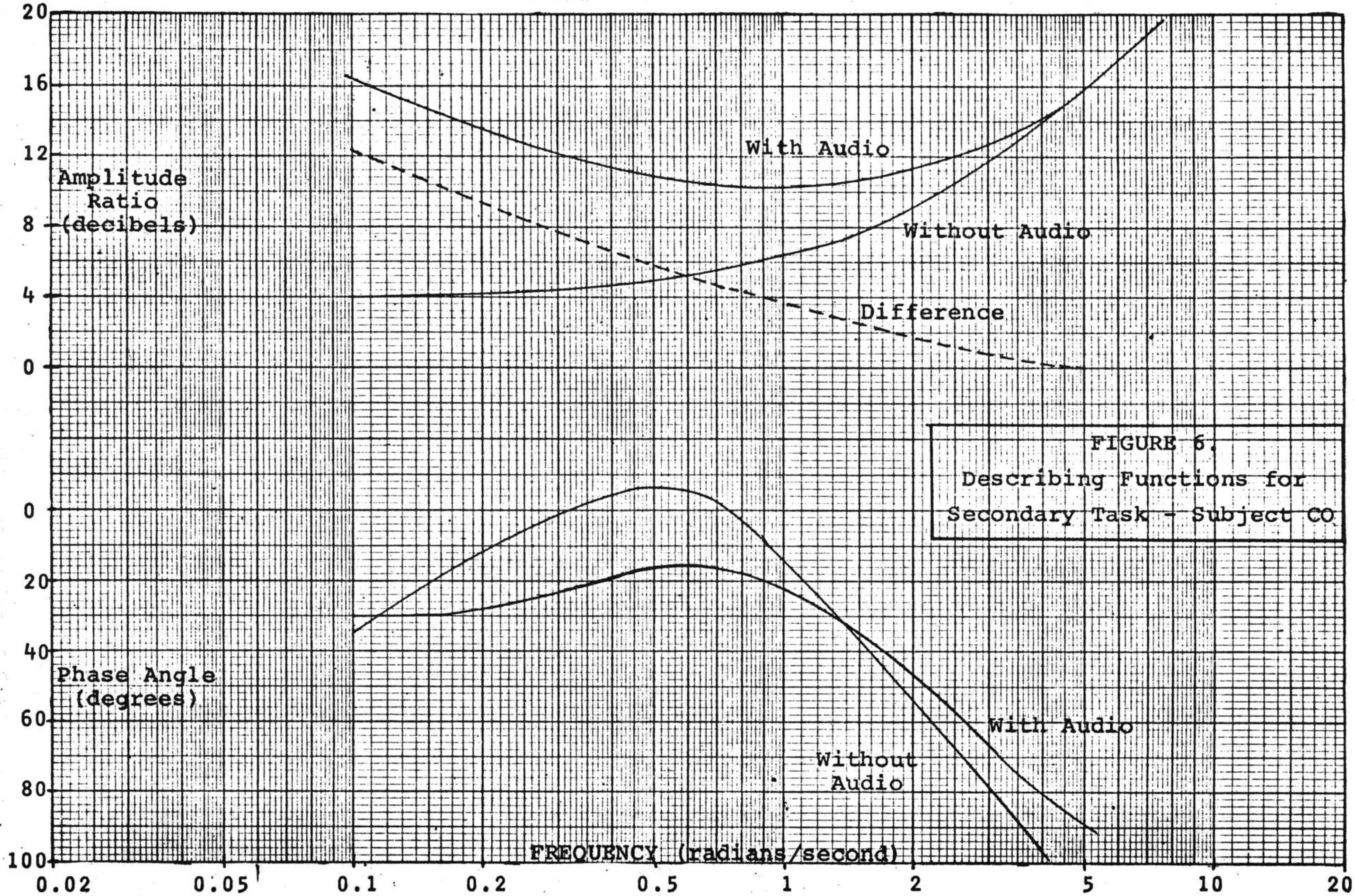


FIGURE 6.
Describing Functions for
Secondary Task - Subject CO

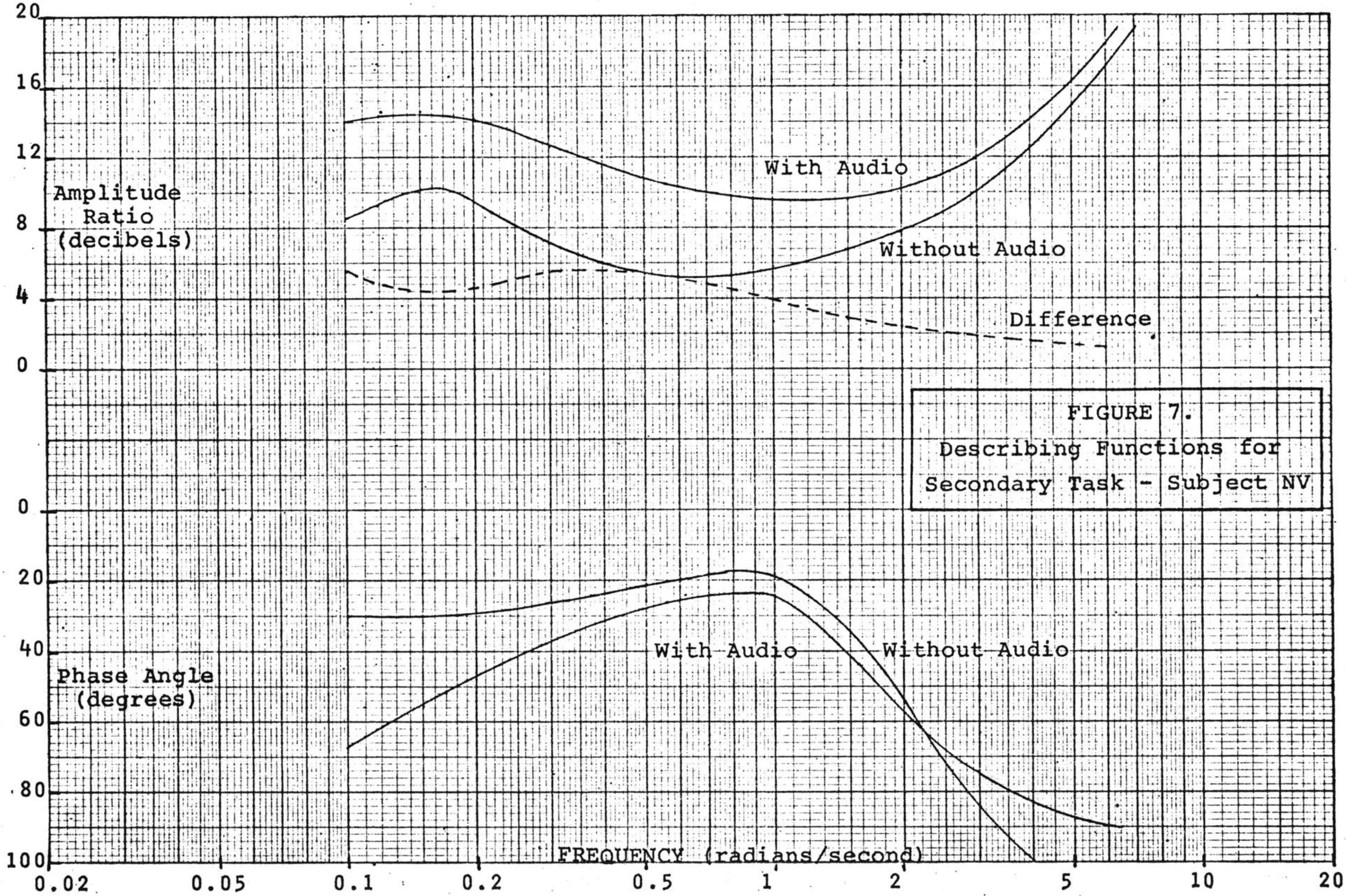


FIGURE 7.
Describing Functions for Secondary Task - Subject NV

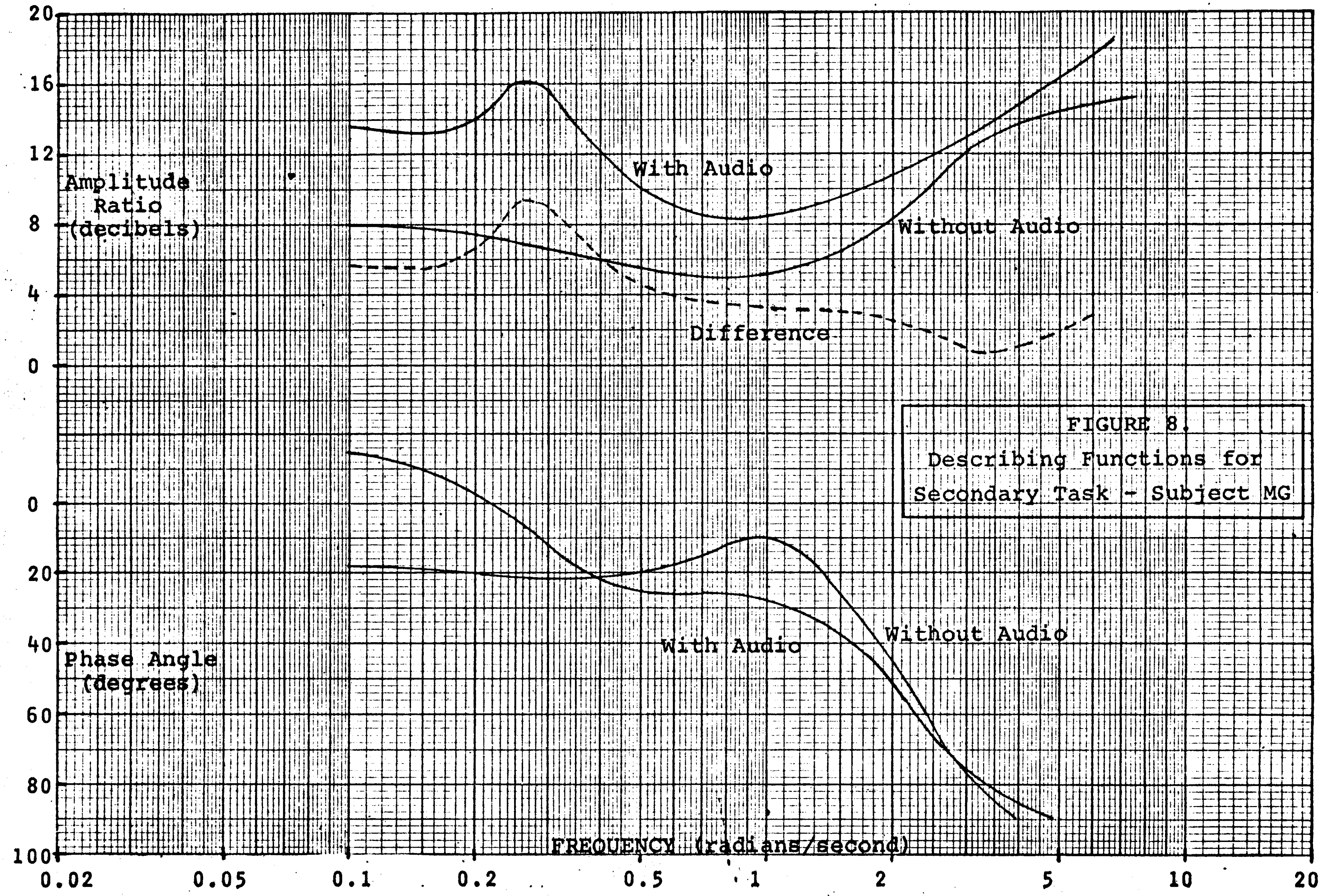


FIGURE 8.
Describing Functions for Secondary Task - Subject MG

performance measure of the secondary task when it was supplemented with an auditory display. The gains at higher frequencies are not included in the table because, for one thing, they did not seem to indicate a constant difference between the two conditions, and for another, as explained earlier (see also Appendix D), a greater amount of remnant at high frequencies makes the plots at high frequencies less reliable.

From basic control theory it can be shown that an increase in gain in the forward loop for such a system improves the performance of the system. More accurately, the time response of the system is improved. For example, if the gain is increased by a factor of two when the original gain is K, then the time response to a step input for the original system is $1-e^{-Kt}$ while the response for the system supplemented with the audio display is $1-e^{-2Kt}$.

SUBJECT	WITHOUT AUDIO	WITH AUDIO	DIFFERENCE
DM	4	10	6
CO	5	13	8
NV	7	12	5
MG	7	13	6

Table 7. Approximate Gains (in decibels) of the Subjects' Describing Functions for the Secondary Task, at Frequencies less than 1 radian/second.

This increase in gain could have been introduced at one or more of the several hierarchical levels of control in the operator/plant system. At the lowest level it could have been introduced at the display itself; the auditory system may have had a higher gain to changes of the state of the system. At a higher level, this increase in gain could have been due to the human operator having a greater sensitivity to changes in the audio signal than to changes in the peripheral visual signal. The increase in gain may have been introduced at still a higher level - in the Central Nervous System. Here there may have been a synergistical combination of the two nervous signals, one due to audio stimulation and the other due to the visual stimulation, to produce a higher gain in the overall control system. However, in this study it was not shown where the increase in gain was introduced; but it was shown that there was an increase in the overall gain of the describing function for the secondary task when it was supplemented with an audio display.

Two other interesting observations can be made from the describing functions for the secondary task. The first is that the effect of time delay of the human operator on the phase shift seemed to be decreased at the higher frequencies when the secondary task was supplemented with an auditory display. It can be seen that in the condition of visual display only, the operator time delay as approximated from the phase angle plots remains close to 0.5 seconds, while in the condition of audio-visual display the phase angle plots indicate a reduced phase shift for higher frequencies. This was observed for all the four subjects.

This effect on phase angle could be due to a decrease in time delay and/or an increase in lead compensation. The decrease in time delay could be explained by the fact that the operator does not have to shift his scan to the visual display of the secondary task before taking an action; as soon as the audio signal is heard the operator takes an appropriate action while he is shifting his scan to the visual display (if he has to). Consideration of the theory of human dynamics[16] could explain the increase in lead as a human operator equalization; since the human operator functions as a "good" servo system, an increase in gain would have to be accompanied by an increase in lead, otherwise instability or a very low phase margin may result. However, due to the high frequency remnant of the operators the quasi-linear representation becomes a less accurate representation of the human operator and the above explanations may not be valid; hence this change in the apparent time delay may be due to human operator non-linearities.

The other interesting observation is that the amplitude ratio plots of the describing functions for the secondary task seem to indicate a first order lead behavior with corner frequency close to 1 radian/second. This observation does not agree with the experimental results of McRuer et al[16] which show that the human operator behaves as a pure gain when controlling a 1/s plant. However, their study was performed for a single axis control task. The lead observed in this experiment may be due to the fact that in this experiment the operator had two axes to control and therefore, had to operate with much more constraint and precision.

It could also be due to human operator equalization as explained above. On the other hand, due to the high frequency remnant of the human operator this could be an experimental artifact and may be due to the inverse of the plant under control (see Appendix D).

Since there appears to be a great deal of high frequency remnant, the obtained quasi-linear representation may not be an accurate and appropriate representation of the human operator and hence one cannot be conclusive about the last two observations.

CHAPTER 4

CONCLUSIONS

Summarizing the important results of the experiment, it was found that the supplementing of the secondary task with an audio display,

(1) decreased the variance in the performance of both the tasks

(2) improved the performance of the secondary task at a significance level of .001, the average percentage decrease in the ISE value for the secondary task being 62%

(3) seemed to improve the performance of the primary task but only at a significance level of 0.1, the average percentage decrease in the ISE value for the primary task being 23%

(4) increased the gain of the quasi-linear dynamical representation of the human operator for the secondary control task in keeping with the error reduction considerations from basic control theory.

These results should indicate that the performance on multi-axis control systems, which require considerable operator training, would probably be improved when one or more of the secondary tasks are supplemented with an auditory display. These findings could have significant effect in present manual control systems. It is quite conceivable that supplementary audio displays in existing systems, such as, in airplanes

(especially helicopters and VTOL), in space maneuvers, in real time command and control systems, in monitoring systems, in dark environments, and in situations where the visual processes of the operator are hampered due to physiological factors, could improve the performance of the systems amd make them more efficient.

Further research in this area is important, in order to utilize the full capability of the human operator in processing peripheral information. Some of the problems that have to be answered are:

(1) What are the effects of an audio display on task interference? Does the supplementing of a single axis control with an audio display cause interference in the control task? Can one quantify the decrease in task interference, when the secondary task is supplemented with an auditory display, using the model of Levinson et al[13]?

(2) What are the exact effects on the describing function of the secondary task when it is supplemented with an audio display? How do those effects depend upon the secondary task, the primary task, and the auditory display?

(3) What is the quasi-linear representation of the human operator in a situation with only an auditory display? What are the possible connections between this representation, the representation for a visual display system (the ones which are now available), and the representation for a combined visual-auditory display system?

(4) Where in the human physiology is introduced the change in the dynamical characteristics of the human operator, when the human operator receives signals from two sensory modes?

APPENDIX A

THE RANDOM INPUT

A pseudo-random input was obtained from a combination of sinusoids in order to provide an input which was not to be predictable by the human operator.[10,20] The pseudo-random input was a sum of sixteen sinusoidal functions which were generated by the digital computer. The sixteen frequencies were prime number multiples of a basic frequency of 0.09525 radians/second. The prime numbers corresponded to 2,3,5,7,11,17,23,29,37,47,59,73,89,107,127, and 149. The amplitude of the first eight sinusoids was 1 volt and of the last eight sinusoids was 0.1 volt. The signal was stored on a tape recorder so that it could be used over and over again without going back to the digital computer to generate it each time it was needed.

A sample of the pseudo-random input is shown below. The digital program used to generate the pseudo-random input is available in reference 21.

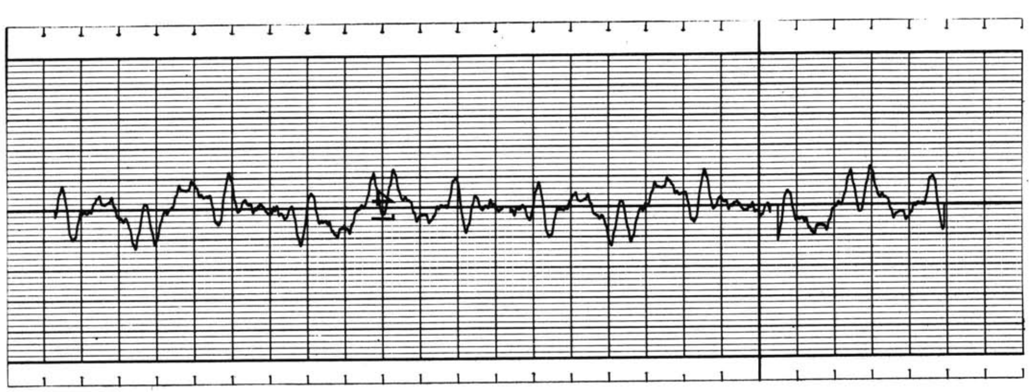
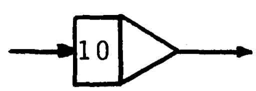
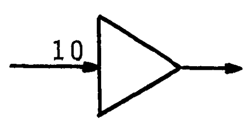
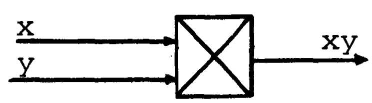


FIGURE A-1. Sample of Random Input from Chart Recorder (chart speed 0.5 mm/sec)

APPENDIX B

INSTRUMENTATION OF THE EXPERIMENT

The analog computer was the main equipment used in the instrumentation of the experiment. The two plants were simulated on the analog computer using integrators, amplifiers, and potentiometers. Figure B-1 gives the analog diagram of the simulation of the secondary task and Figure B-2 gives the simulation of the primary task. The various blocks are drawn with the usual notation, but for clarity, a table of analog components is presented below.

COMPONENT	NOTATION	REMARKS
Integrator		The number in the block indicates integration rate
Amplifier		The number by the input indicates the amplification factor (no number implies unity)
Potentiometer		The number in the block indicates the attenuation factor
Multiplier		

Notation for Analog Components

TABLE B-1

The inputs and outputs of the human operator were sampled periodically and stored in the digital computer via the A/D converters. By multiplying the error by itself, the square of the error was obtained.

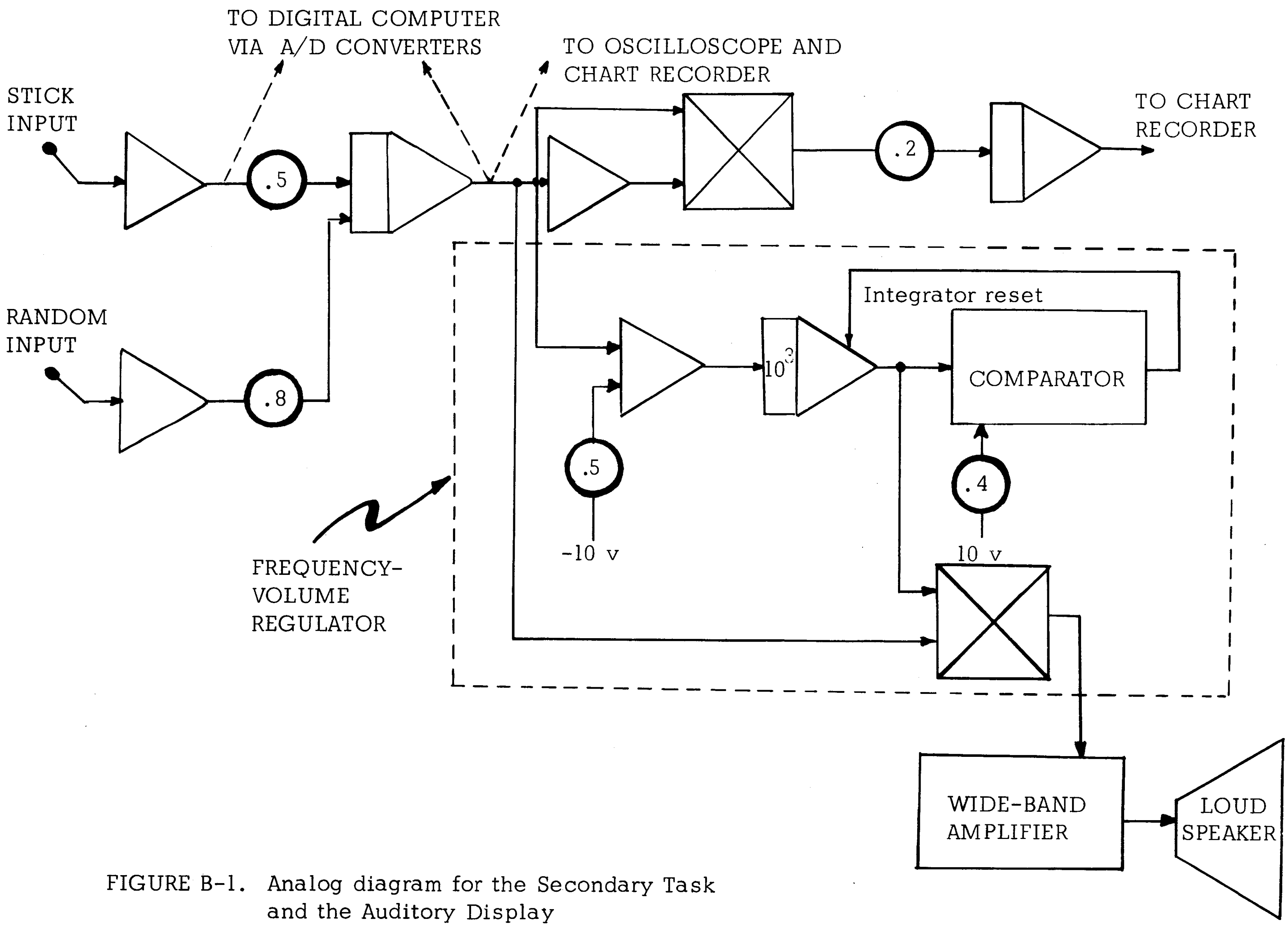


FIGURE B-1. Analog diagram for the Secondary Task and the Auditory Display

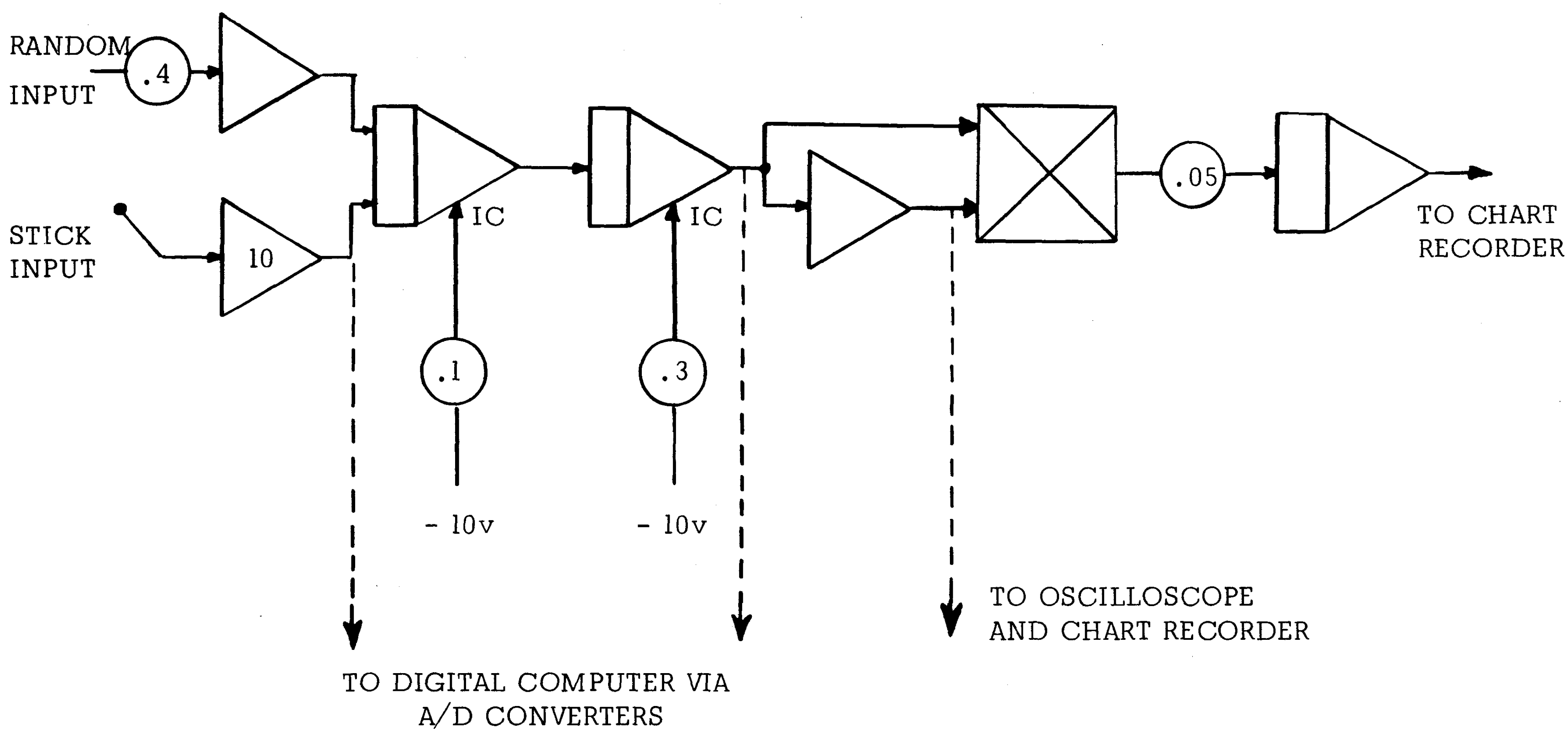
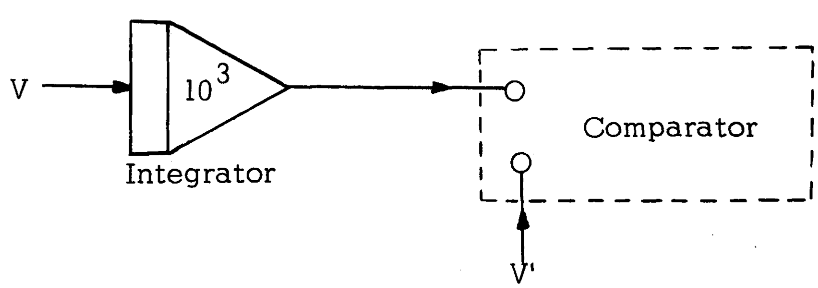


FIGURE B-2. Analog diagram for the Primary Task

This was then integrated over time to give the integral of square error (ISE) performance measure. The ISE measures and the output of the plants were recorded on a chart recorder. The outputs of the plants were also displayed on the oscilloscopes which were used as the visual displays for the experiment.

The analog computer was also used for constructing a voltage-to-frequency converter (see Figure B-3). The error signal was fed into an integrator. Using a comparator, the output of the integrator was compared with a reference voltage; when the output of the integrator reached the reference voltage level, the integrator reset back to initial conditions via some control logic (also shown in Figure B-3). This produced a saw-tooth wave. The integrator had a computing rate of 1000 in order to obtain the audible frequency range. Potentiometer P2 was used to set the amplitude of the saw-tooth wave at a desired value. Once the amplitude had been set, potentiometer Pl enabled one to set the reference frequency to a desired value. In this experimental set-up potentiometer Pl was set at 0.5 and potentiometer P2 at 0.4.



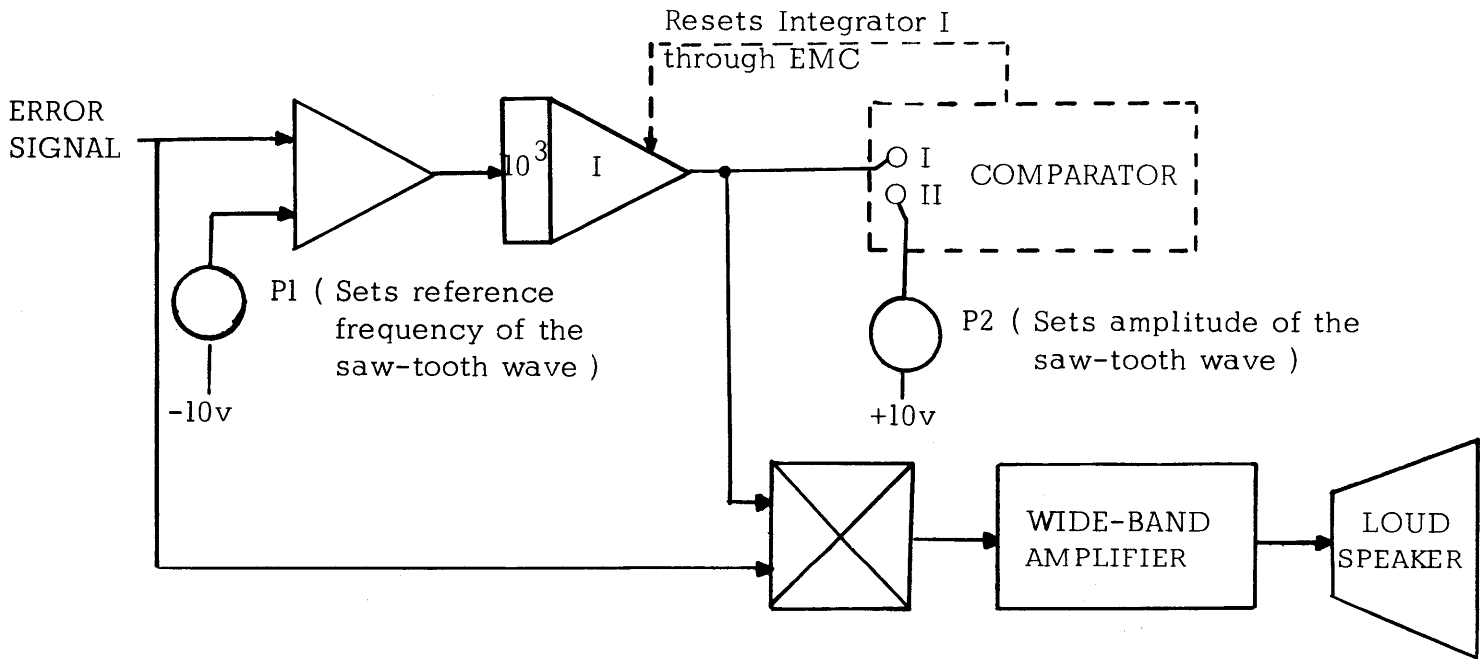
The calculation of the reference frequency and the frequency range is as follows:

If V is the input to the integrator and V' is the voltage which sets the amplitude, then the time of one period is V'/1000V seconds. Hence the frequency is 1000V/V' Hz. When the error is zero, V = 5v and V' = 4v, and thus the reference frequency is 1250 Hz. When the error is +3v (which was approximately the maximum error encountered in the experiment), V = 8v and the corresponding frequency is 2000 Hz. When the error is -3v (minimum error encountered in the experiment), V = 2v and the corresponding frequency is 500 Hz.

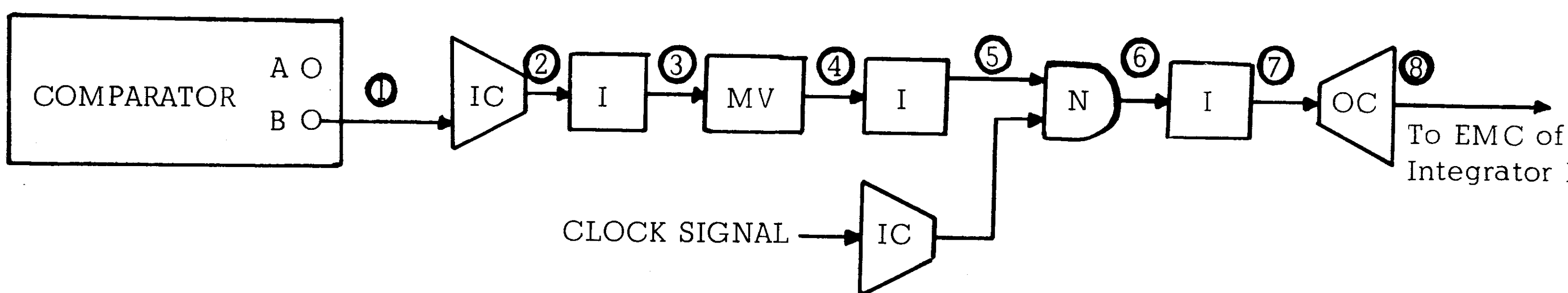
The reference frequency of 1250 Hz was chosen because at that frequency the sensitivity to pitch change is high and the ability of localization is low.[17]

For volume regulation, the output of the integrator was multiplied by the error. The reverse in polarity when the input went negative did not effect the audio output because the wide-band amplifier was indifferent to polarity. A slight bias was provided in the multiplier in order to have a non-zero reference volume when the error was zero.

The control logic of the system is also shown in Figure B-3. The B bus of the comparator produces a 10 volt pulse whenever the sum of the inputs to the comparator becomes zero. The input-converter (IC) and the output-converter (OC) are needed in the control logic because the control of the analog components work on GND/6v level, while the



(a) Analog diagram for the frequency-volume regulator



(b) Control logic for above

FIGURE B-3.

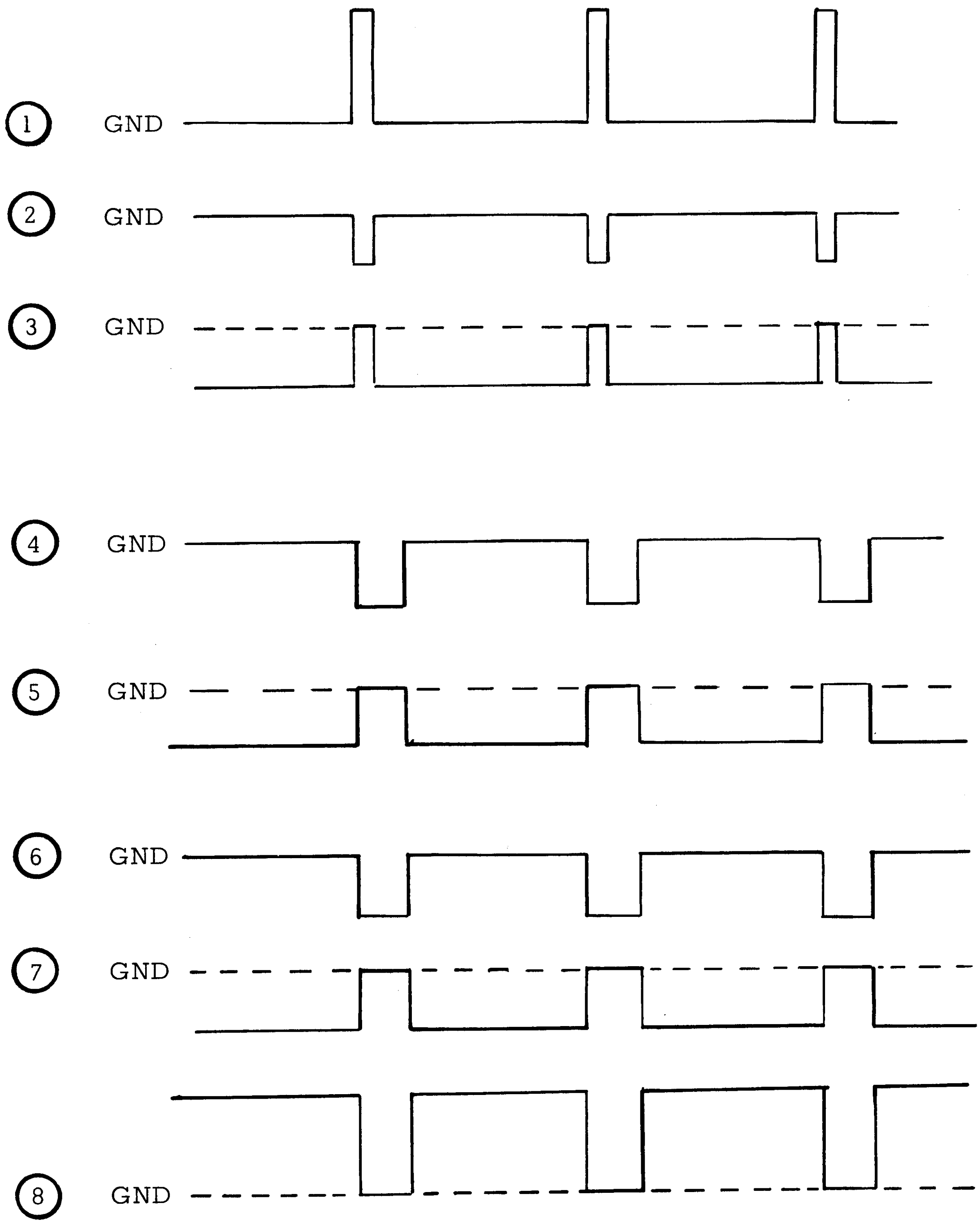


FIGURE B-4. Timing diagrams at various stages of the Control Logic shown in Figure B-3 (b) digital logic works on GND/-3v level. The inverters (I) invert the logical signals, while the multi-vibrator (MV) provides a -3v signal for an adjustable delay time when the input goes from -3v to GND. A delay time in the order of microseconds was used in the experiment, during which the nand-gate (N) produced a -3v level output which set the integrator back to initial condition. The signal from the clock is a continuous signal of 6 volts. A timing diagram for the control logic is shown in Figure B-4.

A description of the analog computer components and their operation is given in reference 9.

APPENDIX C

PROGRAMS FOR STATISTICAL ANALYSIS OF DATA

Programs were written which enabled the analyst to have direct communication with the digital computer. Since large quantities of data were not involved, FOCAL seemed to be the ideal language for programming the computer. FOCAL is an online, conversational, interpretive language for the PDP-8 family of computers. The language consists of short, easy-to-learn English statements. Details of FOCAL programming are available in reference 6.

C.1 Program ME-VA

Program ME-VA was written for calculating the mean and variance for given samples. Essentially, it adds all the samples and divides by the total number of samples (N) to obtain the mean. It then obtains the sum of the squares, subtracts N times the square of the mean, and divides the result by (N - 1) to obtain an unbiased variance of the samples. When the program is executed (by typing in GO and depressing RETURN key), it asks the number of samples that have to be analysed. This sets the value for N. After depressing the RETURN key again, one types in the values of the samples. Once all the samples have been entered, the computer types out the mean, variance, and the standard deviation. The program and an example of its execution are given in the following page.

ME-VA, A PROGRAM TO CALCULATE MEANS AND VARIANCES

C-FOCAL,1969

```
01.05 T "THIS PROGRAM CALCULATES MEANS AND VARIANCES",!!!,
01.10 E
01.20 T "NUMBER OF SAMPLES IS",  ; A N; T !
01.30 F I=1,N; A P(I)
01.40 F I=1,N; S SP=SP+P(I)
01.50 S MEAN=SP/N
01.60 F I=1,N; S SS=SS+P(I)↑2
01.70 S VARIANCE= (SS-SP*MEAN)/(N-1)
01.75 S SD=FSQT(VARIANCE)
01.80 T !!!, "MEAN IS EQUAL TO ",MEAN,!!
01.90 T "VARIANCE IS EQUAL TO ",VARIANCE,!!
01.91 T "STANDARD DEVIATION IS ",SD,!
01.92 Q
*
```

EXAMPLE 1.

```
*GO
THIS PROGRAM CALCULATES MEANS AND VARIANCES

NUMBER OF SAMPLES IS:12

:21 :43 :65 :87 :98 :76 :54 :34 :56 :78 :76 :54

MEAN IS EQUAL TO = 61.83

VARIANCE IS EQUAL TO = 506.15

STANDARD DEVIATION IS =  22.50
*
```

C.2 Program VA (T)

Program VA (T) was written to calculate a value of t for comparison of means between two sets of independent samples. Essentially, it first calculates an estimate of the error variance (EV) by adding the two variances weighted by their degree of freedom and dividing the result by the total number of degrees of freedom. It then calculates an estimate of the standard error (SE) of the difference between the means using the formula, $SE = \sqrt{EV (1/N1 + 1/N2)}$, where N1 is the number of samples for the first set, and N2 is the number of samples in the second set. Finally, it calculates the value of t by dividing the difference between the means by the standard error. When the program is executed (by typing in GOTO 1.99, and depressing RETURN key), it asks for the first mean, number of samples in the first set, the second mean, number of samples in the second set, the first variance, and the second variance respectively. Once these values are entered, it types out the value of t and the associated degrees of freedom. With these results one could look into a statistical t-table to obtain the significance of the difference between the means. The program and an example of its execution are given in the following page.

VA(T), A PROGRAM TO CALCULATE THE VALUE OF T

```
02.01 T "THIS PROGRAM CALCULATES VALUES OF T",!!
02.02 T !,"FIRST MEAN? ",; A MX
02.03 T !,"FIRST VARIANCE? " ; A V1
02.04 T !,"NUMBER OF SAMPLES? " ; A N1
02.05 T !,"SECOND MEAN? " ; A MY
02.06 T !,"SECOND VARIANCE? ; A V2
02.07 T !,"NUMBER OF SAMPLES? " ; A N2
02.08 S EV=((V1*(N1-1))+(V2*(N2-1)))/(N1+N2-2)
02.09 T !, "VALUE OF T IS",(MX-MY)/FSQT(EV*(1/N1+1/N2)),!
02.10 T !, "DEGREES OF FREEDOM ARE" ,N1+N2-2.,!
02.11 Q
```

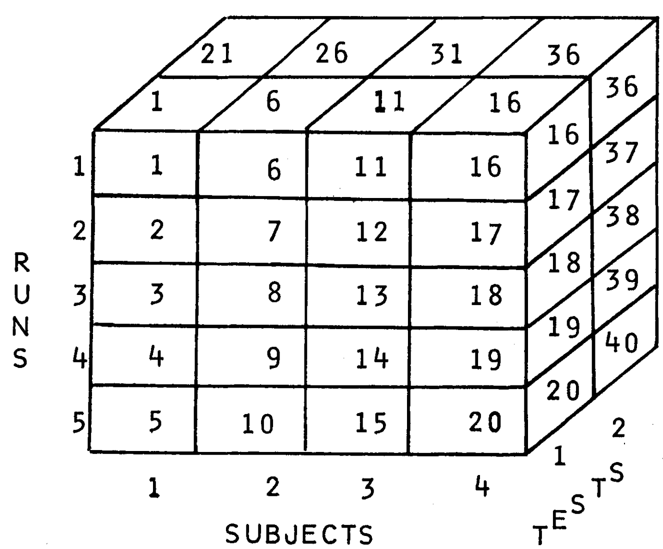
```
*EXAMPLE

GOTO 1.99
THIS PROGRAM CALCULATES VALUES OF T


FIRST MEAN? :15

FIRST VARIANCE? : 6.1

NUMBER OF SAMPLES? :11

SECOND MEAN? :17.5

SECOND VARIANCE? :2.81

NUMBER OF SAMPLES? :9

 VALUE OF T IS=-  2.58

DEGREES OF FREEDOM ARE= 18.00
*
```

C.3 Program ANVA

Program ANVA was written for the analysis of variance between three parameter groups. The three parameter groups in this experiment were SUBJECTS, RUNS, and TESTS. Although it was possible to write a general program to accept any number of elements in each parameter group, this program was specifically written to accept four subjects, two testing conditions and five runs for each subject under each testing condition. These were the numbers of the elements of the respective parameter groups in this study.

Analysis of Variance is a standard statistical test which enables one to test whether a difference between two or more sample means is significant. In effect it sets up a null hypothesis that the means of the population are not different. The variance estimate (VE) of each parameter group is compared with the residual variance (that part of the total variance that cannot be accounted for from the parameter groups, but is assumed to be due to experimental conditions) and a certain ratio called the variance ratio (VR) is obtained. This ratio can be compared with the values of F in F tables[3,15] at various levels of significance. If the obtained VR is larger than the F value given in the tables for a certain level of significance, then the null hypothesis is rejected at that level of significance. If the VR is smaller than the value given in the table, then no conclusions are made on the hypothesis. The theory and the details on the analysis of variance are available in most statistical texts, for example references 3 and 15.

The program is executed by typing GO and depressing the RETURN key. The computer then waits for the operator to enter the data. The data for test 1 are entered first and then the data for test 2. Test 1 was the condition when the secondary task was not supplemented by an auditory display and test 2 was the condition when it was supplemented by an auditory display. For each test, the data for all the runs of subject 1 are entered first, and then for subject 2 and so on. The three dimensional matrix shown below should help visualize the order in which the data is presented to the computer. The number in each box denotes the order of presentation. The set of data for test 2 follows a similar order, numbered from 21 to 40 in the program. Once the entry of the data is completed, the computer first writes out the input data in an ordered form and then presents the results of the analysis (see Tables 5 and 6 of the report).



Essentially, the program first calculates the general mean and variance of all the data. It then calculates the mean and variance for each subject, for each run and each test, and an estimated variance (VE) for each parameter group. It calculates the variance estimate for the residual by subtracting the sum of the variances of the parameter groups from the total variance. Finally the program calculates the variance ratios (VR) of each parameter group by dividing the VE of the respective parameter group by the VE of the residual. With the variance ratios obtained one is able to obtain the significance of the difference between the means of any parameter from the F tables.

The program also calculates the estimates of the standard error of the difference between the means of the elements in each parameter group. This is calculated by using the formula:

$$\text{Standard Error of the Parameter Group, } P = \sqrt{\frac{2\,VE(\text{Residual})}{N_P}}$$

where VE(Residual) is the variance estimate of the residual and N_P is the number of samples in the parameter group P.

The estimate of standard error enables one to calculate t values for comparison of the means between the elements in each parameter group.

The program is given in the following page. Results of execution of the program can be seen in Tables 5 and 6 of the report. The program gives the variance ratios for each parameter group and types out the means of each element in every parameter group. Finally, it types out the estimate of standard error of the difference between the means of the elements in each parameter group.

ANVA, A PROGRAM FOR ANALYSIS OF VARIANCE

C-FOCAL,1969

```
01.10 E
01.20 F I=1,40; A V(I)
01.30 F I=1,40;S X=X+V(I);S Y=Y+V(I)↑2;S Z=(X↑2)/40; S T=Y-Z
01.40 F I=1,4; D 3
01.45 F I=1,5; F J=0,7; S R(I)=R(I)+V(I+J*5)
01.50 F I=1,20; S C(1)=C(1)+V(I); S C(2)=C(2)+V(I+20)
01.60 S C=C(1)↑2/20+C(2)↑2/20
01.70 F I=1,4 ; S P=P+P(I)↑2/10
01.75 F I=1,5 ; S R=R+R(I)↑2/8
01.80 S C=C-Z; S P=P-Z; S R=R-Z; S E=T-C-P-R; S W=E/31

02.10 F I=1,5; D 4
02.20 T !!,"SOURCE       DF          SS           VE         VR"
02.30 T %8.02,!!,"SUBJECTS      3 ",P,"  ",P/3,"  ",P/3*W,!!
02.40 T %8.02,"RUNS          4 ",R,"  ",R/4,"  ",R/4*W,!!
02.50 T %8.02,"TESTS         1 ",C,"  ",C  ,"  ",C/W,!!
02.60 T %8.02,"RESIDUAL     31 ",E,"  ",W,!!
02.70 T %8.02,"TOTAL        39 ",T,!!
02.80 T !," SUBJECTS        RUNS        TESTS"
02.81 F I=1,5; D 5
02.90 T %6.02,!!,"EV(S)",FSQT(W/5),!,"EV(R)",FSQT(W/4),!,
                                  "EV(T)",FSQT(W/10),!
02.91 Q

03.10 F J=((I-1)*5+1),((I-1)*5+5); S P(I)=P(I)+V(J)
03.20 F J=((I-1)*5+21),((I-1)*5+25); S P(I)=P(I)+V(J)

04.10 T !,F J=I,5,I+35; T %4.02, V(J)

05.10 T %5.01,!,P(I)/10,"        ",R(I)/8,"     ",C(I)/20
*
```

APPENDIX D

CONSIDERATION OF ERRORS IN THE OBTAINED DESCRIBING FUNCTIONS

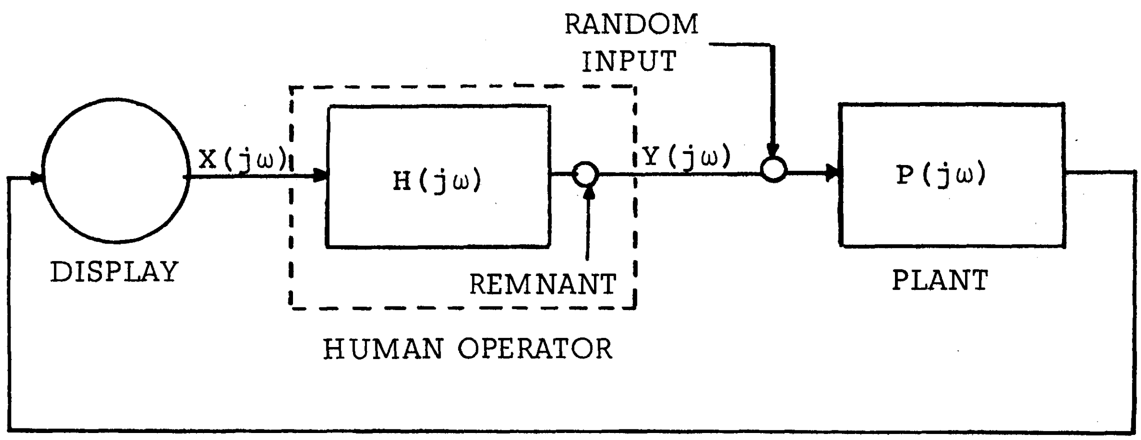
Because the exact representation of the human operator in the two control tasks was not required, but only the approximate changes in his performance when the secondary task was supplemented with an auditory display, it was possible to consider only the specific frequency components of the random input to obtain an approximate representation of the human operator. By considering only these frequencies on the mechanized Bode plots, the describing functions of the human operators were obtained (see Figure 3 of the report). However, by using this method some errors were introduced in the describing functions; this appendix discusses the errors and their sources. More general discussions of errors in the Fourier Transform method are available in references 1 and 2. References 16 and 19 have good treatments of the errors introduced in the experimental obtainment of human operator describing functions.

Some of the errors in the describing function were due to the remnant. One of the effects of the remnant was that the inverse of the plant was superimposed on the quasi-linear representation at the higher frequencies. Let $X(j\omega)$ be the input to the human operator and $Y(j\omega)$ be the operator output. Let the frequency components of the random input be denoted by ω_i and the frequency components of the remnant by ω_k. If the power of the remnant is low then most of the ω_k components in the control system loop will be negligible and for the ω_i components,

$$\frac{Y(j\omega)}{X(j\omega)} = H(j\omega),$$ the describing function of the human operator.

However, if the power of the remnant is high, then for the ω_k components in the loop,

$$\frac{Y(j\omega)}{X(j\omega)} = P^{-1}(j\omega),$$ the inverse of the plant.



If some of the ω_k are equal to some of the ω_i, the remnant and the components correlated with the random input cannot be separated, and thus there would be a superposition of the above two transfer functions on the quasi-linear representation. Print-outs of some of the Fourier Transforms of the operators showed that at low frequencies the remnant components were small compared to the components correlated with the input, and at higher frequencies the components of the remnant were comparable to the components correlated with the input; this explains why the inverse of the plant was superimposed only at the higher frequencies.

Another effect of the remnant was that the frequency spectrum, and hence the Fourier coefficients, were biased due to it. McRuer et al[16] have shown that the remnant can be assumed to be a continuous smooth function of frequency, thus even at the input frequencies the Fourier coefficients would be biased. However, if the remnant is small, the Fourier coefficients would be biased only negligibly. An investigation by Shirley[19] showed that when some describing functions obtained by a similar approach were corrected for remnant, the corrections were generally small compared to one standard deviation of the data. Hence in this experiment it was possible to neglect the effect of the remnant at low frequencies.

Another source of error in the plots was the averaging effect. The Fourier Transformation was at discrete frequencies and these did not necessarily contain all the frequency components of the input signal. Hence the magnitudes of the frequencies closest to the corresponding input frequencies were considered in obtaining the Bode plots. This procedure probably introduced averaging errors in the Bode plots. However, since the basic frequency of the input was very low (.09525 radians/second), the value itself being chosen to include the smallest frequency of the transformation, most of the frequency components of the input signal had nearly equal frequency components in the transform. The input frequency components and the corresponding transform frequency components are listed in Table D-1. Although some discrepancy exists at the higher frequencies, the corresponding values at lower frequencies are nearly equal.

Thus the errors due to the averaging effects were also negligible at the low frequencies.

INPUT FREQUENCIES (cycle/second)	CORRESPONDING TRANSFORM FREQUENCIES (cycles/second)
0.0152	0.0151
0.0227	0.0227
0.0379	0.0380
0.0531	0.0532
0.0834	0.0837
0.1289	0.1296
0.1743	0.1752
0.2198	0.2211
0.2805	0.2822
0.3563	0.3583
0.4472	0.4499
0.5533	0.5568
0.6746	0.6712
0.8110	0.8085
0.9626	0.9611
1.1294	1.1291

TABLE D-1. Frequency Components used to obtain Describing Function of the Human Operators

APPENDIX E

COMPOSITE DESCRIBING FUNCTIONS

The composite describing functions for each subject (DM, CO, NV and MG) and for each condition (with audio and without audio) are given in Figures El - E8.

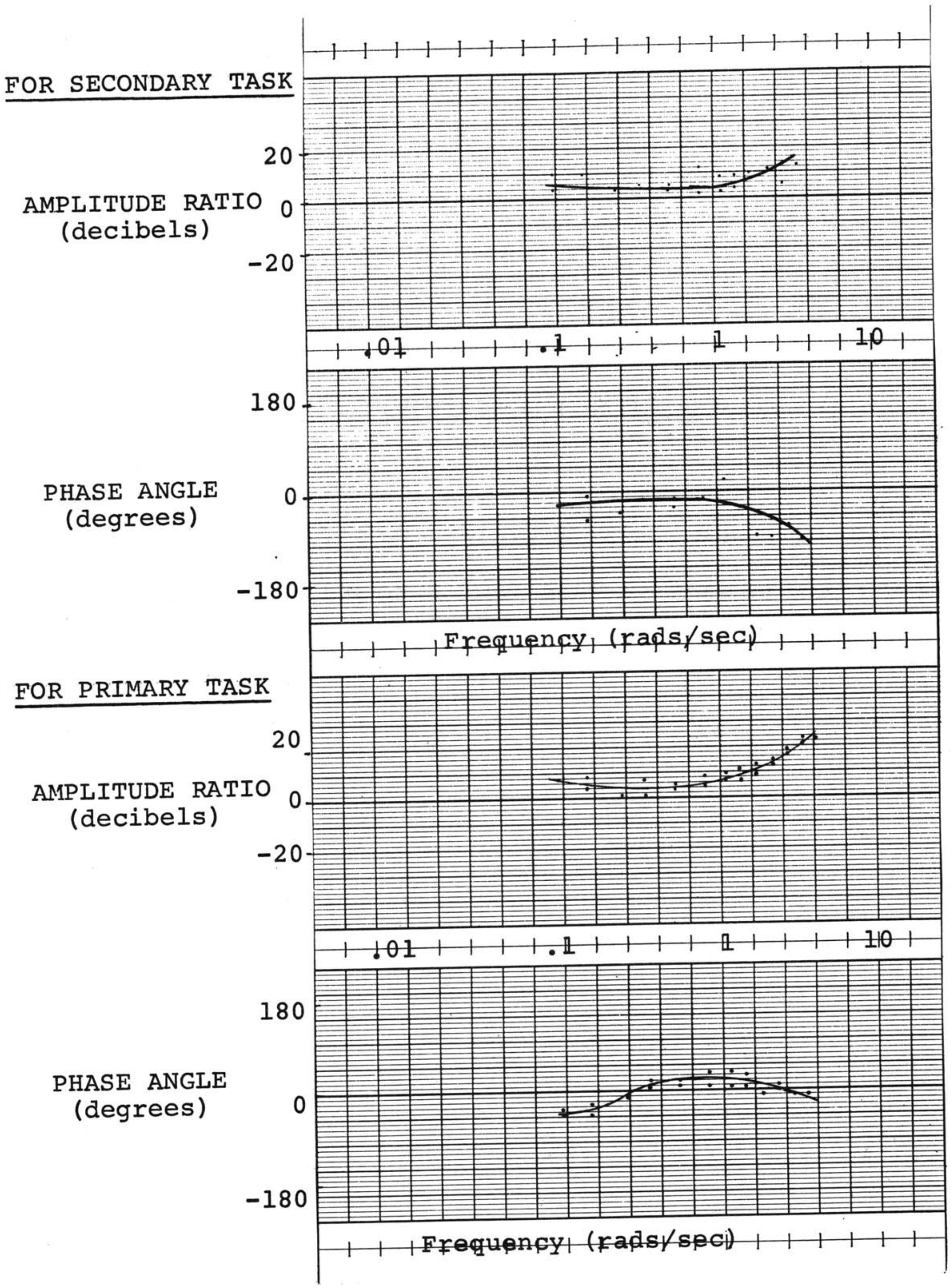


FIGURE E-1. Composite Describing Functions
For subject DM, without audio, runs 3,4.

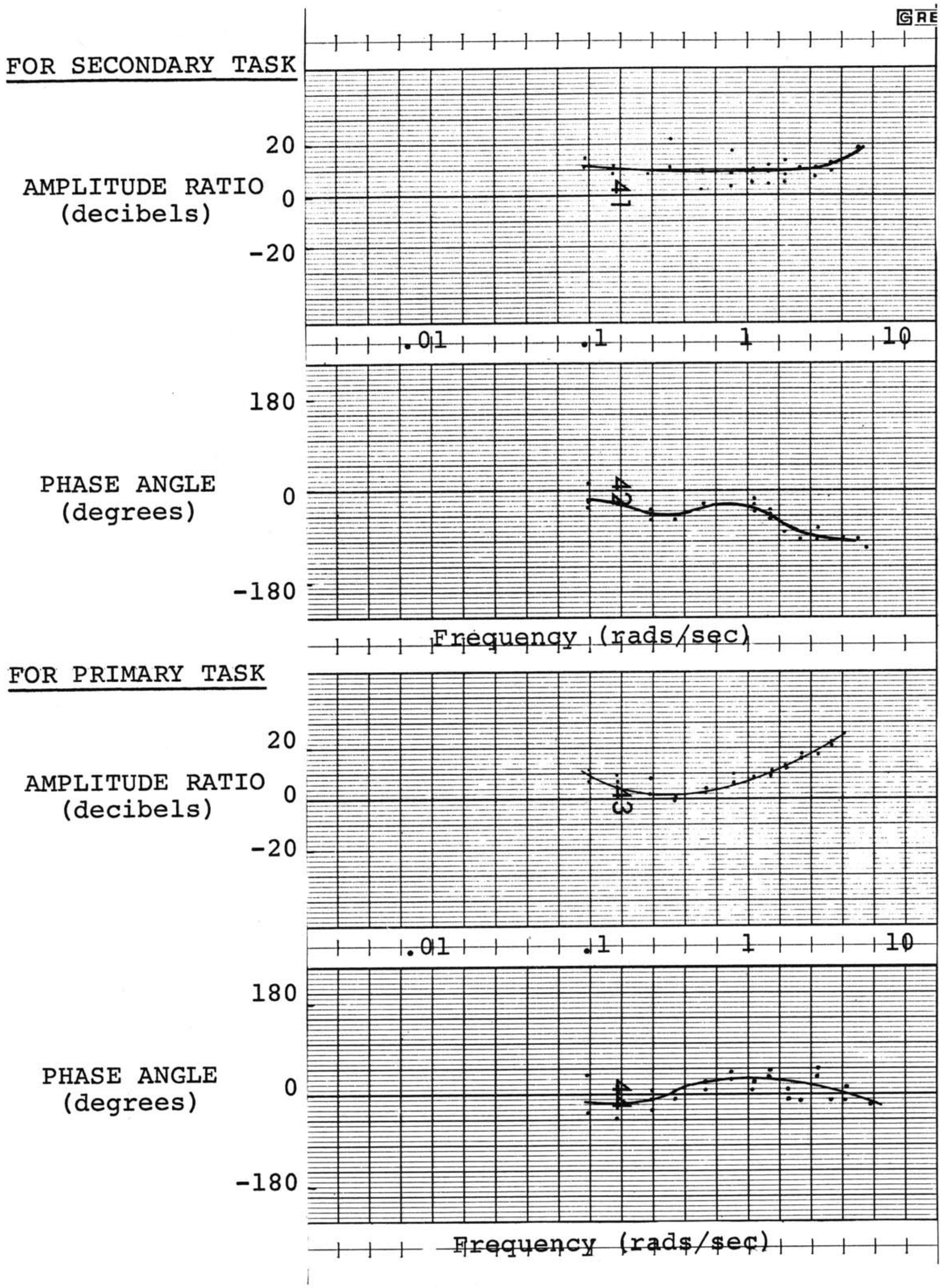


FIGURE E-2. Composite Describing Functions
For subject DM, with audio, runs 3,4,5.

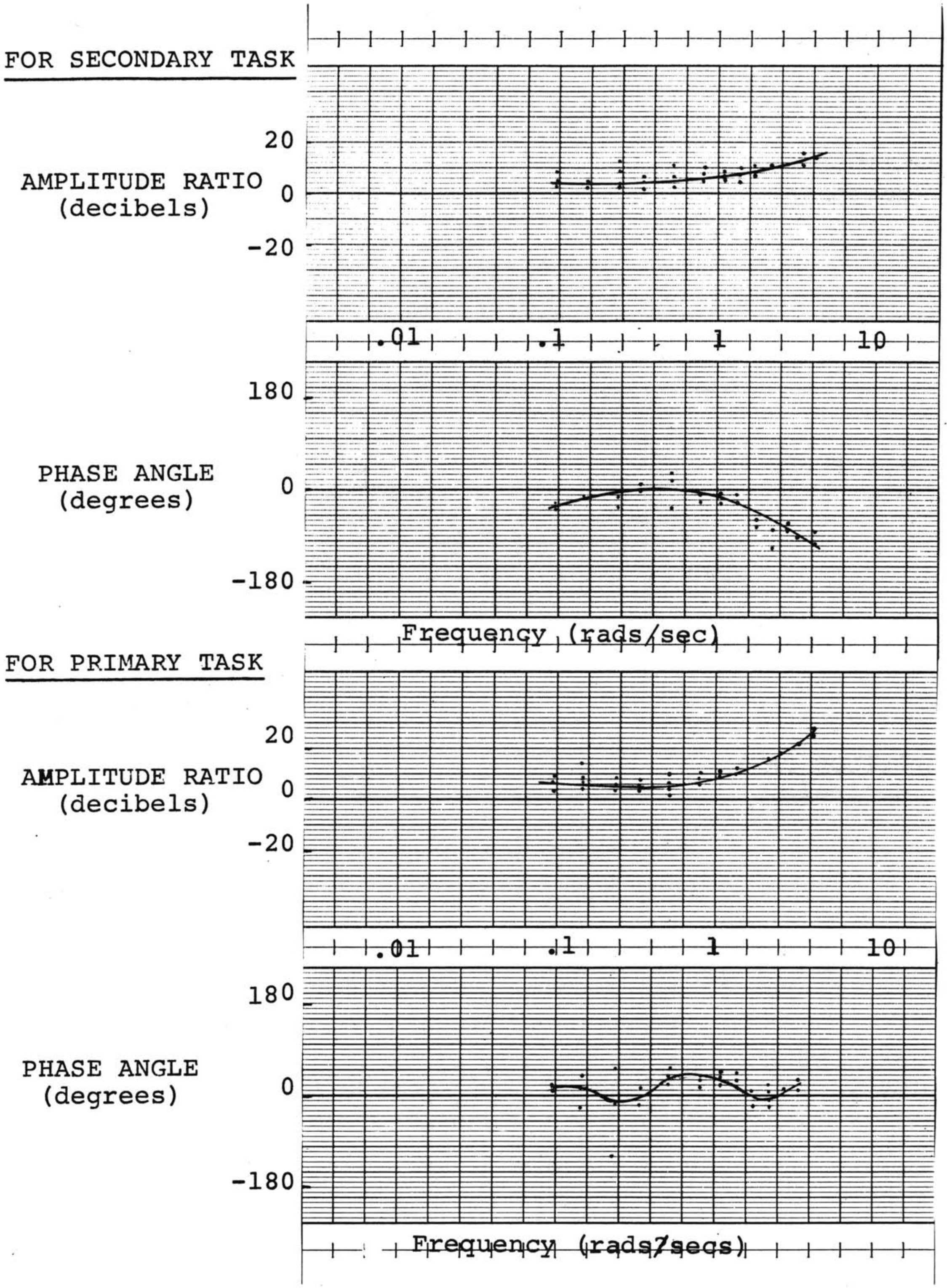


FIGURE E-3. Composite Describing Functions
For subject CO, without audio, runs 2,3,4,5.

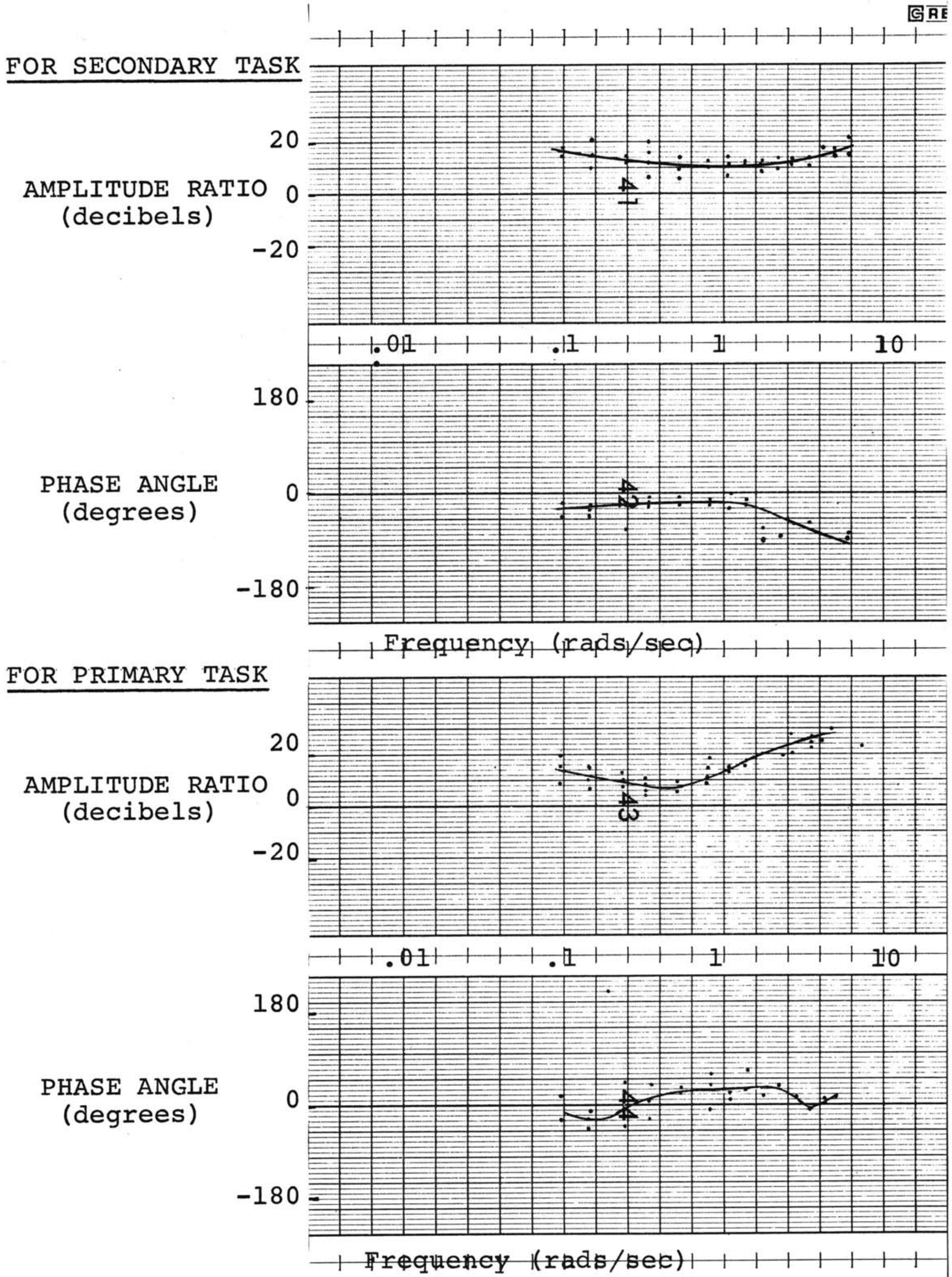


FIGURE E-4. Composite Describing Functions
For subject CO,with audio, runs 2,3,4,5.

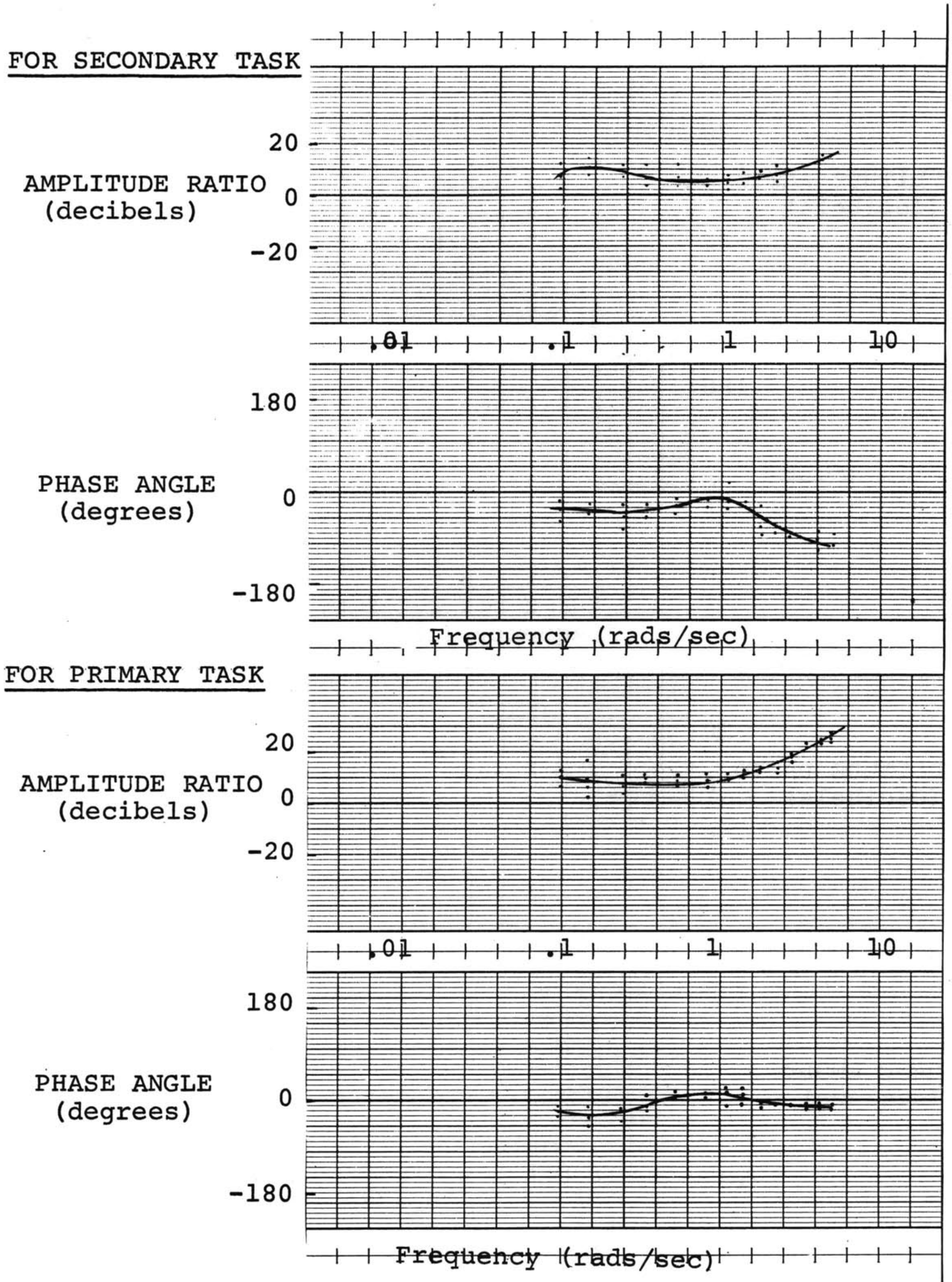


FIGURE E-5. Composite Describing Functions
For subject NV, without audio, runs 2,3,4,5.

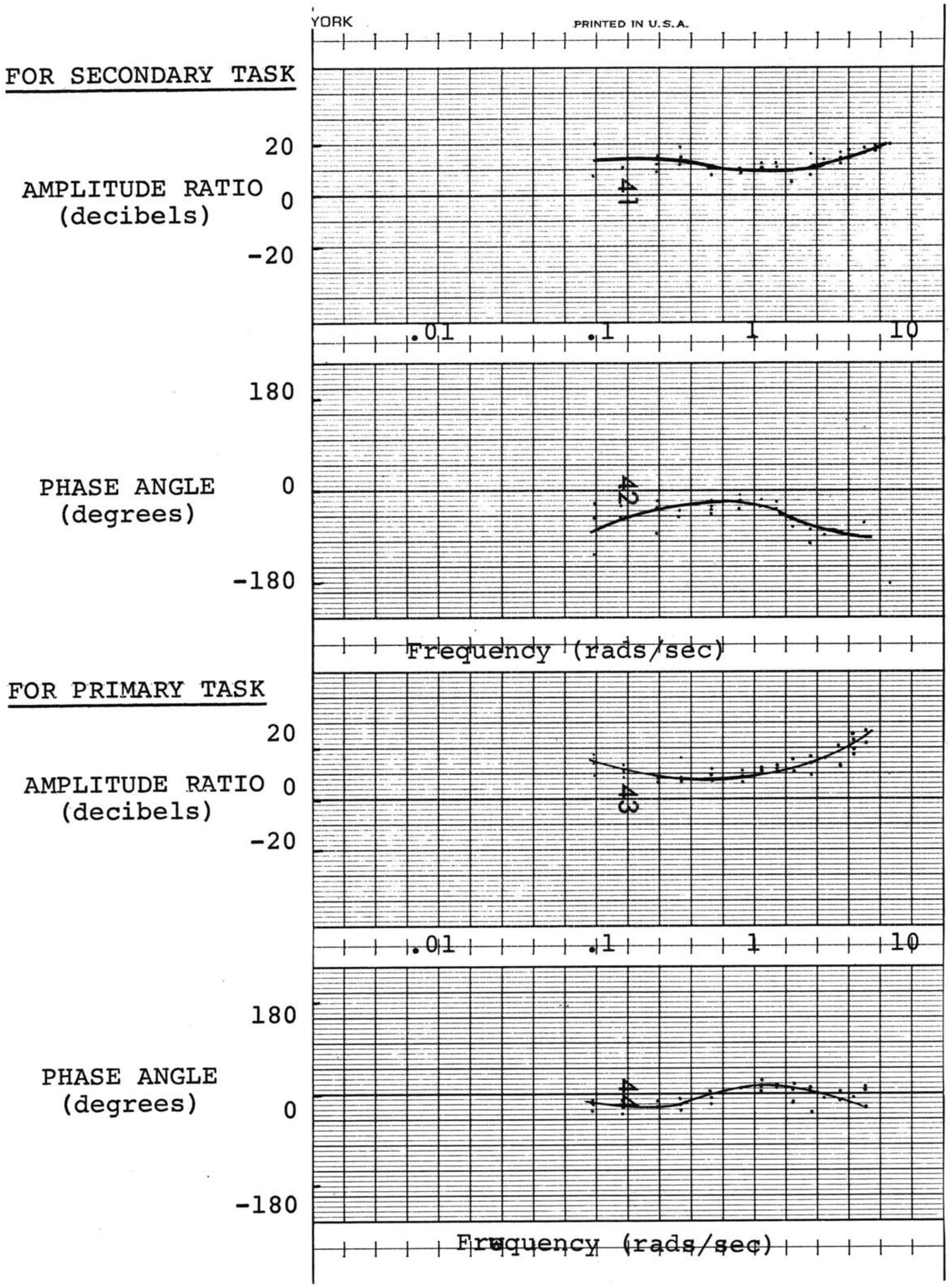


FIGURE E-6. Composite Describing Functions
For subject NV, with audio, runs 2,3,4,5.

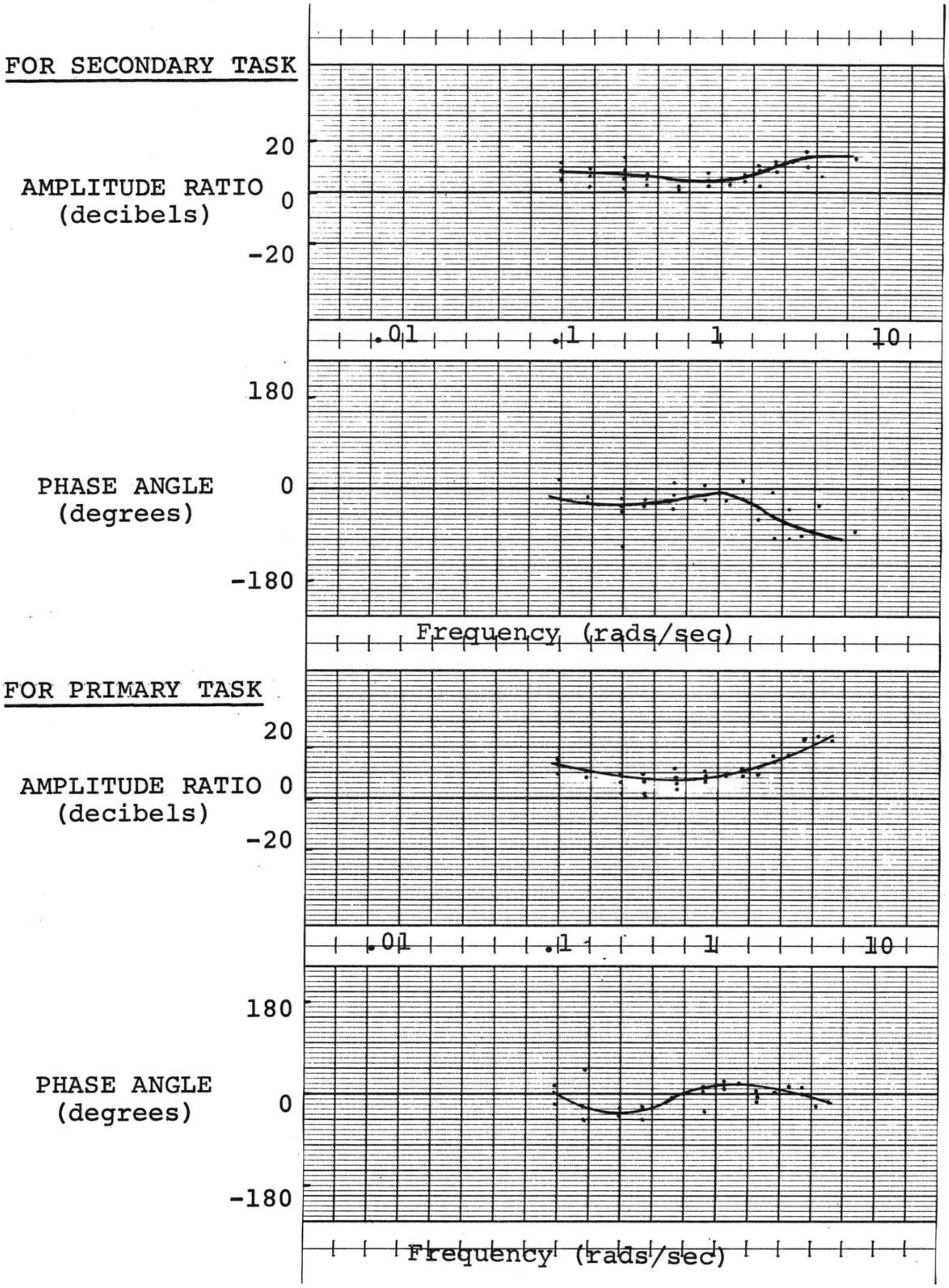


FIGURE E-7. Composite Describing Functions
For subject MG, without audio, runs 1,2,3,4,5.

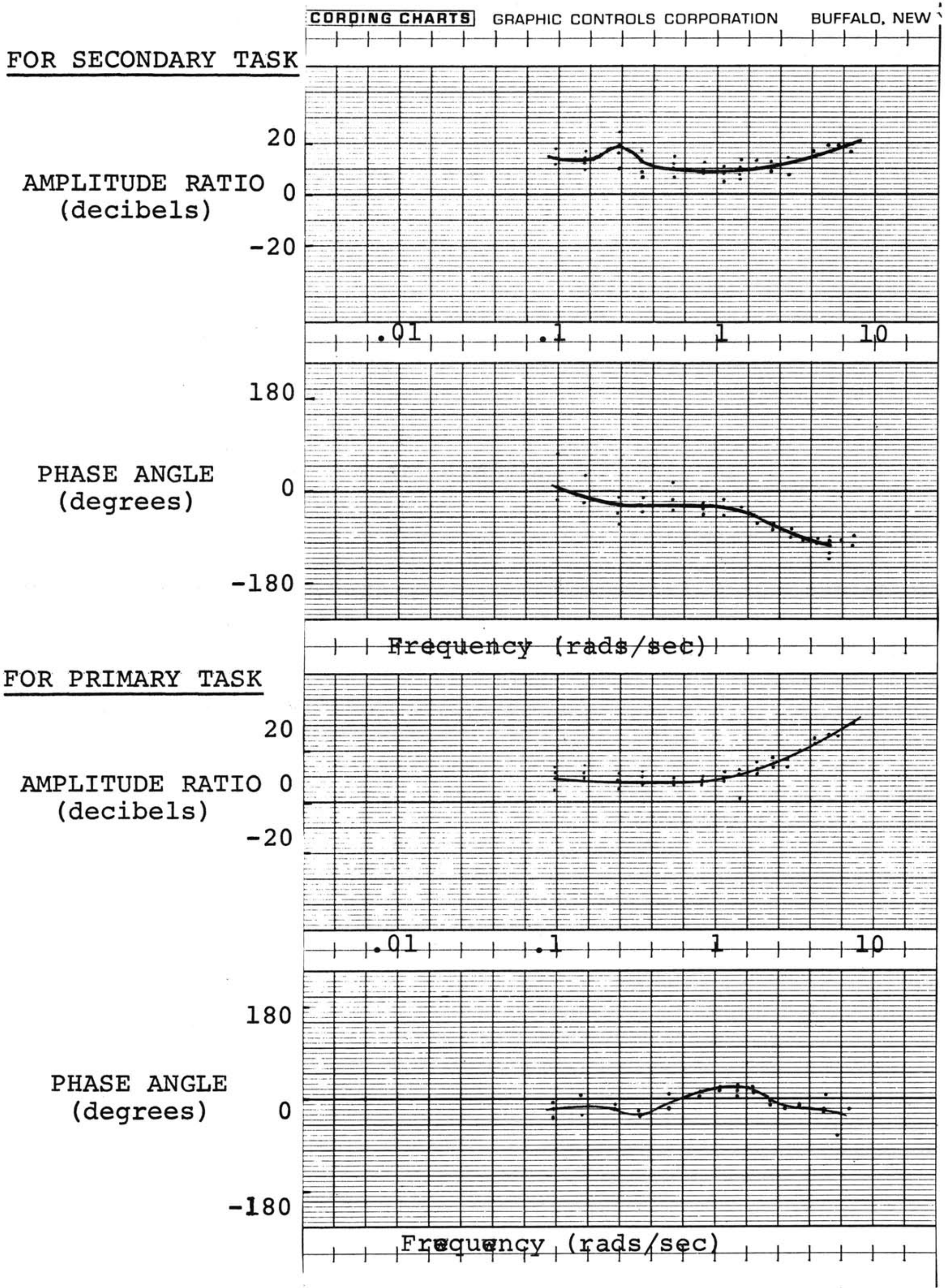


FIGURE E-8. Composite Describing Functions
For subject MG with audio, runs 1,2,3,4,5.

APPENDIX F

ISE PERFORMANCE MEASURES

Tables F-1, F-2, F-3 and F-4 present the ISE performance measures by subjects.

ISE performance measures for each task are presented in Tables F-5 and F-6.

ISE PERFORMANCE MEASURES FOR SUBJECT DM

NO.	DATE	CONDITIONS**	PERFORMANCE ON PRIMARY TASK	PERFORMANCE ON SECONDARY TASK
1	7/27/69	NA	14.5	25.0
2	"	NA	9.0	15.5
3	"	A	13.0	2.8
4	"	A	14.0	2.1
5	8/5/69*	A	18.5	3.0
6	" *	A	15.0	5.5
7	" *	NA	14.6	9.7
8	" *	NA	15.5	8.0
9	" *	A	14.0	3.5
10	"	NA	14.6	8.0

*Describing functions were obtained for these runs

**NA indicates condition without audio display, and
A indicates condition with audio display

TABLE F-1

ISE PERFORMANCE MEASURES FOR SUBJECT CO

NO.	DATE	CONDITIONS**	PERFORMANCE ON PRIMARY TASK	PERFORMANCE ON SECONDARY TASK
1	7/29/69	NA	5.7	6.5
2	"	A	3.0	1.5
3	7/30/69*	A	1.6	2.2
4	" *	NA	11.0	14.0
5	8/15/69*	NA	15.0	15.0
6	" *	NA	7.5	14.0
7	" *	NA	8.0	20.0
8	" *	A	4.0	5.5
9	" *	A	8.0	5.5
10	" *	A	3.0	3.0

*Describing Functions were obtained for these runs

**NA indicates the condition without audio display, and A indicates the condition with audio display

TABLE F-2

ISE PERFORMANCE MEASURES FOR SUBJECT NV

NO.	DATE	CONDITIONS**	PERFORMANCE ON PRIMARY TASK	PERFORMANCE ON SECONDARY TASK
1	8/5/69	A	1.5	5.5
2	"	NA	1.0	6.3
3	8/6/69*	A	3.5	7.0
4	" *	A	1.0	3.0
5	" *	NA	2.0	3.8
6	" *	NA	2.0	3.5
7	8/15/69*	A	5.0	5.0
8	" *	A	6.0	6.0
9	" *	NA	9.5	14.0
10	" *	NA	6.0	16.0

*Describing Function was obtained for this run

**NA indicates the condition without audio display, and A indicates the condition with audio display

TABLE F-3

ISE PERFORMANCE MEASURES FOR SUBJECT MG

NO.	DATE*	CONDITIONS**	PERFORMANCE ON PRIMARY TASK	PERFORMANCE ON SECONDARY TASK
1	8/6/69	A	6.0	4.0
2	"	A	5.0	2.0
3	"	NA	4.0	6.0
4	"	NA	3.0	5.0
5	8/15/69	NA	11.0	18.0
6	"	NA	9.0	20.0
7	"	NA	7.5	16.0
8	"	A	6.0	8.0
9	"	A	6.0	7.0
10	"	A	3.0	5.0

*Describing functions were obtained for all the runs

**NA indicates the condition without audio display
A indicates the condition with audio display

TABLE F-4

ISE PERFORMANCE MEASURES FOR THE PRIMARY TASK

SUBJECT	WITHOUT AUDIO		WITH AUDIO	
	SCORE	DATE	SCORE	DATE
DM	14.5	7/27/69	13.0	7/27/69
"	9.0	"	14.0	"
"	14.6	8/5/69	18.5	8/5/69
"	15.5	"	15.0	"
"	14.6	"	14.0	"
CO	5.7	7/29/69	3.0	7/29/69
"	11.0	7/30/69	1.6	7/30/69
"	15.0	8/15/69	4.0	8/15/69
"	7.5	"	8.0	"
"	8.0	"	3.0	"
NV	1.0	8/5/69	1.5	8/5/69
"	2.0	8/6/69	3.5	8/6/69
"	2.0	"	1.0	"
"	9.5	8/15/69	5.0	8/15/69
"	6.0	"	6.0	"
MG	4.0	8/6/69	6.0	8/6/69
"	3.0	"	5.0	"
"	11.0	8/15/69	6.0	8/15/69
"	9.0	"	6.0	"
"	7.5	"	3.0	"

TABLE F-5

ISE PERFORMANCE MEASURES FOR THE SECONDARY TASK

SUBJECT	WITHOUT AUDIO		WITH AUDIO	
	SCORE	DATE	SCORE	DATE
DM	25.0	7/27/69	2.8	7/27/69
"	15.5	"	2.1	"
"	9.7	8/5/69	3.0	8/5/69
"	8.0	"	5.5	"
"	8.0	"	3.5	"
CO	6.5	7/29/69	1.5	7/29/69
"	14.0	7/30/69	2.2	7/30/69
"	15.0	8/15/69	5.5	8/15/69
"	14.0	"	5.5	"
"	20.0	"	3.0	"
NV	6.3	8/5/69	5.5	8/5/69
"	3.8	8/6/69	7.0	8/6/69
"	3.5	"	3.0	"
"	14.0	8/15/69	5.0	8/15/69
"	16.0	"	6.0	"
MG	6.0	8/6/69	4.0	8/6/69
"	5.0	"	2.0	"
"	18.0	8/15/69	8.0	8/15/69
"	20.0	"	7.0	"
"	16.0	"	5.0	"

TABLE F-6

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