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36. The Effects of Attention Sharing in a Dynamic Dual-Task Environment*

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There are numerous examples of cases where the human operator is confronted with several tasks occurring simultaneously and continuously in time. The current study is an investigation into the nature of attention sharing between two continuous tasks with independent input-output modes. Eleven subjects were tested using a zero order compensatory control task with three levels of difficulty (input bandwidth) for each subject. As a secondary task on half of the trials, the subjects were also required to verbally shadow a random auditory input. Results from an extensive time and frequency domain analysis of the data are presented and discussed. The evidence supports a single channel model for continuous dual-task control.

INTRODUCTION

Man is frequently confronted with two or more tasks demanding his attention simultaneously. Such an everyday activity as driving a car while conversing or listening to the radio provides a common example. In the more highly evolved technological occupations such as air traffic control, piloting aircraft, or process control, the examples are even more numerous, and the consequences of inattention can be potentially more disastrous.

There has been much work on the topic of simultaneous task performance for the case of discrete tasks (Broadbent (ref. 1), Berteleson (ref. 2), and Welford (ref. 3)). Most of this work has centered around dual task studies in which an auditory and a visual stimulus are presented within several hundred milliseconds of each other and the response latency for each of the two stimuli is measured. In general, it is found that the response to the second stimulus must be deferred until the response to the first has been completed. Although this result seems to be dependent on the amount of event and temporal uncertainty to be resolved in the response (Adams (ref. 4)), the general finding is well verified. By far the most widely held explanation of this phenomenon is embodied in what has become known as the '(single-channel theory." This theory views the human as a single-channel processor capable of processing only one stimulus-response pair at a time.

While there has been much work on dual discrete task performance, the work on simultaneous continuous task performance has been minimal. Furthermore, the research that has been done has not generally attempted to look deeply into the possible underlying causality as was the case with the work on discrete tasks.

The major concern of dual-continuous task studies in the past has been to assess the workload of one of the tasks, the primary task, by measuring the effect on performance caused by the addition of a secondary task. Welford (ref. 3) has provided a fairly comprehensive review of this literature. Most studies have shown a decrement in performance when a secondary task is added; however, this seems to have been the extent of the analysis in most cases. There has been no major attempt at a detailed analysis of the operator's response records in search of the underlying processes which might account for the decrement. While the single-channel model

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is often assumed, support for this theory has only come from the discrete task studies.

There have been a number of studies of multiple visual input tasks (Senders (ref. 5), Carbonell et al. (ref. 6), and Merritt (ref. 7)). While these studies have made valuable contributions to our understanding of the allocation of visual attention, they cannot answer the more fundamental questions as to man's ability to control multiple tasks when the task inputs and outputs are independent. This same drawback applies to the numerous studies involving dual auditory inputs (Cherry (ref. 8), and Neisser (ref. 9)).

Wempe and Baty (ref. 10) did look at the effect of the addition of a secondary auditory task on a tracking task. The auditory task involved a binary decision once per second and caused a small (0.18 bit/sec) tracking decrement. Adopting a single-channel model, they attempted to account for the tracking decrement as a sampling loss when the secondary task was added. They found mixed support for this view and felt that sampling alone could not account for the tracking decrement.

A study was undertaken in order to directly investigate the effects of attention sharing for two stimulus-response independent tasks. It was desired that such a study should uncover the underlying mechanisms which account for the decrement in performance so often noted in the workload studies cited above. By using tasks which were uncorrelated and independent with respect to the input receptors and the output effectors, any interaction was limited to the operator's central information processing mechanisms. A visual-manual compensatory tracking task and an auditory-verbal shadowing task were selected as the most appropriate task pair.

DESCRIPTION OF THE TASKS AND PROCEDURES

The subject was seated in a soundproofed room approximately 60 centimeters in front of an oscilloscope displaying a point of light which could move along the 11.5 cm horizontal diameter. In the center was a vertical arrow which represented the zero error condition for the compensatory tracking task. Control was accomplished through a 6:1 cm diameter control knob which had left-right compatability with the display. Figure 1 is a photograph of the tracking station.

The subject was also equipped with headphones through which the shadowing input was received. Volume on the headphones was adjusted for comfortable listening for each subject. The shadowing task required the subject to repeat aloud random number pairs which were received through the headphones. Figure 2 is a sketch of a subject performing both tasks simultaneously. Figure 3 provides a block diagram representation of both tasks, where Y_{E}. and Y_{Ha} represent the human operator's transfer characteristics for the tracking and shadowing tasks, respectively.

The compensatory tracking task—S.T.I. type forcing functions were used as input to the tracking task. Four forcing functions were used and

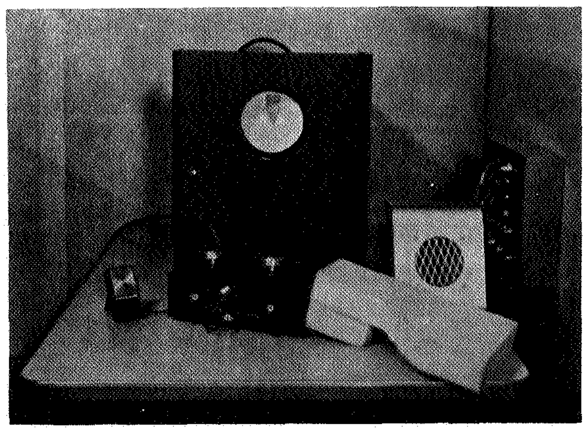

FIGURE 1.—Subjects tracking station.

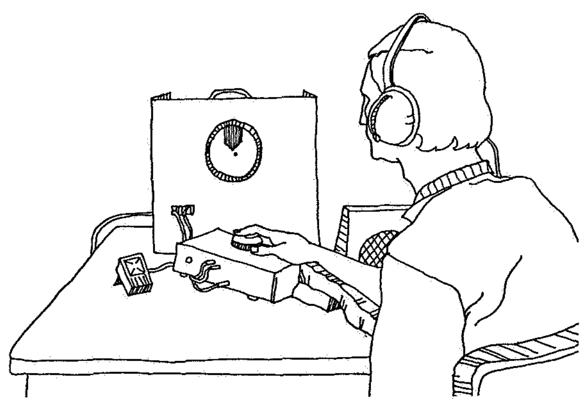

FIGURE 2.—Sketch of subject and equipment.

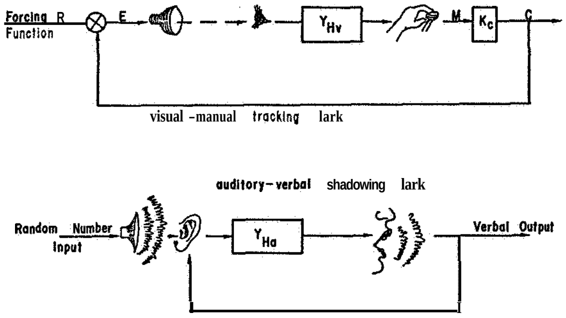

FIGURE 3.—Block diagram of the tasks.

are shown in table *1*. One group of subjects was given forcing functions *A*, *B*, and *C*, while the other subjects were given **3**, *C*, and *D*.

Control was accomplished with a zero order controller ($K_c = 5.0$ cm/30° rotation). The control knob was situated with the rotation axis vertical, and an arm rest was provided so that the knob could be comfortably rotated with just the finger tips. The control potentiometer was a precision *360"* slide wire type with absolute linearity of ± 0.5 percent. The tracking task was implemented on an analog computer which was also programmed to produce an on-line computation of the mean squared error.

***The** shadowing* task.—The shadowing forcing function consisted of random number pairs (e.g., *71, 49, 90, 44, 69, 25, . . .*) ranging from *10* to *99*. The subject's task was to repeat them aloud as he heard them; no retention was required. Based on the vocabulary size there were *6.49* bits of uncertainty per number pair.

Two levels of shadowing difficulty were used. The first level consisted of approximately one random number pair per second (an average of 5.88 bits/sec as actually measured), the second of approximately **1.5** number pairs per sec (an average of *9.13* bits/sec as actually measured). Subjects using forcing function set *A*, *B*, *C* were given the slower shadowing while subjects using forcing functions *B*, C, *D* were given the faster shadowing.

Subjects

All subjects were undergraduates at the University of California, Berkeley, and were paid a standard hourly wage for the time they spent. None of the subjects had previous laboratory tracking experience. The experimental results for eleven subjects will be discussed in this report.* These subjects form two groups: Group I, those who received tracking inputs *A*, *B*, *C* and the slow shadowing (subjects 1 through *6)*; group II, those who received tracking inputs *B*,

* In all, 13 subjects were tested, but results for subjects 7 and 8 have been omitted here. These two subjects were given forcing functions *A*, *B*, *C* and the fast shadowing. Their results were similar to those of the group II subjects discussed in this paper.

TABLE 1.—*Specifications of S.T.I. Type Forcing Functions Used*

S.T.I. frequencies		Forcing functions *A*	Forcing functions *B*	Forcing functions *C*	Forcing functions *D*
Hz	rps	Normalized amplitudes	Normalized amplitudes	Normalized amplitudes	Normalized amplitudes
2.200	13.800	0.1	0.1	0.1	0.1
1.210	7.570	0.1	0.1	0.1	1.0
0.642	4.030	0.1	0.1	1.0	1.0
0.404	2.540	0.1	1.0	1.0	1.0
0.237	1.490	1.0	1.0	1.0	1.0
0.154	0.969	1.0	1.0	1.0	1.0
0.096	0.602	1.0	1.0	1.0	1.0
0.063	0.393	1.0	1.0	1.0	1.0
0.042	0.262	1.0	1.0	1.0	1.0
0.025	0.157	1.0	1.0	1.0	1.0
Rms scope face amplitudes		3.62 cm 1.43 in.	3.42 cm 1.35 in.	3.30 cm 1.30 in.	2.26 cm 1.03 in.

C, D and the fast shadowing (subjects 9 through 13). There were five male subjects (subjects 1, 2, 10, 12, 13) and *six* female subjects (3, 4, 5, 6, 9, 11).

Procedure and experimental design.—Each subject was first required to practice the shadowing until mistakes were seldom made (almost 100 percent transmission in a 5 min session). Following this, a standard set of instructions were read explaining the experimental procedure. Next, 5 min tracking practice was given followed by 5 min practice of simultaneous tracking and shadowing. After this the actual experiment was started and all stimulus and response functions were recorded on magnetic tape for later processing.

Altogether, each subject performed six runs of 5 min duration each. The subjects tracked each of the three forcing functions twice, once without shadowing and once while simultaneously shadowing. The order in which the forcing functions were presented was selected randomly for each subject. The shadowing or no shadowing condition was also selected randomly for the first trial, and the conditions were alternated thereafter. Rest periods were provided between each run.

Motivation.—In order to keep the subjects' motivational level relatively high, it was desired to supply knowledge of results after each run. However, since it was not possible to compute a shadowing score on-line, it was decided to give the subjects pseudo-knowledge of results. The subjects were given a score after each run which they were told could range from 0 to 100 and indicated how well they had done in relation to other subjects who had performed the same task. In actuality, after each run, the subjects were given a score ranging from 85 to 95, selected randomly. In this way it was hoped to provide scores which were high enough to give incentive, along with a feeling that more improvement was still possible. At the end of the experiment subjects were given an opportunity to receive the actual scores in a few days. None of the subjects claimed to have realized that the scores were not real, and all subjects felt the scores had a facilitating value.

GENERAL RESULTS

Tracking results.—The normalized rms error tracking scores for both groups I and II are shown in table 2. As the table shows, there was no consistent difference in Tracking performance between the no shadowing and shadowing conditions for group I. However, for group II there was a consistent decrement in tracking performance when the shadowing was added. A three way analysis of the variance was conducted and the above observations were supported. The complete ANOVA table is presented in table 3.

TABLE 2.—*Normalized RMS Error* Scores

Subject		Forcing functions							
		A		*B*		*C*		*D*	
		N*	S†	N	S	N	S	N	S
Slow shadowing	1	44.5	46.6	54.2	56.2	76.6	69.0		
	2	32.9	33.2	27.9	42.6	47.8	47.9		
	3	40.0	33.6	45.8	44.0	58.7	52.1		
	4	30.1	42.7	42.6	43.6	67.6	70.7		
	5	35.7	33.8	44.3	43.8	58.5	54.4		
	6	37.3	35.9	51.6	46.6	57.7	63.7		
	Mean	36.8	37.6	46.1	46.1	61.2	59.6		
Fast shadowing	9			37.3	42.5	49.3	74.2	64.6	69.9
	10			34.1	67.8	43.0	67.6	54.5	68.2
	11			49.9	56.8	67.8	84.7	67.7	76.2
	12			44.0	52.6	49.5	58.9	61.5	64.4
	13			43.5	58.4	50.5	61.8	70.9	73.3
	Mean			41.8	56.4	52.0	69.4	63.8	70.4

* No Shadowing. † Shadowing.

TABLE 3.—*Analysis of the Variance of Normalized Rms Error Scores*

Subjects 1 through 6

	Source	df	MS	F	p
A:	Subjects	5	206.17	18.88	<0.005
B:	Forcing function	2	1643.70	150.53	<0.005
C:	Shadowing	1	0.32	0.03	Not significant
AB:	Subjects × forcing function	10	29.58	2.71	<0.10
BC:	Forcing function × shadowing	2	4.47	0.41	Not significant
AC:	Subjects × shadowing	5	19.92	1.76	Not significant
ABC:	Error	10	10.92		

Subjects 9 through 13

	Source	df	MS	F	p
A:	Subjects	4	148.98	7.52	<0.01
B:	Forcing function	2	875.76	44.19	<0.005
C:	Shadowing	1	1193.22	60.21	<0.005
AB:	Subjects × forcing function	8	61.31	3.09	<0.10
BC:	Forcing function × shadowing	2	76.63	3.87	<0.10
AC:	Subjects × shadowing	4	65.66	3.13	<0.10
ABC:	Error	8	19.82		

Also, the mean tracking scores for group II have been plotted in figure 4 for both the shadowing and no shadowing case. The greatest percent decrement in tracking occurred with forcing function *C*.

Shadowing results.—The shadowing response records were scored for missed number pairs, and from this result percent transmission rates were computed. Table 4 presents the results for groups I and II. As with the tracking task, group I, who had the slow shadowing input, suffered no shadowing decrement when the shadowing was performed in conjunction with the tracking. However, group II subjects did show a significant shadowing decrement in addition to the tracking decrement previously described.

TRANSINFORMATION ANALYSIS

In an attempt to account for the performance decrement for group II subjects, the results were investigated for evidence of an information channel capacity. Tracking transinformation was computed using the linear correlation coefficient measured between the input and response distributions, that is,

$$\text{Transinformation} = w_c \log_2 \left(\frac{1}{1 - r^2} \right) \text{bits/sec}$$

where

w_c = forcing function bandwidth

r = tracking cross-correlation coefficient.

Results for subjects 9 and 10 are presented

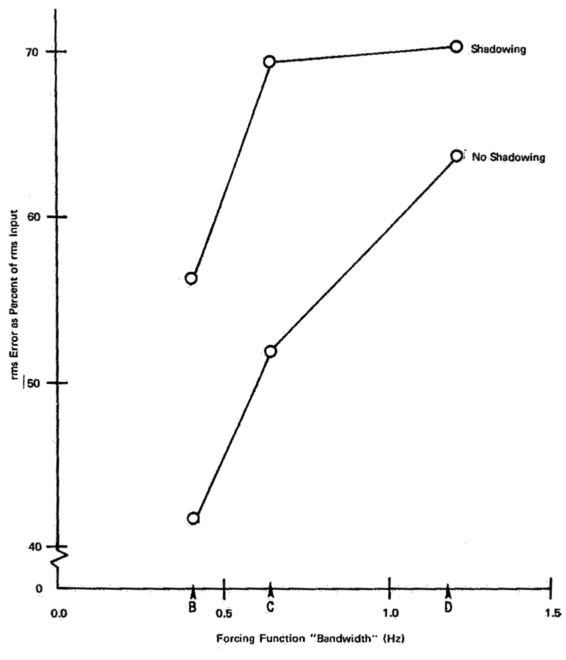

FIGURE 4.—Mean normalized rms tracking error for subjects 9 through 13 vs forcing function bandwidth with and without shadowing.

TABLE 4.—*Shadowing Scores*

[All scores are for 5 min runs and 6.49 bits/message]

	Subject	Trial	Number sent	Number transmitted	Percent transmission	Input, bits/sec	Output, bits/sec	Forcing function
Slow shadowing	1	2	267	265	99.3	5.78	5.73	*A*
		4	284	282	99.3	6.14	6.10	*B*
		6	283	283	100.0	6.12	6.12	*C*
	2	1	263	261	99.2	5.69	5.65	*B*
		3	281	281	100.0	6.08	6.08	*C*
		5	268	268	100.0	5.80	5.80	*A*
	3	2	272	271	99.6	5.88	5.86	*C*
		4	275	272	98.9	5.95	5.88	*A*
		6	269	267	99.3	5.82	5.78	*B*
	4	2	263	257	97.7	5.69	5.56	*C*
		4	278	275	98.9	6.01	5.95	*A*
		6	267	267	100.0	5.78	5.78	*B*
	5	1	269	267	99.3	5.82	5.78	*C*
		3	277	277	100.0	5.99	5.99	*B*
			out	of	Tape			*A*
	6	2	265	264	99.6	5.73	5.71	*B*
		4	277	276	99.6	5.99	5.97	*A*
		6	265	265	100.0	5.73	5.73	*C*
Fast shadowing	7	2	414	338	81.6	8.96	7.31	*B*
		4	417	370	88.7	9.02	8.00	*C*
		6	413	307	74.3	8.93	6.64	*A*
	8	1	426	322	75.6	9.22	6.97	*A*
		3	423	338	79.9	9.15	7.31	*C*
		5	427	338	79.2	9.24	7.31	*B*
	9	2	433	334	77.1	9.37	7.23	*B*
		4	425	340	80.0	9.19	7.36	*D*
		6	429	338	78.8	9.28	7.31	*C*
	10	1	427	337	78.9	9.24	7.29	*C*
		3	411	360	87.6	8.89	7.79	*B*
		5	417	383	91.8	9.02	8.29	*D*
	11	1	433	288	66.5	9.37	6.23	*C*
		3	413	311	75.3	8.93	6.73	*D*
		5	417	340	81.5	9.02	7.36	*B*
	12	2	436	198	45.4	9.43	4.28	*C*
		4	412	148	35.9	8.91	3.20	*D*
		6	425	191	44.9	9.19	4.13	*B*
	13	2	413	373	90.3	8.93	8.07	*D*
		4	422	384	91.0	9.13	8.31	*B*
		6	430	391	90.9	9.30	8.46	*C*

graphically in figure 5. Tracking information lost by the addition of the shadowing was greatly offset by the additional information added due to the shadowing. There was no evidence for a simple information rate channel capacity. Even using normalized information scores, the decrement produced by the addition of the shadowing was not sufficient to fit a channel capacity model. While other measures of tracking transinformation are possible (Wempe and Baty (ref. 11)) further effort in this direction was abandoned.

ANALYSIS OF TRACKING AND SHADOWING HOLDS

Tracking Holds

In the process of examining the tracking records, a striking difference was noted between the subjects' tracking response functions with and without shadowing. During tracking runs which included the shadowing task, the tracking response records were interspersed with periods of

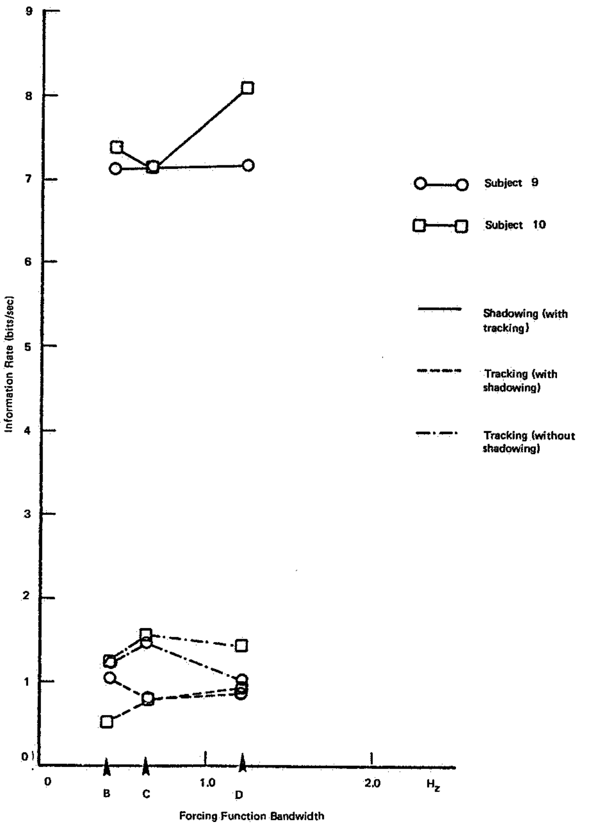

FIGURE 5.—Transinformation.

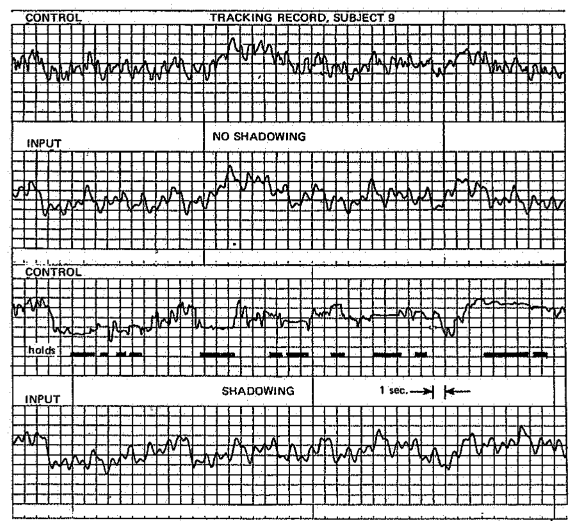

FIGURE 6.—Tracking records for subject 9 with tracking forcing function *D*, illustrating typical input and response (control) functions for tracking both with and without the simultaneous shadowing task. Tracking response holds generated while shadowing have been marked.

complete inactivity or holds on the subjects' tracking output function. In contrast, tracking without shadowing was relatively smooth and uninterrupted. Figure **6** shows a typical portion of tracking record for both the shadowing and no shadowing conditions, and clearly illustrates the difference.

Since forcing function *C* produced the greatest decrement in tracking performance, the input and the operator's control output data for these runs were analyzed for the tracking response holds. Each of the five subjects had two runs with forcing function C, one without shadowing (referred to as condition N) and one with shadowing (condition S). Each of these runs lasted 5 min, and was divided into two consecutive parts of **141** seconds each. The first and last halves of each run are referred to as parts I and II, respectively. The input and response data for these parts were sampled and digitized every **0.1** sec **(1410** samples per part of a run). This data was then digitally analyzed for holds by taking finite differences between successive samples. An interval between samples was counted as **a** hold if the difference was within the specified noise tolerance. Since the forcing function was composed of sinusoids, the input signal also contained some flat splots or apparent "holds" that were within the tolerance limits. For this reason the input was also analyzed in the same manner. The important result is the comparison of the distribution of "holds" for the input forcing function and the holds in the subject's tracking control output. Table 5 presents the results of this analysis.

Referring to table 5, it can be seen that holds in the subjects control output roughly matched the input distribution for the no shadowing condition; however, during runs with shadowing there was a marked increase in the total number of holds and also in the length of the tail of the hold distribution. In every case the addition of the shadowing task produced an increase in the number and mean duration of holds.

One possible explanation for the holds was that they were the result of a fatigue phenomenon. The data were analyzed in several ways to test

TABLE 5.—*Results of the Hold Analysis*

Subject	9								10							
Condition	N				S				N				S			
Part of run	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
Input, I or control, C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C
Hold length, number of points in tolerance																
2	125	106	133	155	108	104	102	112	144	157	134	131	103	108	114	102
3	50	60	47	62	44	30	42	47	36	61	39	51	38	35	46	38
4	18	28	10	22	17	16	20	24	14	21	15	20	29	16	20	12
5	1	19	1	12	4	12	10	15	2	1 1	6	6	6	4	4	1 0
6	2	3	2	2	2	6	2	5	4	2	3	3	3	5	3	9
7		7			1	6	1	4		2	1	3		6		6
8		1				10		2				1		5		6
9		1				10		4		1		1		1		3
10						3								3		3
11		1				2						1		1		2
12						1						1		1		
13						2		2						1		1
14						1								1		1
15														1		
16								1								2
17														1		1
18						1		1								
19														2		3
20																
21														1		1
Over 21 points, length/#						24/1 26/1 31/1								23/1 48/1		
Mean length [points] (total of 1410 pts/part)	2 49	3 07	2 40	2.59	2.59	4 23	2.71	3.25	2.43	2 63	2 53	2.77	2.70	3.96	2.59	3.97
SD [points]	0.77	1.45	0.71	0.89	0.91	3.98	1 0 1	2.23	0 83	1.04	0.93	1.43	0.97	4.75	0.88	3 55
Total number of holds	196	226	193	253	176	207	177	217	200	255	198	218	179	194	187	200
Total number of points	489	694	464	656	455	873	479	706	486	671	500	604	484	768	484	793

this hypothesis. The mean duration of the hold lengths for parts I and parts II was compared across all five subjects. A t-test failed to indicate any significant difference in mean duration between the two halves of the runs. Similarly, a test for increased number of holds gave no significant differencebetween parts I and 11.

Since it was possible that a five minute run was not sufficiently long enough to produce a differential fatigue effect between the two halves of each run, one other test was applied. If the holds were recuperative in effect, it might be assumed that the longer the period since the last hold, the longer the next rest period, or hold, would be. This hypothesis was tested by generating the distribution of elapsed times since the last hold and classifying according to hold lengths. Based on this analysis, there was no significant

11								12								13								
N				S				N				S				N				S				
I		II		I		II		I		II		I		II		I		II		I		II		
I	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	
105	52	96	72	114	18	97	16	124	146	138	129	132	118	155	132	95	102	119	102	114	97	135	117	2
40	49	29	52	48	26	45	12	57	36	35	49	56	**44**	51	27	33	69	36	52	58	53	47	47	3
17	34	24	**44**	16	15	**20**	18	16	19	20	24	13	**20**	12	12	18	36	26	39	20	32	13	29	4
7	22	11	11	2	14	4	8	1	8	1	8	3	9	1	8	16	28	7	18	1	15	**7**	17	5
2	1 8	2	2 6	4	3	4	5	2	4	1	5		2		4	3	12	1	12	2	10		10	6
1	9		11		2		4		4		2		3		7	2	6	1	1 2		6		5	7
	7		9		3		6				2		3		2		2		5				4	8
	6		6		4		2				1		4		1				3		2		1	9
	2		1		5		3		1		1		1		1						3		1	10
	3		1		1										1								1	11
	2		1				3						1		1		1				2			12
	1				1		2														1		1	13
	2				1		2								1				1		2		1	14
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	1				4																1			18
					5		2						1											19
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	2				2		2														1			21
	40/1				22/2		22/1						24/1		26/1									
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							52/1																	
							54/1																	
							80/1																	
2.63	4.87	2.73	4.04	2.55	9.69	2.66	11.24	2.50	2.65	2.42	2.81	2.45	3.21	2.36	3.18	2.89	3.27	2.62	3.51	2.56	3.65	2.47	3.36	
0.97	4.11	1.02	2.29	0.86	10.63	0.94	12.78	0.75	1.21	0.74	1.33	0.68	2.64	0.61	2.82	1 1 9	1.49	0.95	1.99	0.78	2.74	0.77	2.22	
172	214	162	236	184	127	170	110	200	218	195	221	204	208	219	200	157	256	190	245	195	226	202	236	
452	1042	442	953	470	1230	453	1236	500	578	472	620	499	667	516	636	453	837	498	859	499	825	498	792	

difference between elapsed time since last hold for short and long holds, and once again there was no support for the fatigue hypothesis.

Shadowing Holds

Next, the shadowing function was examined. Most of the shadowing decrement was a result of not responding to the input and thereby missing one or more input numbers. Seldom did a subject respond to the input with an incorrect number. Thus, the shadowing decrement was associated with a no response or "hold" condition rather than an incorrect response. In order to analyze the shadowing holds, the recorded shadowing response was passed through a voice key. The output of the key consisted of two exclusive states, either talking or no talking. Figure 7 is a

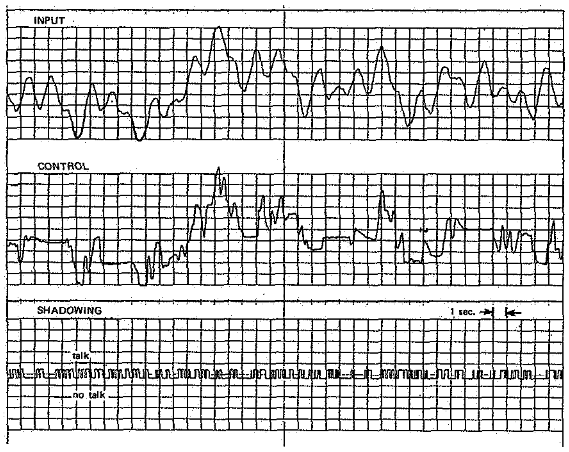

FIGURE 7.—Typical tracking and shadowing records for subject 9 with tracking forcing function *C* and fast shadowing input, illustrating both tracking and shadowing response holds.

typical portion of tracking record and provides a sample of the keyed shadowing response function. Once again each 5 min run was divided into two parts and the hold distributions compiled. Each part of a run consisted of 1435 samples taken at 0.1 sec intervals. The results are provided in table 6.

As was the case with the tracking, the shadowing holds have a long tailed, skewed distribution. Again, the short holds are primarily due to the properties of the input function. Holds up to three tenths of a second are attributable to normal interverbal spacings and not missed numbers. A t-test indicated no significant difference between the mean hold lengths in parts I and II, once more indicating no support for the fatigue hypothesis.

Test for Tracking and Shadowing Hold Interaction

The next step was to examine both the tracking and shadowing holds to test for possible correlation between the two. This was accomplished by computing the 2 X 2 contingency table of the percent time spent on the four possible hold and no hold combinations for the two tasks. To test the hypothesis of independence of holds on each task, a chi-squared contingency test was conducted. Under an independence hypothesis the percent expected simultaneous hold time *EC* during a run was calculated by taking the product of the percent of total time held on each task. The expected contingency table under independence and the measured table were compared using the chi-squared statistic. If the independence hypothesis were rejected, significant association between the shadowing and tracking holds could be assumed.

In analyzing the records and compiling the contingency tables, the holds were partitioned into two groups. Since short holds were attributable mainly to the properties of the respective forcing functions, these holds (those less than 0.3 sec) were analyzed separately. The results of this analysis are given in table 7. The analysis included subjects 9 through 13 using runs with forcing function C. Again, each run was divided into two parts. The table gives the measured percent time spent in tracking holds, in shadowing, and in simultaneous holds on both tasks. Also the expected percent time in simultaneous holds calculated under the independence hypothesis has been tabulated along with the chi-squared values for goodness of fit (values significant at 0.05 level or greater have been marked with an asterisk).

None of the interactions for the short holds were significant as would be expected, since the short holds are due mainly to the two uncorrelated input functions. However, for the long holds subjects 10, 13 and 9 in part II had significantly more simultaneous holds than would have been expected under independence. Subjects 12 and 11 showed no significant deviation from the independence hypothesis. Although these results are mixed, it is important to note that even though the difference from independence was significant for subjects 9, 10 and 13, the percentage difference was only 2 to 4 percent of the total time. This difference would mean about 6 to 15 sec more simultaneous holds out of a five min run than expected. Thus, the interaction effect which was found was small, albeit significant.

A Detailed Analysis of the Tracking Holds

Based on a single-channel model, it might have been hypothesized that when there was a

TABLE 6.—*Distribution of Shadowing Holds for Runs with Forcing Function C*
[1435 points/part of run]

Subj.	9		10		11		12		13	
Part of run	I	II	I	II	I	II	I	II	I	II
hold length, number of points in tolerance										
2	131	133	80	59	54	57	66	56	96	91
3	88	60	32	48	56	35	35	32	64	81
4	26	21	28	20	26	31	14	10	43	28
5	16	13	29	19	17	15	10	9	14	21
6	13	12	13	12	15	14	9	9	14	19
7	11	11	15	15	10	17	11	10	14	9
8	6	8	5	14	11	6	10	7	12	12
9	6	5	11	17	4	6	13	9	9	5
10	3	6	7	4	8	1	9	7	5	10
11	4	3	2	4	5	5	5	2	1	6
12	1	3	1	2	1	5	11	5	3	1
13	1	3	5	2	7	3	6	5	3	1
14	1	1	3	3	3	3	5	2	2	1
15	1				3	1	2	3	1	2
16		1	3	1		1	1	2	1	1
17				2	1	4	3	5	1	
18					3	1		1	1	
19				2			1	1		
20				1	2			3		1
21					2	3	2			
Over 21 points, (length/#)			23/1	24/2	22/1	22/2		24/1	23/1	
			27/1	25/1	26/1	23/2		25/1		
			29/1	26/1		28/1		28/1		
						37/1		39/2		
								32/1		
								35/1		
Mean	2.56	2.75	3.95	4.51	4.54	4.87	4.89	5.82	3.34	3.26
SD	2.30	2.69	3.99	4.41	4.50	5.34	4.40	6.46	3.18	2.92

response hold on one of the tasks the probability of a simultaneous hold on the other would be lower, since the attentional mechanisms were now freer to deal with the other task. This hypothesis was not borne out by the above findings; in fact, there was a tendency in the opposite direction. However, one might view a hold not as a period of freed attention, but rather as a period demanding attention in order to regain control. Furthermore, correlations between holds may be misleading due to the reaction time lags inherent in each task. A more direct approach to investigating the interaction between the two types of holds would involve some indication of the subject's attention as a function of time.

Although it was not possible to obtain a direct record of the attention function, it was possible to isolate times when the focus of attention was fairly well specified. It seemed reasonable to assume that at the termination of a tracking hold, the attention was focused on the tracking task. Based on this assumption, an analysis of the onsets and offsets of tracking holds was made.

At both the start and end of a tracking hold the error state was classified as high H, medium M, or low L, so that for the total error distribution the probabilities of each of these three error classifications were equal (i.e., $P_H = P_M = P_L = 1/3$). The slope of the error magnitude function was also classified as to whether it was increasing (condition I), decreasing (condition D), or approximately zero (condition Z). By classifying the displayed tracking error state

TABLE 7.—*Hold Interaction Results*

[Subjects 9 through 13, forcing function C]

	Subj. 9, part I		Subj. 9, part II		Subj. 10, part I		Subj. 10, part II	
	Long	Short	Long	Short	Long	Short	Long	Short
% SH	23.9	31.4	28.2	25.7	41.4	24.1	52.0	20.3
% CH	28.8	17.6	10.8	25.5	24.7	15.7	24.3	18.4
% Com	7.3	5.0	4.7	6.5	13.8	3.5	16.9	4.4
% EC	6.9	5.5	3.1	6.6	10.2	3.8	12.6	3.7
χ_1^2	0.5	0.9	14.0 *	0.0	28.3 *	0.3	39.6 *	1.8
	Subj. 11, part I		Subj. 11, part II		Subj. 12, part I		Subj. 12, part II	
% SH	52.0	21.8	53.7	19.7	57.6	15.2	62.1	13.0
% CH	66.9	11.5	71.9	7.9	11.0	21.7	12.4	17.1
% Com	34.1	2.7	39.3	1.8	7.0	3.5	7.7	2.3
% EC	34.8	2.5	38.6	1.6	6.3	3.3	7.7	2.2
χ_1^2	0.9	0.2	0.9	0.5	1.8	0.2	0.0	0.0
	Subj. 13, part I		Subj. 13, part II					
% SH	38.0	28.6	37.2	29.4				
% CH	14.6	25.0	11.4	26.2				
% Com	7.9	7.3	6.5	8.3				
% EC	5.5	7.2	4.2	7.7				
χ_1^2	18.8 *	0.0	21.6 *	0.9				

Symbols:
%SH = Percent of time not shadowing (shadowing holds).
% CH = Percent of time not controlling (control holds).
% Com = Percent of time SH and CH simultaneously.
% EC = (% SH) × (% CH).
χ_1^2 = Chi squared value (1 degree of freedom).
* = Significant chi squared value at <0.05 level.

in these two ways, it was hoped to uncover any rationale underlying the choice for the time of onset and offset of the tracking holds.

Along with the tracking error state, the state of the shadowing task was also examined. At both the onset and offset of each tracking hold the shadowing function was examined for ± 1.0 sec. The shadowing function was then classified into one of four categories: no shadowing hold within ± 1 sec (condition *N*); a shadowing hold which terminated within 1 second before the onset or offset point of interest (condition *B*); a shadowing hold ongoing during the onset or offset point of interest (condition *D*); and a shadowing hold which started after the onset or offset point of the tracking hold (condition *A*). In the *B* condition, the time between the end of the shadowing hold and the onset or offset point was tabulated. In both the *A* and *D* conditions, the time between the start of the shadowing hold and the onset or offset of the tracking hold was tabulated. Thus, for the *B*, *D*, and *A* conditions, both a frequency of occurrence and a time distribution were tabulated.

The frequency distributions for both the tracking error and the shadowing hold classifications described above were converted to percentages in order not to differentially weight subjects. These normalized results have been presented in table 8 for subjects 9 through 13. Again the runs using forcing function *C* were analyzed. The composite results in the form of the means and standard deviations for the results pooled over subjects have been presented at the bottom of the table. Also, the mean times between shadowing holds and tracking holds have been given for the *B*, *D*, and *A* cases described above. While much can be said about the results in table 8, only the main findings will be summarized here.

TABLE 8.—*Analysis of Onsets and Offsets of Trucking Hold*

[See text for complete explanation]

Subject 9:

Tracking error state, % occur

	Onset I	Onset D	Onset Z	Offset I	Offset D	Offset Z
L	51.2		4.7		4.7	
M	20.9			2.3	9.3	4.7
H	11.6	2.3	9.3	27.9	34.9	16.3

Shadowing holds (Time, 0.1 sec)

	Onset %	Onset Mean	Onset SD	Offset %	Offset Mean	Offset SD
N	39.5			26.2		
B	11.6	3.6	1.7	20.3	3.6	1.7
D	23.3	3.8	1.2	14.3	5.7	3.4
A	25.6	3.8	2.5	28.6	3.8	1.8

Subject 10:

	Onset I	Onset D	Onset Z	Offset I	Offset D	Offset Z
L	65.9			4.3	10.6	
M	10.6	4.3	4.3		6.4	
H	6.4	6.4	2.1	14.9	46.8	17.0

	Onset %	Onset Mean	Onset SD	Offset %	Offset Mean	Offset SD
N	43.2			43.2		
B	4.5	2.5	0.5	22.7	4.9	2.7
D	25.0	4.4	3.8	25.0	5.7	4.6
A	27.3	3.3	2.1	9.1	3.0	1.2

Subject 11:

	Onset I	Onset D	Onset Z	Offset I	Offset D	Offset Z
L	60.9			2.4	2.4	2.4
M	2.4	12.2			2.4	7.3
H	4.9	14.6	4.9	24.4	51.2	7.3

	Onset %	Onset Mean	Onset SD	Offset %	Offset Mean	Offset SD
N	61.5			61.0		
B	10.3	5.0	0.7	14.6	4.3	1.9
D	12.8	3.4	5.3	12.2	2.0	1.8
A	15.4	3.2	2.5	12.2	6.6	1.3

Subject 12:

	Onset I	Onset D	Onset Z	Offset I	Offset D	Offset Z
L	84.0				11.5	
M	4.0		12.0		3.8	
H				34.6	38.5	11.5

	Onset %	Onset Mean	Onset SD	Offset %	Offset Mean	Offset SD
N	12.0			24.0		
B	24.0	3.5	2.7	20.0	3.2	2.1
D	26.0	3.0	2.3	24.0	7.0	7.0
A	28.0	4.7	3.8	32.0	3.5	1.8

Subject 13:

	Onset I	Onset D	Onset Z	Offset I	Offset D	Offset Z
L	56.4		2.6	2.6		
M	15.4	7.7		10.3	12.8	5.1
H	12.8	2.6	2.6	17.9	41.0	10.3

	Onset %	Onset Mean	Onset SD	Offset %	Offset Mean	Offset SD
N	66.7			61.5		
B				20.5	2.5	2.2
D	7.7	3.3	1.2	10.3	3.5	2.7
A	25.6	4.1	2.8	7.7	5.7	1.2

Means:

		Onset I	Onset D	Onset Z	Offset I	Offset D	Offset Z
L	M	63.7		1.5	1.9	5.8	0.5
	SD	11.3		1.9	1.7	4.5	1.0
M	M	10.7	4.8	3.3	3.0	7.9	2.0
	SD	6.9	4.7	4.7	3.8	3.0	2.4
H	M	7.1	5.2	3.8	23.9	42.5	12.5
	SD	4.7	5.1	3.2	7.0	5.8	3.7

	Onset Mean	Onset SD	Onset Mean time, 0.1 sec	Offset Mean	Offset SD	Offset Mean time, 0.1 sec
N	44.6	19.3		43.2	16.2	
B	10.1	8.1	2.9	21.6	5.1	3.7
D	21.0	9.0	3.6	17.2	6.1	4.7
A	24.4	4.6	3.8	17.9	10.3	4.5

There was an extremely high probability **(65.2** percent) that the tracking error was in the low state at the onset of a tracking hold ($p > 0.005$). This result was still high (by about **25** percent), even if the error distribution excluded errors due to tracking holds. Thus, it seemed that the subjects did not start a hold at random, but that the subjects either chose to start a hold when the error state was low or that they took steps just prior to the hold in order to secure low tracking error. The former explanation seemed to be the case, as there was no evidence of sharp control discontinuities just prior to the onset of the holds. As would be expected at the start of a hold, the most probable **(81.5** percent) state for the error rate was an increasing error magnitude.

At the ends of the tracking holds, there was a large proportion **(78.9** percent) of high error states; this condition was to be expected at the end of a hold. There was a surprising result however. The rate of change of the error magnitude was most often **(71.2** percent) decreasing or zero at the point tracking control was resumed. It appeared as if the subjects had waited for an ideal time to resume tracking control, that is, when the forcing function was headed back toward the subject's current controller position or was at an inflection point and about to head back. If this were the case, it seems that some active monitoring of the tracking task must have gone on during the hold in order to determine when to re-establish control.

The only significant difference between the distribution of shadowing holds at the start of a tracking hold and at the end was an increase in the percent occurrence of shadowing holds which had ended just prior to the end of the tracking hold (condition ***B***). This result was mainly due to the fact that there was a fairly high probability of a shadowing hold beginning near (± 1 sec) the onset of a tracking hold, and that these shadowing holds often ended within the **1** see interval prior to the end of the tracking hold.

A PRELIMINARY MODEL

Assuming that the operator is a single-channel processor, a structure was hypothesized which might account for the above findings. Under the single-channel assumption, the operator must rapidly switch his attention from one task to the other in order to maintain simultaneous control. This simultaneous control was accomplished with no signs of decrement when the slow shadowing task was added. With the addition of the fast shadowing task, there was a consistent performance decrement on both tasks, and response holds were generated. It was hypothesized that with the fast shadowing input, the switching rate was not rapid enough to keep pace with both tasks continuously. The evidence may suggest that the subjects took advantage of times when the tracking task was well under control (i.e., low error) in order to allocate extra attention to the shadowing. This would account for the increased probability of holds starting in the low error state condition. If too much time were spent on the shadowing task, then upon the return of attention to the tracking task, the error could have grown too large, thus forcing the operator to hold. In this light, a hold would not be viewed as a release of attention from one task for the benefit of the other, but as an inadvertant

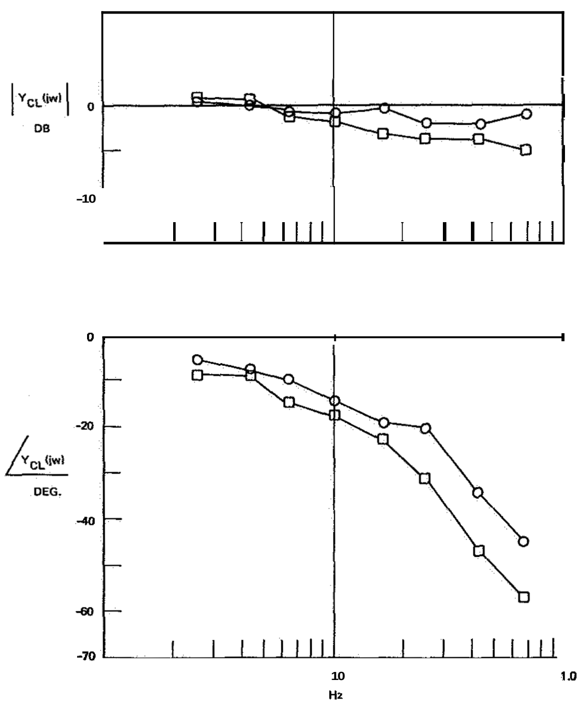

FIGURE 8.—Subject 9 closed loop Bode plot—forcing function *C*.

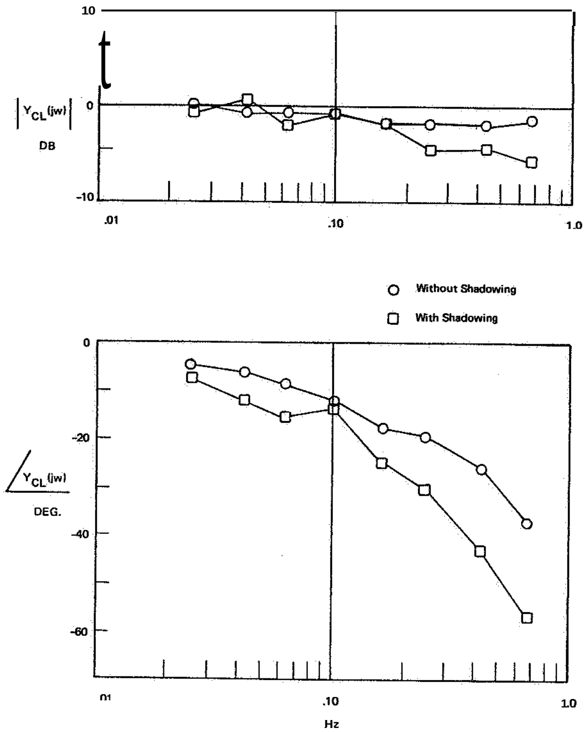

FIGURE 9.—Subject 10 closed loop Bode plot—forcing function *C*.

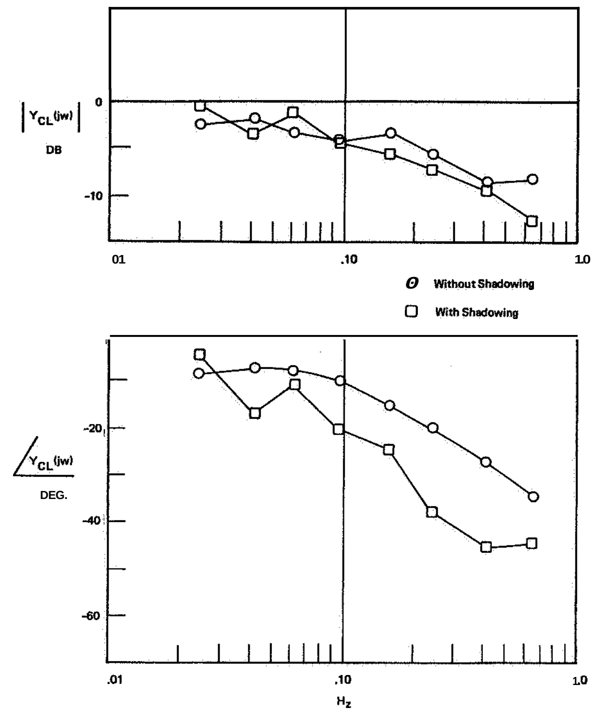

FIGURE 10.—Subject 11 closed loop Bode plot—forcing function C.

loss of control due to the combined effects of a relatively long absence of attention and the local properties of the forcing function at that point. The actual process of regaining control in order to terminate a hold may have even demanded a greater share of attention than ongoing tracking. Consequently, holds on the shadowing task would result from too infrequent sampling of the shadowing input. If the tracking holds do demand more attention than the ongoing tracking, this would account for the increased probability of simultaneous holds.

Although the above discussion is highly speculative and cannot be entirely verified with the data available from the present study, there are some further implications. If there is a single-channel attention mechanism, then the tracking lag should be greater when the shadowing task is added. In addition, if both types of holds actually require more attention than ongoing control, then there should be a differential increase in tracking lag during a shadowing hold. Both of the above hypotheses were tested.

THE TRACKING TRANSFER FUNCTION

The closed loop tracking transfer functions were computed using the Gabor transform technique. The resultant phase and gain plots are presented in figures 8 through **12** for subjects **9** through **13** respectively. As can be seen from the graphs, there is greater closed loop phase lag for the case of tracking with shadowing. This result does support the single-channel assumption. The open loop tracking lag was directly assessed by examining the cross-correlation functions between tracking error and the operator's output. These correlation functions have been plotted in figures **13** through **17,** with the time shifts for maximum correlation interpolated to the nearest 0.05 sec and indicated on the graphs. The resulting differential lag increase with the addition of the shadowing ranged from 0.05 to **0.3** sec.

An attempt was also made to test for the hypothesized differential increase in tracking lag when there was a shadowing hold. To accomplish

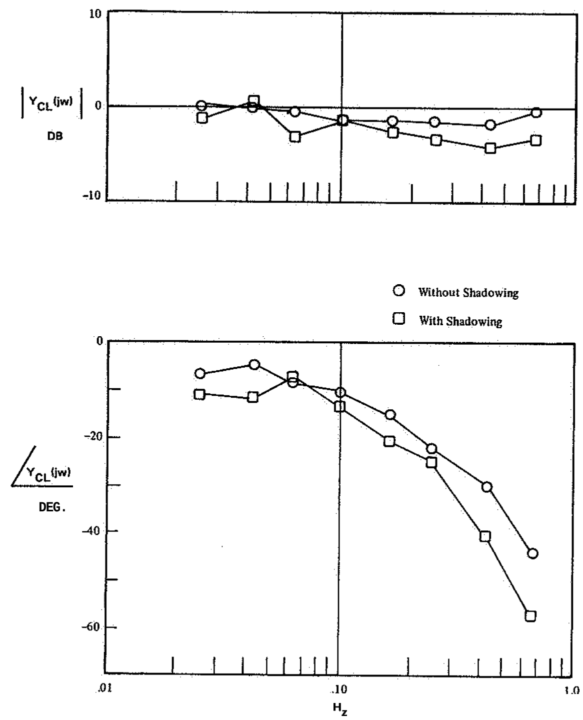

FIGURE 11.—Subject 12 closed loop Bode plot—forcing function C.

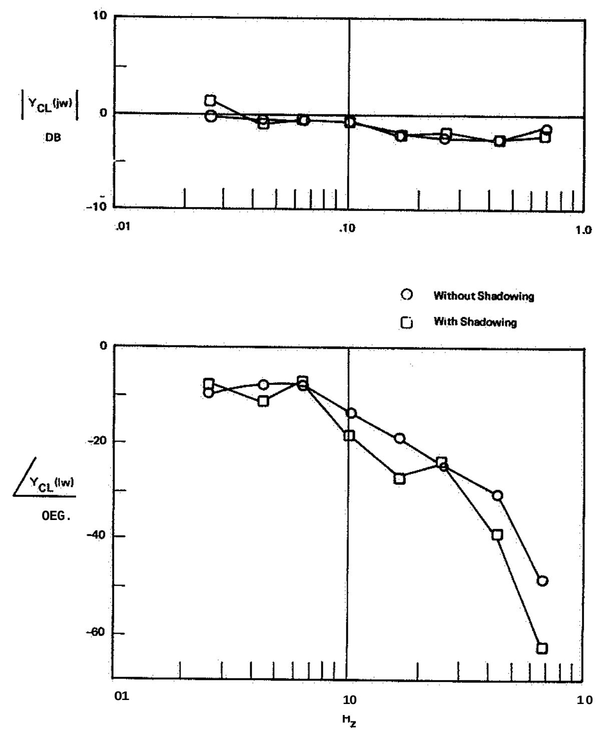

FIGURE 12.—Subject 13 closed loop Bode plot—forcing function C.

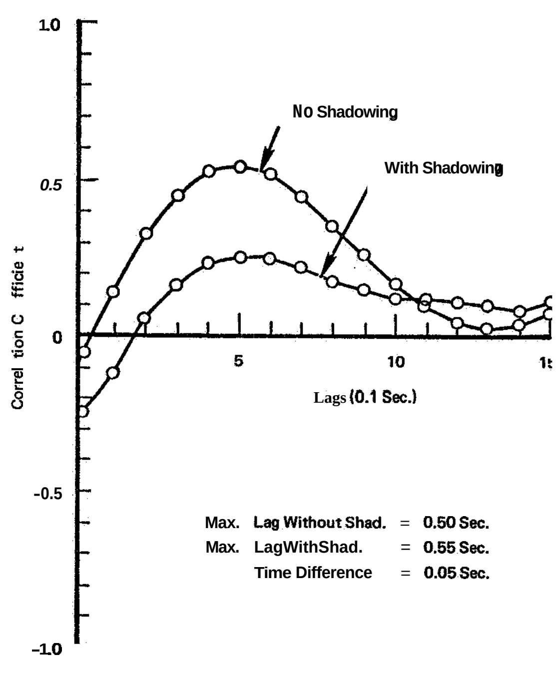

FIGURE 13.—Subject 9 open loop crosscorrelation functions with input *C*.

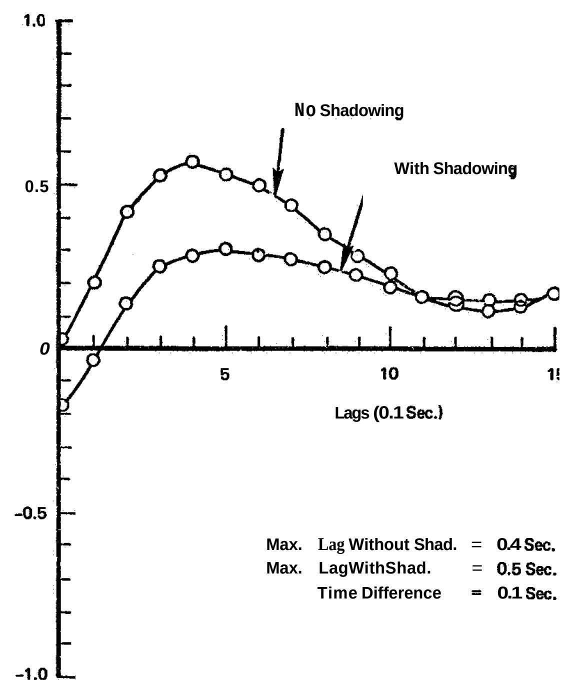

FIGURE 14.—Subject 10 open loop crosscorrelation functions with input C.

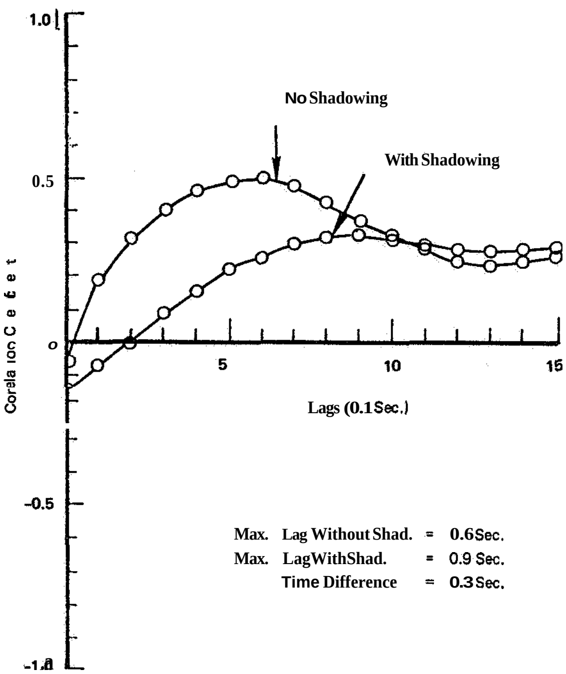

FIGURE 15.—Subject 11 open loop crosscorrelation functions with input *C*.

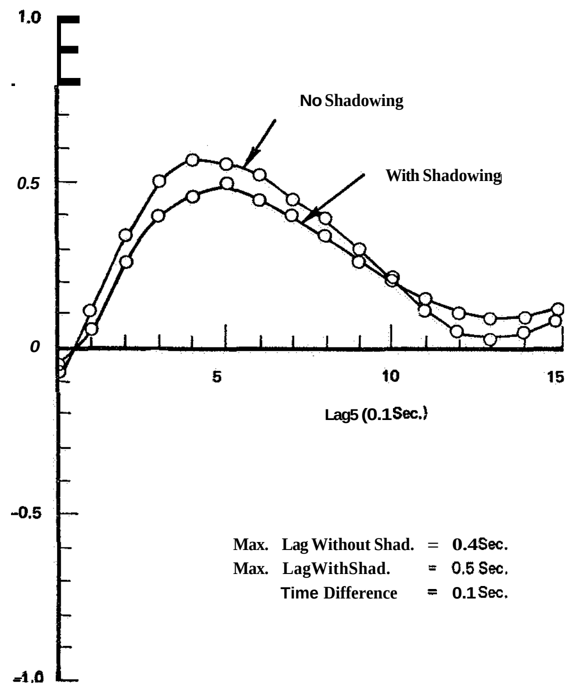

FIGURE 16.—Subject 12 open loop crosscorrelation function with input C.

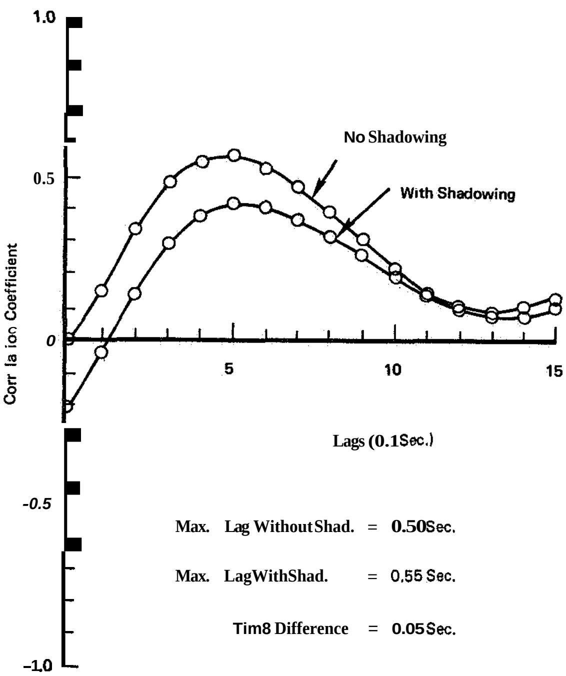

FIGURE 17.—Subject 13 open loop crosscorrelation function with input C.

this, the correlation functions were computed for sections of tracking where there were a number of closely grouped shadowing holds, and also for sections where there were relatively few shadowing holds. For two of the subjects, **11** and **13,** the shadowing holds were so evenly distributed throughout the run that the two types of tracking could not be partitioned. Although records for subjects 9, **10,** and **12** were analyzed, it was very hard to find relatively long sections of record which fit the above two descriptions; therefore, the results from this analysis must be viewed as tentative at best. For subjects 9 and **10** there was a measured increase in tracking lag during times when there were numerous holds on the shadowing function. The average increase for subject 9 was 0.18 sec and for subject **10** was **0.01** sec. For subject **12** there was a decrease of **0.01** sec. At this time the most reasonable conclusion is that the results are mixed and questionable, and that further experimentation is needed to test this specific point. Also further assessment must be made of the attentional demands of the tracking holds.

SUMMARY AND CONCLUSIONS

The experimental findings are summarized below.

(1) When slow shadowing (about one random number pair per second) was performed simultaneously with a zero order compensatory tracking task (forcing functions ***A, B,*** and ***C),*** there was no evidence of a performance decrement on either the tracking or shadowing task attributable to their concurrent performance.

(2) When fast shadowing (about one and a half random number pairs per sec) was performed simultaneously with a zero order compensatory tracking task (forcing functions *B*, ***C*,** and D), there was a consistent performance decrement on both the tracking and shadowing tasks attributable to their concurrent performance.

(3) The tracking decrement, as measured by normalized rms error, increased with forcing function bandwidth. The differential increase due to the addition of shadowing was greatest for forcing function ***C*.**

(4) There was no evidence to support the view that the dual task decrement could be accounted for by a simple information channel capacity model.

(5) A major source of the dual task decrement on both tasks seemed to stem from holds or cessation of response output for brief periods of time.

(6) It was not possible to account for the holds on either task in terms of a fatigue phenomenon.

(7) A contingency analysis of the shadowing and tracking holds revealed that for three of the five subjects analyzed there were slightly more simultaneous shadowing and tracking holds than would be expected if the two types of holds had been generated independently.

(8) A close analysis of the onsets and offsets of the tracking holds indicated that there was a high probability that the tracking error state was quite low at the onset of a hold, and that the subjects seemed to wait for the error magnitude to begin decreasing before resuming control.

(9) Closed loop frequency plots of the tracking response indicated less loop gain and greater phase lag when the shadowing task was added to the task environment.

(10) Cross-correlation analysis of the tracking records revealed that the open loop tracking lags increased from 0.05 to **0.10** sec with the addition of the shadowing task.

Although there is admittedly still much to be uncovered, these results have helped to illuminate some of the underlying factors which account for the dual task performance decrement. One of the major values of the present study was to offer substantiation for the single-channel hypothesis in the case of independent stimulus-response tasks. It now seems valid to undertake a detailed examination of the determinants of visual attention in an independent, dual, visual task environment. In this way the attention function can be made explicit through the eye position records. With this type of data, fundamental inquiries can be made to clearly define not only the exact function of a hold, but but also the factors which determine when a hold will begin or terminate.

Some very promising progress has been made toward the development of a deterministic model of simultaneous tracking and shadowing control under the single-channel assumption. The model assumes an inherent internal human operator "cycle time" of about 50 msec which governs input, output and switching of attention in relation to the two tasks (Kristofferson (refs. **12** and **13).** Based on the findings in this report, attention is normally allocated to the shadowing task only when the tracking error is in a low state. If, upon return of the attention to the tracking task, the error is in a high state, a tracking hold is initiated. Once a hold is ongoing, the error function is sampled twice in order to determine the slope of the error magnitude. An increasing magnitude results in an attention shift to the shadowing task, while a decreasing magnitude initiates the termination of a hold. The above algorithm implies that more attention is required by the tracking task during a hold, and gives rise to a slightly greater probability of a shadowing hold occurring.

Although the above assumptions need further verification, the model results are promising and show a remarkable similarity to those of the actual subjects. Details of this modelling effort will **be** made available in the near future.

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