N73-10139

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35. Human Transinformation Rates During One-to-Four Axis Tracking With a Concurrent Audio Task

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An experiment was conducted to determine the information processing rates of six subjects performing one-, two-, three-, and four-axis compensatory tracking tasks, with and without a concurrent four-choice auditory task. The purpose **was** to obtain further evidence concerning the nature of an hypothesized ceiling on human transinformation rates. Interference was found **among** tasks, but the evidence concerning **a** ceiling on information processing rates was inconclusive.

INTRODUCTION

This study was a continuation of research (refs. **1, 2,** and **3)** investigating the utility of measures of transinformation (infgrmation processing rate in bits/sec) in describing and predicting human performance in tasks related to aerospace missions.

Specifically, this experiment was designed to increase the number of simultaneously performed tasks beyond that used in prior experiments in order to obtain evidence that would either support or refute the evidence found in a prior study (ref. **2)** that a ceiling on total transinformation may exist. That study used a one- and two-axis integrated compensatory display controlled with a single two-axis controller. The subjects responded to a two-choice audio input task with the free hand. **A** portion of the results of that study suggested that a ceiling of some sort existed with the K and K/S dynamics with no evidence for a ceiling with K/S^2, even though the total transinformation was less than for the other two dynamics.

For the present experiment, provision was made for one, two, three, or four axes of tracking using K, K/S or K/S^2 dynamics. In addition, a four-choice audio task was added for half the trials. When the experiment was designed the choice of which one-axis task, or which two-axis task, etc., should be presented was rather arbitrary. **To** have used all possible combinations of one-, two-, and three-axis tasks would have required too many experimental conditions.

The following, fairly general, hypotheses were made prior to the experiment.

(1) With the successive addition of tasks a limit (ceiling) on total transinformation would be found as evidenced by an approach to some asymptotic value.

(2) The ceiling would be related to the order of the dynamics, i.e., K/S^2 would have a lower ceiling than K/S, which would in turn have a lower ceiling than K.

(3) Each additional task would cause a decrement in transinformation on a "per channel" basis regardless of whether a ceiling was shown. This decrement would be related to the order of the dynamic, i.e., K more than K/S, and K/S more than K/S^2.

(4) When (if) a ceiling was demonstrated with two, three, or four tracking channels, the addition of the auditory task would decrease the total transinformation of the two, three or four channels by at least the amount of transinformation computed for the audio task.

Before the selection of subjects for this experiment began, a few ((interested volunteers" spent considerable time learning the task. **It** was generally agreed that the limits of the subjects would

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indeed be found. A fairly extensive coverage of subject selection procedures will be given since it probably had a large influence on the results of the experiment, and it is assumed this will be of general interest to other experimenters because of the ever present problem of subject selection. For this experiment the selection was deemed especially important because the object was to find subjects who could perform well enough that data could be obtained on all conditions.

Following a description of the experiment, the results will be discussed in terms of task interference and the hypothesized transinformation ceiling. Performance comparisons will then be made, both between separate parts of this experiment and between this experiment and prior experiments. The final part of the discussion will be on the more tentative subjects of motivation and transinformation model assumptions.

TASKS AND PROCEDURES

Tasks

Continuous Compensatory Tracking *Task.*—The elements for this task were displayed on a 30 cm (12 in.) oscilloscope. Two 0.635 cm (1/4 in.) reference circles, 6.35 cm (2-1/2 in.) apart remained centered on the scope as shown in figure 1. The two 0.95 cm (3/8 in.) cross hair followers could be electronically driven anywhere on the face of the scope. The two cross hairs were oriented differently as shown to prevent confusion about which was the right and left follower when doing four-axis tracking. The subject's eye was held at 66 cm (26 in.), so that the visual angle between the two references was approximately 5.5° or ±2-3/4° from an imaginary center point.

The task forcing functions were provided by a multichannel FM magnetic tape system. The filtered output of a low-frequency gaussian noise generator had been prerecorded on magnetic tape. The recorded signal had been shaped by a second-order filter, providing a -40 dB/decade power spectrum beyond the break frequency ω_n for a forcing function. All runs were made with ω_n set at 1 rad/sec which corresponds to an effective bandwidth of 0.24 Hz, calculated as in prior studies (refs. 1 through 3). The inputs for multi-axis tracking were all statistically independent. The 1 rad/sec forcing function was chosen as a compromise between two limitations. As shown in an earlier study (ref. 1), transinformation plotted against signal bandwidth generates a unimodel curve with the peak appearing between 2 and 4 rad/sec. The desire was to choose a frequency as high as possible (without passing this peak) and still have a task that could be controlled in four axes for all dynamics. Preliminary tests showed that 1 rad/sec was the best compromise.

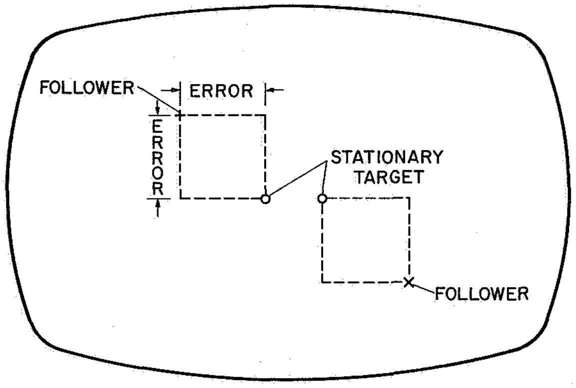

FIGURE 1.—Four-axis compensatory display.

Error control was provided through compatible movements of two, two-axis MSI Model 438 sidearm controllers with special flexible control sticks. The sticks were mounted upright and would deflect 1 cm at the tip with a 6×10^5 dyne side force.

Three controlled element dynamics were used: displacement (5×10^{-5} cm error displacement per dyne stick force), velocity (25×10^{-5} cm/sec error displacement per dyne), and acceleration (25×10^{-5} cm/sec^2 error displacement per dyne).

Discrete Auditory Task.—A four-choice audio input task was generated by random selection of a 1000 or 350 Hz tone; either was randomly presented as a clear tone or with white noise added. The tones were presented at a rate of 40 per min (i.e., a maximum information rate of 1-1/3 bits/sec). Responses were made with the feet which rested on metal plates pivoted under the arch of the foot. The 350 Hz tone was associated with the left foot and the 1000 Hz tone with the right foot. Clear tones were associated with toes while tones with noise went with the heels. For example, for a clear 1000 Hz signal the response was made by pushing down with the right toes. This activated a switch under the foot plate and turned off the signal. If an incorrect response was made the tone signal remained on.

Test Subjects

Since the experiment was to be long and difficult, a special effort was made to select *six* subjects who were highly motivated and potentially skillful trackers. First 19 male college students were selected who expressed interest by phone and said they would be available through the entire school year. Subsequently, each of these 19 students made 160 runs on the critical task device (ref. 4), which is a tracking task that gives a measure inversely related to effective reaction time (i.e., high scores were related to quick corrections to changes in target position). At the end of the day each man was given a simple questionnaire that was designed to point out any differences in goal setting behavior or intentions (ref. 5). The questionnaire, as designed did not prove to be of any use in establishing a selection criteria.

Seventeen of the students were willing to spend a second day making another 160 runs on the critical task device. The six students with the highest score averaged over the last 120 runs were chosen for the experiment. The mean scores for 17 students ranged from 7.07 to 4.19. All knew beforehand that their performance on this task would determine whether they would have a chance to participate in a long experiment with pay.

Table 1 shows the criteria task average score for the six selected subjects, along with relative total scores based on cumulative transinformation totals from the entire experiment. Although the pretest scores did not predict the final ranking for the experiment, the selection procedure was considered a success. Not one subject "dropped-out" of the experiment which ran almost seven calendar months, and every one was able to learn each task to a "scorable" criterion. One would not expect to be able to predict final ranking within a group whose members were originally so near each other in performance.

Of the six subjects, two were left-handed, all had normal corrected vision, and none had participated in any prior tracking experiments. It may be of interest to note that this selection procedure selected *six* very active young men, which caused some scheduling difficulties. Activities ranged from student government to other jobs. One man had three other jobs plus a full academic load. In retrospect, it would have been of interest to have correlated critical task score with I.Q. or some general measure of vitality.

Procedure

Instructions.—For the compensatory tracking task, the subjects were told, "Keep the crosses as close to the center of the circles as possible at all times; the score is related to the average value of the error for the entire run." For the audio task, they were instructed to respond to each tone within 1-1/2 sec or less after the onset of the tone. They were told that their score was the number of correct responses minus the number of incorrect responses divided by the total number of tones presented during the test

TABLE 1.—Relative Performance: Critical Task and Main Experiment

Subject	Average critical task score, $\bar{\lambda}$	Relative rating main experiment K	K/S	K/S^2	Average relative rating	Rank on experiment
D	7.07	98.1	86.6	77.1	87.3	3
A	6.92	91.0	83.8	74.0	82.9	6
C	6.83	90.6	87.2	78.0	85.3	4
B	6.80	100.0	85.2	100.0	95.1	2
E	6.44	91.3	81.0	83.4	85.2	5
F	6.29	99.5	100.0	87.4	95.6	1

period. They were told that they were not scored on how quickly they responded, so long as they responded within the 1-1/2 sec interval. If an incorrect response was followed by a correct response within the 1-1/2 sec time period, both a correct and an incorrect response were scored.

When the tracking task(s) and the auditory task were presented together, the subjects were not told how to weigh the two tasks. They were only told to do their best on both. At the beginning of each day the subjects were informed of their performances on the previous day and urged to lower their (error) scores. On multiaxis tasks the separate scores for each axis were available but generally the subjects concentrated on bringing down the average score across axes. It was repeatedly emphasized throughout the experiment that each condition was of equal importance and that maximum effort was to be extended on each run, whether it seemed like an easier task or not. It is believed that one other point had considerable bearing on the outcome of the experiment. At no time was it ever conveyed to the subjects that there was any doubt that they would learn the assigned tasks.

Performance Measures.—Two scoring procedures were used for the compensatory tracking task. An on-line relative rms error score was computed for each axis for each run to give a day-to-day indication of subject progress and to inform the subjects of this progress. The other procedure was to digitize and store directly on magnetic tape the system input and output signals for each axis being tracked. These data were used in the off-line computation of transinformation measures.

For the auditory task, the number of input signals, the number of correct responses, and the number of incorrect responses were recorded during each run. To obtain the auditory task transinformation rate for each run, the maximum transinformation rate of 1-1/3 bits/sec ($2/3 \log_2 4$) was multiplied by the ratio formed by subtracting the number of incorrect responses from the correct responses and dividing by the total number of stimuli presented during the run.

Training and Experimental Design.—Table 2 summarizes the sequence of the experiment for the six subjects. Each subject trained with a given controlled-element dynamics, then all data were recorded with those dynamics before presenting him with a new set of dynamics to learn. Using six subjects made it possible to present the dynamics in all possible sequences. The subjects were randomly assigned to each sequence. For phase I there were 75 training runs—15 per day for 5 days. For phases II and III there were 60 training runs (4 days) except for K/S^2 dynamics where 75 training runs were given. This meant that subjects A and D had one day less of training than the other four subjects during the experiment. After the initial introduction to the audio and tracking tasks, training was carried out in the same manner as the main part of the experiment; that is, the ten experimental conditions were presented in random order. For the main experiment, each subject ran six replications of the ten conditions for each set of dynamics in random sequence, making 60 runs per set.

Table 3 shows the combinations of tasks used to make the ten experimental conditions, along with the code designations.

Generally, two subjects were run per day, one resting in another room while the other was tracking so that there was always at least 1/2 hr between each of the three daily sessions for a given subject. The runs were 3-1/2 min long. During a session of five runs, the rest periods were 1-1/2 min between runs.

TABLE 2.—*Sequence of* Experimental Conditions

	Subject					
Phase	**A**	**B**	**C**	**D**	**E**	**F**
I	K/S^2	K/S	K	K/S^2	K/S	K
II	K	K/S^2	K/S	K/S	K	K/S^2
III	K/S	K	K/S^2	K	K/S^2	K/S

TABLE 3.—*Experimental* Condition Codes

Number of axes tracked	1	2	2	3	4
Axes tracked	LV*	LV and LH	LV and RV	LV, LH, and RV	LV, LH, RV, and RH
Without audio task	*S*	D	*P*	*T*	*F*
With audio task	*S*+	*D*+	*P*+	*T*+	*F*+

* LV—left vertical axis
LH—left horizontal axis
RV—right vertical axis
RH—right horizontal axis.

Data Reduction.—The input and output signals for each of the tracking tasks were digitized on-line (sampled from track-and-store units at the rate of 10/sec). For each pair of input and output signals, 1800 samples per channel were obtained for each run and stored onmagnetic tape for off-line computation. Cross correlation and auto-correlation values with 90 lags and subsequent power spectral densities were computed. The transinformation values were obtained by the following formula:

Transinformation =

$$\int_0^\infty \log_2\left[1+\frac{S(f)}{N(f)}\right]df \cong \Delta f \sum_f \log_2\left[1+\frac{S(f)}{N(f)}\right]$$

where

$$1+\frac{S(f)}{N(f)}=\frac{\Phi_{00}(f)}{\Phi_{00}(f)-\dfrac{|\Phi_{i0}(f)|^2}{\Phi_{ii}(f)}}$$

also

$$\text{Relative error}=\frac{\sqrt{\dfrac{1}{\pi}\displaystyle\int_0^\infty \Phi_{ee}(f)\,df}}{\sqrt{\dfrac{1}{\pi}\displaystyle\int_0^\infty \Phi_{ii}(f)\,df}}$$

RESULTS AND DISCUSSION

Primary Performance *Measures*.—Figures 2, 3, and 4 show the combined performance for the six subjects for *K*, *K*/*S*, and *K*/*S*^{2}, respectively. These figures show the total transinformation for each condition, the solid lines indicating continuous tracking transinformation and the dotted lines the audio task transinformation. Also shown part way up on each column are bars indicating the average transinformation per channel for the continuous tracking tasks. From figures 2, 3, and 4 it is difficult to detect the variation of the audio task transinformation so the actual values are listed in table 4. It can be seen that the differences in rate were small but consistent, dropping in value as the number of axes tracked increased, and dropping from *K* to *K*/*S* to *K*/*S*^{2}.

The average transinformation per channel for the continuous tracking tasks is shown in figure 5. This figure provides a gross comparison of all conditions for this experiment. Taking the average of all conditions for each dynamic, the average transinformation per channel was 3.71 bits/sec for the *K* dynamics, 3.12 bits/sec for *K*/*S*, and 1.64 bits/sec for *K*/*S*^{2}. The total difference between *K* and *K*/*S*^{2} of 2.07 bits/sec was essentially the same as that found in an earlier study (ref. 2). However, where the earlier study showed the *K*/*S* results to be more or less equally spaced between *K* and *K*/*S*^{2} (i.e., 1 bit/sec difference either way), these results showed the difference to be considerably less between *K* and *K*/*S* (0.59 bit/sec) than between *K*/*S* and *K*/*S*^{2} (1.48 bits/sec). These results are not directly comparable since the earlier data were obtained using three different forcing function frequencies ($\omega_n=0.5$, 2.0, and 8.0 rad/sec), but the range did span that used for this experiment (i.e., 1 rad/sec).

Also shown in figure 5 are the averages for each set of dynamics both with and without the concurrent audio task. The difference in transinformation between the tiacking tasks with and without the audio task was 0.27 bit/sec for *K* dynamics, 0.13 bit/sec for *K*/*S*, and 0.09 bit/sec for *K*/*S*^{2}. Although the differences

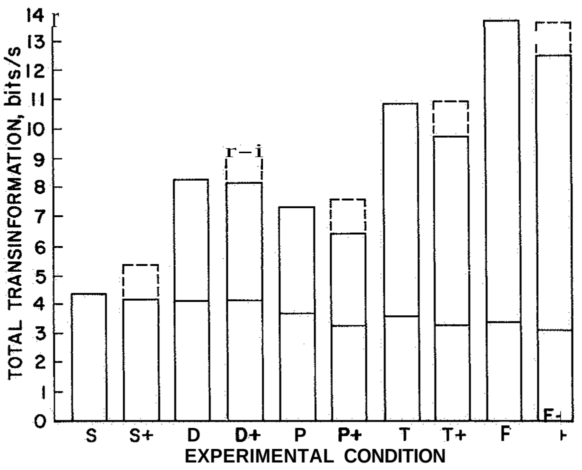

FIGURE 2.—Transinformation rates, *K* dynamic, all conditions, average 6 subjects.

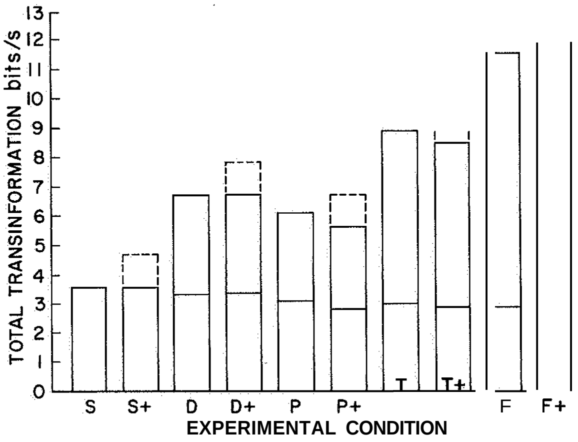

FIGURE 3.—Transinformation rates, *K/S* dynamic, all conditions, average 6 subjects.

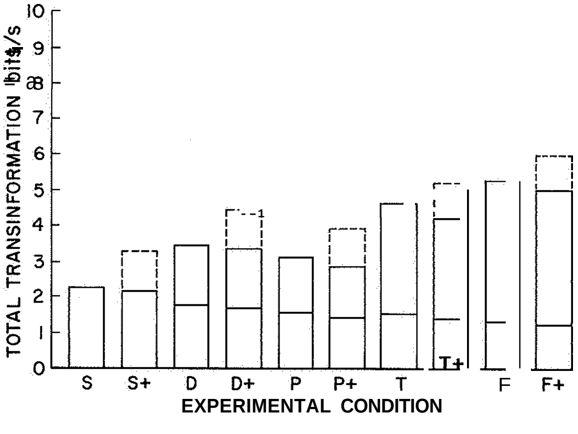

FIGURE 4.—Transinformation rates, K/S^2 dynamic, all conditions, average 6 subjects.

TABLE 4.—*Audio Task Transinformation (bits/sec)*

Condition	K	K/S	K/S^2	Avg
$S+$	1.18	1.18	1.11	1.16
$D+$	1.16	1.16	1.08	1.13
$P+$	1.18	1.14	1.08	1.13
$T+$	1.16	1.12	1.02	1.10
$F+$	1.12	1.12	1.00	1.08
Avg.	1.16	1.14	1.06	1.12

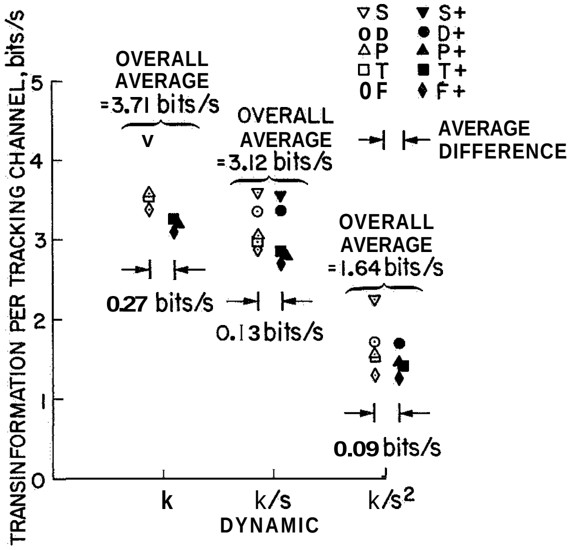

FIGURE 5.—Summary-average transinformation per tracking channel.

are small it can be seen by referring to table 4 that the tendency was to trade performance on the audio task for performance on the tracking tasks as the order of the dynamics is increased.

Table 5 provides a comparison of three different measures of tracking performance for this experiment, transinformation, relative error and open-loop crossover frequency ω_c, shown as overall averages on a per-channel basis. Generally the three measures follow the same trend, best performance (on a per axis basis) for the single task with progressively lower performance as tasks were added. This similarity in trend between performance measures was also found in an earlier study (ref. 3). Figure 6 shows that for this experiment given a value of relative error, one could fairly accurately predict the value of transinformation, particularly for *K* and *K/S*. This

TABLE 5.—*Comparison* of Performance *Measures* (average per tracking channel)

Dynamic		Experimental condition									
		S	$S+$	D	$D+$	P	$P+$	T	$T+$	F	$F+$
K	I, bits/sec	4.36	4.16	4.14	4.07	3.67	3.21	3.61	3.26	3.44	3.13
	Relative error	.208	.209	.214	.219	.248	.268	.243	.263	.263	.278
	X_{ovr}, Hz	.943	.915	.932	.886	.812	.760	.834	.768	.782	.758
K/S	I, bits/sec	3.60	3.56	3.38	3.39	3.07	2.81	2.99	2.84	2.90	2.71
	Relative error	.259	.267	.277	.280	.320	.344	.320	.339	.332	.348
	X_{ovr}, Hz	.771	.734	.749	.736	.646	.615	.657	.618	.634	.606
K/S^2	I, bits/sec	2.25	2.16	1.72	1.69	1.58	1.43	1.55	1.43	1.34	1.27
	Relative error	.520	.540	.614	.632	.672	.728	.682	.738	.742	.777
	X_{ovr}, Hz	.570	.540	.522	.500	.463	.461	.466	.450	.436	.438

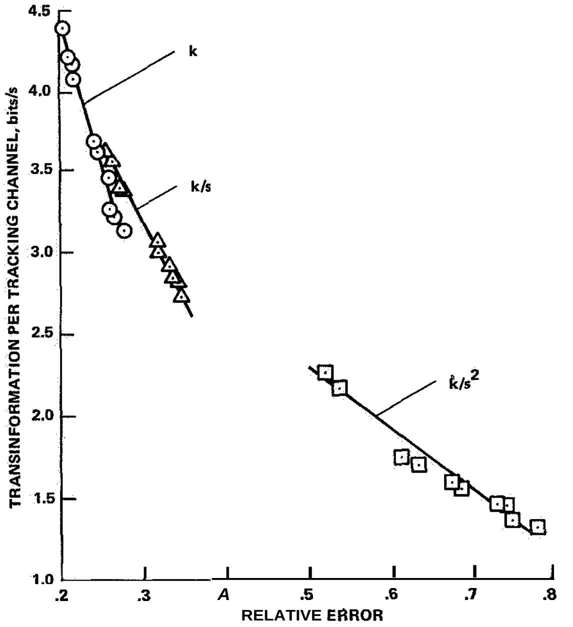

FIGURE 6.—Relationship between transinformation and relative error.

relationship is good only for the averages as calculated, however, and in a random sample of individual runs some showed marked deviations from these curves. Also it is to be stressed that this particular set of curves is good only for the conditions for this experiment. Any change in forcing function, gain, etc., would produce another set of curves.

Task Interference.—It can be seen in figures 2 through 4 that there was additional interference each time a task was added to any task set. For example, when tracking only one axis with K dynamics, the average transinformation was 4.36 bits/sec. When tracking the D condition the total transinformation was 8.28 bits/sec. If there had been no interference (i.e., if the second task had not affected performance on the first task and was of equal difficulty as the first task), the D total transinformation would have been twice 4.36 or 8.72 bits/sec. In like manner, the interference due to the addition of a third tracking channel to a two-axes task would be the difference between three-halves of the two-axes score and the total three-axes score, etc. This is shown graphically in figures 2 through 4 by the lines indicating average transinformation per tracking channel. The downward slope of these values indicate successive task interference.

The above discussion has answered the first part of the third hypothesis (Introduction) concerning per channel decrements in transinformation (interference) with additional tasks. Table 6 and figure 5 together answer the second part of the hypothesis relating to whether the amount of the decrement is related to the order of the dynamics. Listed in table 6 are the average values of transinformation per tracking channel for both single axis tracks (X and $S+$), all two-axes tasks ($D D+$, P and $P+$), etc. for the three dynamics. Adjacent to these values are the incremental decrements with an additional tracking channel. From this table no clear statement can be made about the relationship between the amount of decrement and the order of the dynamics. It is seen that the largest decrement was for K/S^2, adding a second tracking channel to a single channel. In turn the K and K/S data show larger decrements in going from 2 to 3

TABLE 6.—*Transinformation Decrement With Increaed Number of Tracking Tasks* *

Tracking channels	K Transinformation per tracking channel	K Decrease due to added channel	K/S Transinformation per tracking channel	K/S Decrease due to added channel	K/S^2 Transinformation per tracking channel	K/S^2 Decrease due to added channel
1	4.26		3.58		2.21	
2	3.77	0.49	3.16	0.42	1.61	0.60
3	3.44	.33	2.92	.24	1.49	.12
4	3.28	.16	2.80	.12	1.30	.19

* All values in bits/sec.

tracking channels. However, it has already been noted (fig. 5) that the average decrement with the addition of the audio task was 0.27 bits/sec for K dynamics, 0.13 bits/sec for K/S, and 0.09 bits/sec for K/S^2. At least with the addition of the audio task the decrement was related to the order of the dynamics and in the direction indicated.

In a similar experiment using K/S^2 dynamics Levison and Elkind (ref. 6) found that adding a second axis of control resulted in little or no interference. Their experimental conditions corresponded to conditions S and D of this experiment. This does not agree with the present results where the decrement was 1.06 bits/sec (twice the single axis value, 2.25 bits/sec, minus the two axes value, 3.44 bits/sec). Their estimate of 3.6 bits/sec for two axis transinformation was, however, very close to the 3.44 bits/sec found for this experiment.

In an experiment with four separated displays, two hand controllers and no visual scanning allowed, Levison et al. (ref. 7) found that interference was less when two side-by-side axes were tracked with two hands than when two axes (one above the other) were tracked with one hand on a two-axis controller. In the present experiment (figs. 2 through 4) performance was degraded more when the second axis was added as a separate right vertical task to be tracked with two hands than when added as the left horizontal task to be tracked with one hand. These two results are not in disagreement but rather point to the disadvantages of an integrated control when the display is not integrated. Conversely, the results of the present experiment show the advantages of an integrated control and display over a separated control and display.

Transinformation Ceiling

Three of the four hypotheses stated in the Introduction dealt with finding and describing a ceiling on transinformation. The evidence for that ceiling was to be an approach to an asymptotic value of transinformation with additional tasks. The finding of task interference in these results does not necessarily indicate the existence of a transinformation ceiling. Figure 7 was obtained by plotting only the data from conditions S, D, T, and F for each set of dynamics to isolate the effects of successively adding tracking tasks only. If the assumption is made that each additional axis is an equal additional increment of total task load, then the points can be connected as shown by the solid lines. Strictly on the basis of the tracking task results alone it is obvious that there is no evidence for a ceiling on total transinformation, at least for K and K/S. (If condition P had been used instead of condition D a straight line would have been a good approximation for all four points.)

While the combination of tracking tasks alone did not show evidence of an information processing ceiling (figs. 2 through 4), the addition of the audio task did yield results that suggest some kind of limit. The effect is most evident for K, less for K/S and least for K/S^2. For all dynamics the decrease of transinformation with the addition of the audio task was small when all tracking was being done by the left hand, either one- or two-axis. When tracking was done with two hands, however (2, 3, or 4 axes), the interference due to the audio task was evident. For K dynamics this interference was such that the total transinformation for five tasks $F+$ was less than for four tasks F.

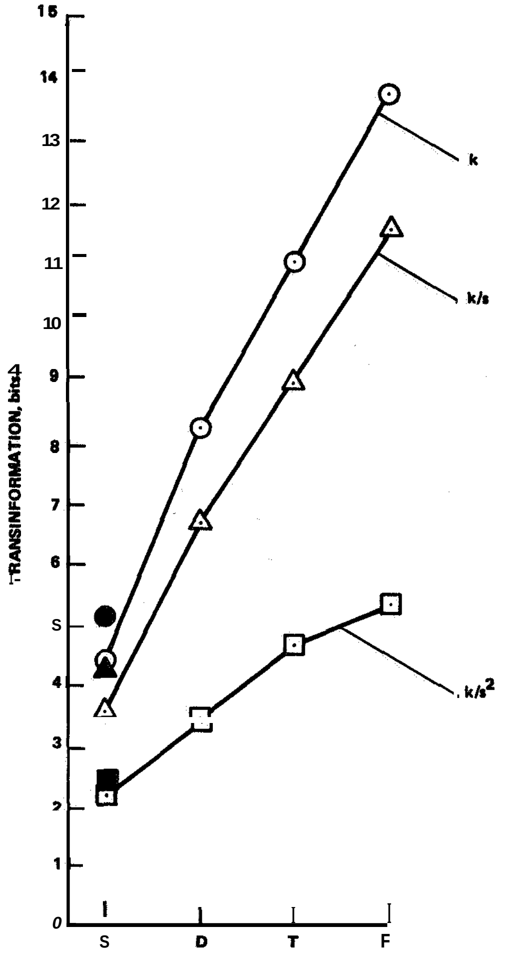

FIGURE 7.—Continuous tracking tasks, showing absence of transinformation ceiling.

Comparison Model for Three Dynamics

Transinformation performance has been presented separately for K, K/S, and K/S^2 data (figs. 2 through 4). From these figures it is difficult to compare the relative effects of additional tasks. It was decided to "adjust" the K/S and K/S^2 data to the magnitude of the K data by some simple mathematical model. The average differences between dynamics shown in figure 5 suggested one approach, That is, the average difference between K and K/S was 0.50 bits/sec per tracking channel. To each data point for K/S was added 0.59 times the number of axes being tracked for that data point. In a similar manner, to each K/S^2 data point was added 2.07 times the number of axes tracked. The results of the application of this procedure are shown in figure 8. Considering that the adjustment values used were gross averages and were also multiplied by as much as a factor of four, the clusters of data points are surprisingly close. If performance with K dynamic is taken as the reference, this means that performance on K/S and K/S^2 can be closely approximated by simply adding a common factor to each tracking channel.

With the data all in the same relative proportion (fig. 8) some of the differences between dynamics can be pointed out. The one-axis performance was very nearly the same. Performance on the two-axis integrated tasks was nearly the same with or without the audio task. There was about 0.9 bit/sec difference between K performance and K/S^2 performance in both cases. Finally, note the small but consistent relationship between K and K/S^2 performance for all two-handed tasks. For tracking without the audio task, performance is nearly the same but with K higher in each case. For the tracking with the audio task, K is lower in each case by an average difference of nearly 0.5 bit/sec. This reinforces the position stated earlier that the addition of the audio task affected performance more for the K dynamics than for the K/S^2 dynamics, both on a relative and an absolute basis.

Comparison of Integrated and Split Axis Tracking

It was pointed out in the Introduction that it would have been prohibitive to have used all possible task combinations as experimental conditions. However, two different ‘two-axis tasks were used and the performance on the two tasks was different. The performance was poorer for the P and $P+$ conditions than for the D and $D+$ conditions for all three dynamics but the following discussion is for the K dynamic only.

It was first thought that the subjects' perceptually sampling between the displays might account for this loss. To explore this hypothesis, estimates were made of changes in the subjects' reaction times. The phase angles of the open-loop transfer functions for conditions D, $D+$, P, and $P+$ were measured at 0.67 Hz (where changes in

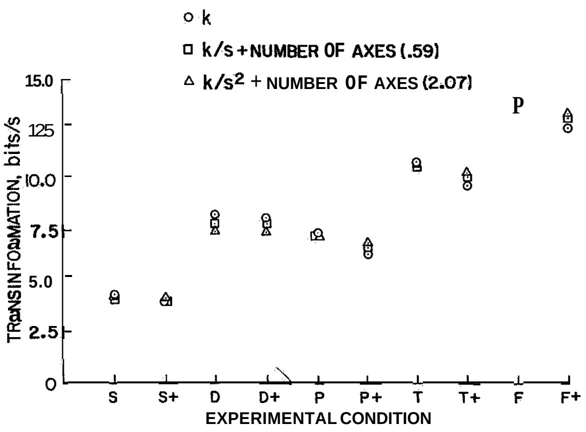

FIGURE 8.—Adjusted data for three dynamics.

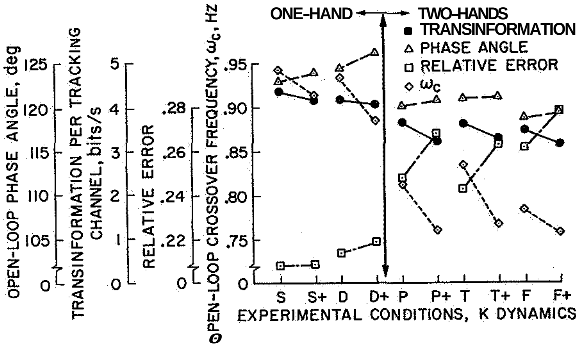

FIGURE 9.—Differences between single **and** two-handed performance.

reaction time would produce a relatively large change in phase angle, and changes in a lag time constant would produce a relatively small change in phase angle) and averaged across axes for the six subjects. The average phase angle difference between the integrated tasks and the separated tasks was approximately 5° which would occur with a change in reaction time of **0.014** sec, but was in the opposite direction to that needed to support the sampling hypothesis. The integated tasks ***D*** and $D+$ had larger phase angles than the separated tasks, P and $P+$.

The next step was to look at this result in context with the same calculations for all conditions. Figure 9 shows the phase angle for all conditions (K dynamics) along with the per channel values of transinformation, relative error and crossover frequency shown for comparative purposes. In this figure it is apparent that the task results can be partitioned into two groups, those that are one-hand tasks and those that are two-hand tasks. The first pertinent point is that the phase angles for all two-hand tasks are less than for the one-hand tasks. If the subjects perceived all two-hand tasks as more difficult than one-hand tasks, the result could have been a tightening of their control thereby reducing their reaction time. This explanation leaves the problem of explaining why average transinformation was reduced and average relative error increased, opposite from the direction that would be indicated by a reduction in reaction time. In the "crossover model" of the human operator (ref. 9) crossover frequency ω_c is directly proportional to the operator open-loop gain. Referring to figure 9 it can be seen that at the same time the subjects decreased their reaction time they also decreased their gain ω_c. **It** is tenable that the decrease in gain was large enough to offset the effects of the reduction in reaction time.

Comparison With Prior Study

Data from the earlier study (ref. **2**) that led to this experiment and comparable data from this experiment will be compared to show that there was a performance level difference between the two groups of subjects. The closest points of comparison are those where the two-axis tracking was performed with one two-axis controller, the present ***D*** and $D+$ conditions. The forcing function frequency for the points of comparison was **2** rad/sec for the earlier study, compared with **1** rad/sec for this study. (The effect of this difference will be discussed later.) The secondary task for the earlier experiment was a two-choice auditory task.

With a K/S^2 controlled element, the prior subjects were able to add the auditory task to the two-axis tracking task with only a small decrease in tracking performance, with a total transinformation of **2.7** bits/sec while tracking alone and a total of **3.6** bit/sec with the audio task. **A** similar small effect on tracking due to an added task was also found for the current subjects.

Next, with K/S, the prior subjects showed a decrease in total transinformation of 0.55 bits/sec with the addition of the auditory task. The current subjects added the transinformation of the

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audio task to the tracking task with no decrease in tracking performance.

With K, the prior subjects were different in their response, one showing a total decrease of 1.5 bits/sec and the other showing a total increase of 1.5 bit/sec with the addition of the auditory task. The current subjects were able to add nearly all of the transinformation of the auditory task to the total, with little decrease in tracking performance.

The above references to the decrease in total transinformation with the addition of the auditory task was the primary evidence in the earlier study from which a transinformation ceiling was inferred. That evidence has not been refuted by this study but the suggestion is made that subjects selected for this experiment performed at a higher proficiency level than the earlier subjects and therefore did not show the evidence for a ceiling at this task level. Compare directly the differences in total transinformation between the two studies for the two-axis tracking without an auditory task. These differences were: 1.0 bit/sec for K, 1.2 bits/sec for K/S, and 0.7 bit/sec for K/S^2, higher for the present study in each case. As already mentioned, another study (ref. 1) of single axis tracking showed that transinformation increases with forcing function frequency and peaks at a value slightly above a 2 rad/sec input. Although further experimentation would be necessary to determine whether this peak would be at the same frequency for two-axis tracking, it does appear that the subjects had a greater transinformation potential at the 2 rad/sec task than those at the 1 rad/sec task. If this were so the performance disparity between these two groups of subjects was even larger than that shown by the above comparison and stands in favor of the hypothesis that the selection procedures for this experiment picked subjects that did not exhibit transinformation limiting at the task levels expected.

ADDITIONAL OBSERVATIONS

Motivation

Levison et al. (ref. 7) found that subjects originally trained with unstable controlled element dynamics were then able to track stable dynamics (K/S^2) such that the operator remnant (observation noise) was 6 dB below that which they had found in several previous experiments.

> The most likely explanation for the relatively low noise ratio is that training on the unstable dynamics provided strong motivation for the subjects to reduce their observation noise. . . . Once trained to achieve a low noise level, the subjects apparently retained this ability when presented with the stable-vehicle tasks.

Motivation *can* cause large variations in performance, even in well controlled experiments. Following this line of reasoning for the present experiment, it is possible that as the number of tasks increased, the subjective difficulty increased with a resulting increase in subject effort. If this happened the total transinformation would have been proportionately inflated for the more complex tasks, masking any actual trend toward a transinformation ceiling. The only protection against this effect during the course of the experiment was by instruction to the subjects. At the beginning of the experiment and at the beginning of each day, after going over the previous day's scores, it was emphasized that maximum effort should be expended on every condition on every run. After the experiment was over each subject was asked to write a review of the experiment covering certain specified areas. Every subject made some mention of this continual emphasis toward overall maximum effort. They generally agreed that: (1) it was impossible to put out absolutely maximum effort on that many runs per day (15); (2) they did attend to all tasks, simpler ones included, with as much effort as possible; and (3) the audio task, although it did interfere with the tracking somewhat, did prevent inadvertent lapses of attention. Two of the subjects affectionately referred to the audio task as being "very irritating to my ears and mind" and as "that infernal beeping."

In order to get some rough idea of what "maximum effort" might be for the simplest task (i.e., one axis without audio) a special session was run at the end of the experiment. Each subject ran five successive runs of the S task with the third dynamic of his sequence (see table 2), therefore, there were data for two subjects for each dynamic. The subjects were informed that this was the last of the experiment, that it was realized that the effort being asked for would have been impossible for the entire experiment, but now they were being asked to "give everything." They were given their score at the end of each run and then urged to break that score. The average of the resulting ten scores per dynamics is shown as the "filled in" symbols on figure **7.** These scores are in fact greater than those obtained from the main experiment, by about **16** percent for K and K/S, and **10** percent for K/S^2. When looking at these differences there are two things to consider: **(1)** these scores were made by subjects with a high degree of skill since it was the end of a lengthy experiment and *(2)* the subjects did indeed put out extra effort in order to get the higher scores as evidenced by their comments and interest in scores after the runs and reports of hand and forearm cramps from the strain of "really bearing down." (There had been only passing mention of such tensions at the beginning of the experiment.) These reports of the effort needed to get the relatively modest increases in performance are taken as evidence that the level of effort on the simplest task was on the average commensurate with that of the more complex tasks throughout the main experiment.

This conclusion does not agree entirely with the prior discussion concerning the results of the dual integrated tasks and the split axes tasks. Clearly there was an interaction between subject set, motivation and task interference that cannot be fully separated on the basis of these data.

Parallel Channel Hypothesis

Moray (ref. 8) cites the results of an experiment that may provide some further insight into the lack of evidence for a transinformation ceiling for the continuous tasks. His purpose was to test the efficacy of the "many-to-one convergence model" of information processing. The central idea of this model is that there is one limited "narrow throat" or single channel through which information must be processed. In his simple but germane experiment Moray simultaneously presented his subjects with discrete audio stimuli in pairs. When provision was made for making two responses simultaneously, one with each hand, it was found that the subjects could respond at a rate of more than twice that found for other methods of response. He concluded that the "many-to-one convergence model" did not apply **(1)** for practiced subjects and **(2)** for compatible input-output systems. These two conditions are both applicable to the present experiment. Moray's results provide evidence that two parallel channels can function with essentially no interference between them. The present data show that up to four parallel channels can function with fairly small increases in interference as each channel is added.

Task Organization Hypothesis

Lying behind this and prior experiments are two basic, although at this time unproven, assumptions. The first of these is that there is some finite limit to the amount of information the human can process, no matter how cleverly the tasks are designed. Viewing the human subject as a set of input/output devices with an intervening complex central information processer it is intuitive that there is some task or set of tasks which can overload any part of this system.

The other assumption is that there is a lawful combination of tasks and functions. By this it is meant that each function performed ties up some portion of the total capacity so that it is not available for other functions or tasks. This allocation of capacity to function is lawful in the sense that if all these functional allocations could be measured, they would be the same each time under the same conditions and the sum of their proportions would equal unity. These functions include not only those directly associated with external task performance, but also such other ones as set, motivation, attention fluctuation, emotion, and conflicts. This discussion will be confined to task oriented functions.

On the basis of the data from the present experiment the hypothesis of an existing '(task organizing function" will lend a useful structure. This hypothetical function will tie-up" a certain amount of the total capacity as discussed above. Even though the experimenter thinks of a multitask situation as the sum of individual tasks, the operator, when faced with the actual task of doing his best on all tasks at the same time, approaches the situation with an overall task strategy **or** "task organization." That is, with some learning the operator decides the best approach to take to a particular combination of tasks and then proceeds as if it were one composite task. The performance of each task (in the experimenter's sense) ties up capacity and the "task organizing functions" tie up capacity. The amount used by the organizing function depends on the nature of the tasks combined.

Refer again to figure 2. (The trends for the following discussion are the same for K/S and K/S^2 (figs. 3 and 4) though less pronounced.) Adding the fourth tracking task F to the three-axes tracking task T reduced the average transinformation less than the amount of reduction caused by the addition of the audio task $T+$ to the three-axis task T. Adding the third tracking task T and the fourth tracking task F to the two split-axes tracking task P both reduced the average transinformation less than the amount of reduction caused by the addition of the audio task $P+$. Addition of the second tracking task D to the single task S caused the same reduction in average transinformation as caused by the addition of the audio task $S+$.

Three levels of "task organization" can be inferred from this. First, as tracking channels are added there is some reduction in transinformation per tracking channel. Second, there was a discontinuity in going from a one-handed task to a two-handed task. Some additional amount of organizational capacity was called into play in this case. And third, tracking was affected the most when the auditory task was added. The organization capacity needed was the highest here with less capacity left to each tracking channel.

There is still another way to state the above hypothesis. Similar tasks can be added together with less interference between them (tracking only) than when dissimilar tasks are added together (tracking and audio). Taking another step away from the data one might further conjecture that there would be less interference between the two tasks of aircraft control and throttle control than say between aircraft control and communication with air traffic control.

CONCLUSIONS

On the basis of the results of this experiment the following conclusions are indicated:

(1) There was task interference for each additional step in task complexity, that is, for each additional task, performance was poorer on the original task(s) than it had been without the added task.

(2) There was no clear evidence for a ceiling on human information processing capacity. The asymptotic approach to a maximum value of transinformation with additional tasks was not found. The addition of the four-choice audio task interfered most with the four-axes tracking score when the controlled element was K, less when it was K/S, and least when it was K/S^2. This is the correct trend assuming the existence of some sort of absolute ceiling on total transinformation, but this was not sufficient evidence that such a ceiling exists.

(3) Comparison of results with a prior experiment provided evidence that the careful selection of subjects had a large impact on the results of this experiment. The requirement that all tasks be controlled within defined boundaries for the entire period of each run placed a constraint on performance that disallowed performance degradation below certain limits.

(4) There was a consistent but small variation in performance on the four choice audio task. The transinformation rate decreased as tracking axes were added, and decreased when the order of the controlled element was increased. The small change and consistency of these values attest to the attention demanding nature of this task.

(5) The order of the controlled element imposed a limit on the amount of transinformation for each channel. A loss of 0.59 bits/sec was found as the order increased from K to K/S, and a loss of 2.07 bit/sec as the order increased from K to K/S^2.

SYMBOLS

K	gain of controlled element
S	Laplace operator used in defining controlled element
$S(f)$	signal power at frequency f
$N(f)$	noise power at frequency f
Φ_{00}	output power spectral density
Φ_{ii}	input power spectral density
Φ_{i0}	input to output cross power spectral density

Φ_{ee} error power spectral density

ω_n natural frequency of the filter used to generate the forcing function

ω_c system crossover frequency

REFERENCES

1. WEMPE, T. E.; AND BATY, D. L.: Usefulness of Transinformation as a Measure of Human Tracking Performance. NASA SP–128, pp. 111–129, 1966.
2. WEMPE, T. E.; AND BATY, D. L.: Human Information Processing Rates During Certain Multiaxis Tracking Tasks With a Concurrent Auditory Task. IEEE Trans. on Man-Machine Systems, vol. MMS–9, no. 4, Dec. 1968, pp. 129–138.
3. BATY, D. L.: Effects of Display Gain on Human Operator Information Processing Rate in a Rate Control Tracking Task. IEEE Trans. on Man-Machine Systems, vol. MMS–IO, no. 4, Dec. 1969, pp. 123–131.
4. JEX, H. R.; MCDONNELL, J. D.; AND PHATAK, A. V.: A Critical Tracking Task for Man-Machine Research Related to the Operator's Effective Delay Time. Part **I:** Theory and Experiments With a First-Order Divergent Controlled Element. NASA CR–616, 1966.
5. LOCKE, E. A.; AND BRYAN, J. F.: Goals and Intentions as Determinants of Performance Level, Task Choice, and Attitudes. American Institute for Research, (AD 646 393), Feb. 1967.
6. LEVISON, W. H.; AND ELKIND, J. I.: Studies of Multi-Variable Manual Control Systems: Two Axis Compensatory Systems With Compatible Integrated Display and Control. NASA CR–554, 1966.
7. LEVISON, W. H.; ELKIND, J. I.; AND WARD, J. L.: Studies of Multivariable Control Systems: a Model for Task Interference. Rept. **No.** 1892, Bolt Beranek and Newman (NASA CR–1746, in press).
8. MORAY, N.: Where Is Capacity Limited? A Survey and a Model. Acta psychologica, vol. 27, 1967, pp. 84–92.