HUMAN INFORMATION PROCESSING RATES DURING CERTAIN MULTIAXIS TRACKING TASKS WITH A CONCURRENT AUDITORY TASK

By T. E. Wempe* and D. L. Baty*

Ames Research Center, NASA
Moffett Field, California 94035

*Research Scientist.

SUMMARY

A series of experiments were conducted to determine the information processing rates of several subjects performing one and two axis compensatory tracking tasks with a secondary auditory task. The experimental variables were the order of controlled element dynamics, the forcing function and the addition of a secondary task.

Human information processing rates decreased on each tracking channel with the addition of the second tracking channel or the secondary auditory task. Other than this effect, the information processing channels were additive like parallel channels until a limit in the total information processing rate was reached. This limit was related to the order of the controlled element.

INTRODUCTION

This study is a continuation of research (refs. 1 and 2) in investigating the utility of measures of transinformation (information processing rate in bits/sec) in describing and predicting human performance in tasks related to aerospace missions. It would appear that if future research is to span the gap, in the sense of predicting human limitations, between the typical laboratory experiment involving one or perhaps two tracking channels or some other set of relatively simple tasks and the multiplicity of dissimilar tasks occupying a pilot's attention, then some measure, such as transinformation, will be the medium. Certainly any hope of being able to describe workload for a complex set of heterogeneous tasks will be dependent upon the validation of some generalized unit of measure such as bits/sec.

What is known about human transinformation capability in tracking tasks? Figure 1, a possible model of a human one-channel information processing system, is offered for discussion (some of the terms are borrowed from Melton (ref. 3)). To an observer, the only evidence that information was processed appears in a comparison of the signal source and the system output. The information processed, as measured across the serial portion of this block diagram, cannot be any greater than the least information processed through any single block of the series. Conversely, each block in a series must have an information processing rate of at least the magnitude of the transinformation indicated between the system input and the system output.

Two prior studies (refs. 1 and 4) of single axis tracking with a displacement controlled element have established the general shape of transinformation curves. When plotted against signal bandwidth the curves were unimodal, having peaks of about 4 to 7 bits/sec (depending upon subjects and forcing function shapes and whether the task was pursuit or compensatory) at a bandwidth of about 0.7 Hz, and were skewed toward the high bandwidth end of the scale. Additional evidence in another study (ref. 5) indicated that two-axis tracking with homogeneous dynamics (K/S^2) and either homogeneous (3.5, 2.5, or 1.5 rad/s) or heterogeneous forcing function bandwidths (3.5 and 1.5 rad/s) yielded essentially the same transinformation per channel as single-axis tracking (a slight loss of 0.1 bit/sec in the dual axis task was attributed to "visual-motor interference effects").

The foregoing experimental evidence suggests that most of the human transinformation limitations in tracking are due to restrictions in visual perception and response execution (neuromuscular output). It is not until experimental data for heterogeneous dynamics (K and K/S^2 both at 3.5 rad/s) of that same report (ref. 5) are admitted that there is a suggestion that the box labeled "recognition and response selection" in figure 1 places a restriction on system transinformation. In this case a loss of 1 bit/sec in the K tracking axis could be attributed to interference from the large displayed error on the K/S^2 axis; however, the loss of 0.5 bit/sec in the K/S^2 axis suggests interference at a higher level mental process other than visual perception or motor response.

The aims of the present study were to verify the essentially parallel dual-tracking channel effects noted by Levison and Elkind (ref. 5) for both homogeneous and heterogeneous inputs when the controlled elements were similar and to replicate the effect of heterogeneous controlled elements. Also, a secondary auditory task, intended to separate perception and motor channels, was added to bypass the effects of visual-motor channel interaction.

SYMBOLS

K gain of controlled element

S Laplace operator used in defining controlled element

W_{eff} effective bandwidth of forcing function

$$\left(\left[\int_0^\infty \Phi_{ii}(f)df\right]^2\right)\Big/\left(\int_0^\infty \left[\Phi_{ii}(f)\right]^2 df\right), \text{ Hz}$$

$S(f)$ signal power at frequency f

$N(f)$ noise power at frequency f

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

Φ_{oo} output power spectral density

Φ_{ii} input power spectral density

Φ_{io} input to output cross-power spectral density

$\bar{\lambda}$ performance measure of the critical task device ($\approx$ 1/effective reaction time)

(S) single-axis tracking only

(S+) single-axis tracking with concurrent secondary auditory task

(D) dual-axis tracking only

(D+) dual-axis tracking with concurrent secondary auditory task

Rel.(E-N) relative error with noise component removed

$$\left(\sqrt{\frac{(\text{mean square error}) - (\text{mean square noise})}{\text{mean square input}}}\right)$$

Rel.N relative noise $\left(\sqrt{\frac{\text{mean square noise}}{\text{mean square input}}}\right)$

TESTS AND PROCEDURES

Test Setup

Both manual control tasks, the primary task of visual compensatory tracking and the secondary task of pressing the audio button, were performed by the subjects while seated inside a small portable cab. The doors were closed during the runs and every effort was made to eliminate disturbing outside noises. The small ventilating fan in the cab provided sufficient background noise to mask any conversation in the room. A light inside of the cab was just intense enough to light the frame of the scope. The subject sat erect with his forehead on a headrest which maintained his eyes approximately 50 cm from the face of the scope.

Continuous compensatory tracking task.- The elements for this task were displayed on a 14 in. Dumont 436 oscilloscope. A 1/4 in. reference circle remained centered on the scope and a 3/8 in. cross hair follower could be electronically driven anywhere on the face of the scope.

The task forcing functions were provided by a multichannel FM magnetic tape system (Ampex CP-100). The filtered output of a low-frequency Gaussian noise generator had been prerecorded on magnetic tape. The specifications of the noise generator were: Gaussian amplitude distribution within ±1 percent and output spectrum uniform to ±0.1 dB from 0 to 35 Hz. The recorded signal was then shaped by a second-order filter having the transfer function $G/(S^2 + 1.4\omega_n S + \omega_n^2)$, providing a -80 dB/decade power spectrum beyond the break frequency for a forcing function. The filter gains at each bandwidth were adjusted so that the standard deviations of the recorded signals were essentially the same. The effective bandwidths* used for this study were

*Effective bandwidth is defined as the bandwidth of a rectangular power spectral density that has the same area and variance as the power spectral density being described.

0.12, 0.47, and 1.88 Hz which correspond to ω_n settings of 0.5, 2.0 and 8.0 radians/sec. The rms scope deflection of the uncorrected input was slightly under 1 cm, which at 50 cm from the eye gave an uncorrected visual angle of approximately 1^o rms.

Error control was provided through compatible movements of a two-axis MSI Model 438 sidearm controller. A specially made flexible control stick 9.0 cm long with a 1.5 cm diameter ball on the end was used in place of the standard rigid one. The stick was mounted upright and would deflect 1 cm at the tip with a 6×10^5 dyne side force. The controller provided two independent electrical outputs, one proportional to the horizontal and the other proportional to the vertical component of deflection. The stick was allowed to move freely in both axes in all parts of the experiment. When the task was either vertical only or horizontal only, the error indication was clamped electronically at zero displacement in the inactive channel (one exception to this will be noted later in this report).

Three controlled element dynamics were used for this task: displacement (1.6×10^{-5} cm error displacement per dyne of stick force), velocity (7.8×10^{-5} cm/sec error displacement per dyne), and acceleration (7.8×10^{-5} cm/sec^2 error displacement per dyne).

Discrete auditory secondary task.- Two audio tones (350 and 600 Hz) were presented in random order through the cab speaker. A small box with two push buttons was strapped to the subject's left leg. His task was to press the button that corresponded to the audio tone being presented, using his index or middle finger of his left hand. When he pressed the correct button, the tone ceased. One tone per second was the rate of presentation. The two buttons for this task were mounted at one edge of a 5 × 13 × 15 cm metal box, which was large enough for the subject to rest the heel of his left hand while pushing the buttons. The switches required approximately 1×10^5 dyne of force to close contacts.

Test Subjects

Four male college students served as subjects for this set of experiments. They were all right handed, had normal corrected vision and had not participated in any prior tracking experiments. Subject C held a current pilot's license.

One of the experimenters who had fairly close contact with the subjects during the experiments described them as follows:

Subject A appeared to be a fairly easy-going type who did not seem to get very involved with the experiment.

Subject B was always interested in how well he had done and indicated displeasure when he thought he had done poorly. He was the only subject who stated that he had set some error criteria as a goal. At the end of Experiment I, he left the project for personal reasons.

Subject C never appeared to have more than a mild interest in performing the tasks and occasionally demonstrated undesirable independence by not following instructions exactly.

Subject D seemed to be the slowest to comprehend the instructions and the slowest to attain stable performance at the tasks; however, he always seemed interested in improving his performance.

Procedure

Instructions.- For the compensatory tracking task, the test subjects were told, "Your score on this task is directly related to how close you can keep the cross to the circle throughout the entire run." For the audio task, they were instructed to respond to each tone within 1 second or less of 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 period. They were told that they were not scored on how quickly they responded, so long as they responded within the 1 second interval.

When the tracking task 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.

The subjects were informed of their prior day's performance at the beginning of each day and were urged each time to better their scores.

Performance measures.- Two scoring procedures were used for the compensatory tracking task. An on-line relative RMS error score was computed for each run to give a day-to-day indication of subject progress and for informing the subjects of this progress. The other procedure was to directly digitize and store on magnetic tape the system input, output, and error 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, number of correct responses and the number of incorrect responses were recorded during each run. The method of scoring from these values has been stated in the instructions to the subjects.

Training and experimental design.- The general experimental plan was to have each subject train with the same controlled element in one and two axes, with and without the secondary auditory task. Then Experiments I and II were conducted. Each subject was then trained with a different controlled element, and Experiment III was conducted. The final part of the plan, Experiment IV, was to measure performance with the two learned controlled elements in two axes combined. Table I summarizes the details of the experiments. Table II presents the details of the Latin squares used in Experiments I and IV (Experiment III was similar to Experiment I and is not shown).

Generally, two subjects were run per day, one resting in the subjects' waiting room while the other was being tested, so that there was always at least 1/2 hour between each of the three daily sessions for a given subject. The runs were 3-1/2 minutes long when W_{eff} of the inputs were 0.12 or 0.47 Hz, and 2-1/2 minutes when the input W_{eff} was 1.88 Hz. During a session, the rest periods were 1-1/2 minutes between runs. A seventh run that was not recorded was added to each session of the last day of the initial training period and maintained throughout Experiments I and III. The condition for the seventh run was randomly chosen from the preceding six conditions (see Table II) of each session.

For Experiment IV each session contained six runs, each condition being run twice in succession (see table II). The results of the second run of each pair were recorded.

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 rates of 10/sec for $W_{eff} = 0.12$ and 0.47 Hz and 20/sec for $W_{eff} = 1.88$ Hz). For each pair of input and output signals, 1800 samples per channel were obtained for each run and stored on magnetic tape for off-line computation. Cross-correlation and autocorrelation values with 90 lags and subsequent power spectral densities were computed. The transinformation values were obtained by the following formula:

$$\text{Transinformation} = \int_0^\infty \log_2\left[1 + \frac{S(f)}{N(f)}\right] df$$

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

where

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

RESULTS AND DISCUSSION

Preliminary Tests and Training Data

Though it was not intended that this paper should be concerned with individual differences, it was necessary to be cognizant of these differences where they would have a major effect on conclusions. Just prior to the sequence of experiments of this paper, each subject made 170 runs on the critical task device (ref. 6) which gives a measure that is inversely related to effective reaction time. Subsequent to the current experiments, each subject made an additional 120 runs on this device. The averages of the 40 runs just before, and the 40 runs just after the current experiments, are presented in Figure 2 along with the single axis performance averages of Experiments I and III.

The improvement in critical task performance shown in this figure was not significantly different from that noted between any other adjacent averages of 40 runs, indicating no transfer of training from the extensive tracking experience (a total of 20-1/2 hours of actual tracking for each subject completing the experiments) of the current sequence of experiments. The ranking of the subjects by use of the critical task device, which fulfills more of the criteria for eliciting maximum effort from the subjects than the current experimental setup (ref. 7), was not very different from the ranking by the data of Experiments I and III. Only Subject D changed position in the ranking. Differences, as will be discussed later, were partly due to motivational differences, particularly for the relatively easy single-axis task without the secondary task.

The training data from the first day were recorded and transinformation measures computed. These data are presented in figure 3 along with the comparable values from Experiment I. Subject A had difficulty in learning the tasks that were more complex than the single axis (K/S^2) condition. His results on Experiment I look much like Subject B's first efforts. Subject B established stable performance more quickly and showed rapid and consistent improvement in the most difficult condition of two-axis plus secondary task. Subject C (K/S) showed essentially equal performance in the single and dual-axis tasks with only little improvement. He had distinct trouble when the secondary task was present and showed the most improvement in the single-axis with secondary task. Subject D (K) showed considerable improvement throughout the training which was consistent with his low rank on the critical task, his slowness to "catch on," and the seriousness with which he approached each of the tasks. Like Subject C, he initially showed about equal proficiency at the single or dual axis tasks, but had difficulty with the secondary task.

Homogeneous Test Conditions

Secondary auditory task.- Performance for the secondary task was fairly uniform across all conditions and the few trends that were noted were attributed to subject differences and were not considered significant. The average for the secondary task when it accompanied the K/S^2 controlled element tracking task was 0.88 bits/sec (though Subject D's performance averaged 0.97 bits/sec with this controlled element); the average with the K/S controlled element was 0.95 bits/sec; and the average with the K controlled element was 0.97 bits/sec.

Days, sessions and sequence effects.- Experiments I and III were planned to counterbalance the effects of variations in performance from day to day, from session to session, and throughout the test sequence during a session. Although the averages of the controlled variables were not affected, there were some significant results from these unwanted variables. On Experiment I, Subject B's performance evidenced a significant (0.05)* drop of approximately 0.25 bit/sec on the third session of each day and a significant (0.01) drop on the last day; Subject C showed a consistent decrease in performance (0.01) of 0.4 bit/sec from the first session to the last session; Subject D displayed

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*Levels of significance resulting from analysis-of-variance statistics are shown in parentheses.

erratic behavior showing a session's effect (0.05), a sequence effect (0.05), a days by sequence interaction (0.05), and a sessions by sequence interaction (0.05). By the time the three subjects who continued the experiments reached Experiment III, none of these effects was present.

Analysis of transinformation data.- The per channel transinformation results (averages of six data points or three data points when the horizontal and vertical channels were significantly different and are shown separately) of Experiments I and III are shown in figure 4.

To study the effects of the secondary task, a table of differences ((S) minus (S+) and (D) minus (D+)) was prepared for each session. The purpose was to minimize the variability due to days and sessions mentioned before. (It was noted later that the results would have been the same had an analysis of variance been performed directly on the transinformation measures.) A similar table was prepared for (S) minus (D) and (S+) minus (D+) to investigate the effects of adding the second tracking channel. For both of these tables, the horizontal and vertical channels were combined to achieve some level of generality. An analysis of variance was performed, and the data were combined where the confounding of significant effects did not result. These results are presented in table III.

With the exception of the data for Subject D at the K controlled element task, the interactions indicated in table III for the K/S and the K controlled element seemed excessive. Some interaction was attributed to the subjects' reacting to a more lively task, such as Subjects A and C performing better on the (D) task than on the (S) task (see fig. 4), but this did not seem to account for all of the interactions among the experimental conditions.

The significant interactions among these data could also have been caused by a ceiling on the total transinformation for each run. A ceiling would cause the (D+) transinformation values to be lower than would be expected if only the effect of the additional tracking channel and the effect of the added secondary task were influencing this measure.

Total transinformation.- Figure 5, the total (sum of all active channels) transinformation for each run, shows evidence of ceilings in some cases. Both Subjects C and A operating the K/S controlled element (figs. 5(b) and 5(c)) were unable to add the secondary task to the dual channel task to achieve a higher total transinformation than when they were performing at the dual task alone. Their apparent ceiling for the K/S controlled element was approximately 5-1/2 bits/sec. At the K controlled element task (fig. 5(d)), Subject C performed noticeably poorer in total transinformation on the (D+) condition than on the (D) condition suggesting some functional degradation in addition to reaching a ceiling. These examples are considered evidence that a fairly low ceiling for total transinformation exists for the (D+) condition, although it may have been higher if these subjects had been more highly motivated. Subject D, a harder working subject, performing with the same controlled element, K, as Subject C (fig. 5(e)), showed no indication that he had reached a ceiling at 8-1/2 bits/sec. This subject's early learning total transinformation data are shown in figure 6 to demonstrate that even for him total transinformation was limited when he was operating at a lower level of proficiency. None of the three subjects using the K/S^2 controlled element (fig. 5(a)) showed any evidence of a total transinformation limit at their highest average of 3-1/2 bits/sec.

Effects of adding a second tracking axis.- To determine the effect of adding the second tracking axis, the use of the differences between the (S+) and (D+) measures was not considered valid where an apparent ceiling on total transinformation would limit the (D+) values.

Thus, the table III values showing a single to dual axis loss of 0.26 bit/sec (0.01) for the K/S^2 task and a loss of 0.27 bit/sec (0.05) for Subject D on the K task are considered valid since there was no apparent ceiling for these results. The data for test conditions without the auditory task were used for the remaining comparisons. Subject C operating the K controlled element showed a gain of 0.57 bit/sec (0.05 from table III), and Subjects A and C operating the K/S controlled element showed no significant effect from the addition of the second axis.

From this it is concluded that, with the more demanding K/S^2 controlled element task, a loss of 0.26 bit/sec was noted when the second axis was added. (This conclusion is consistent with the findings of Levison and Elkind (ref. 5) who noted a significant single to dual axis loss of 0.1 bit/sec with a K/S^2 controlled element tracking task.) However, while the subjects were performing with the easier K/S or K controlled elements, this small effect was obscured by a tendency for the subjects to track even better when the second axis was added. That this small effect should have been present, even though not evident in the subjects' performance, will be demonstrated when the results of Experiment II (two axis tracking with an input in only one of the two tracking channels) are discussed.

Effects of adding the auditory task.- When the effect of the addition of the auditory task was examined with the exclusion of dual axis data where a ceiling on total transinformation was indicated, the data of table III for Subjects A and C on the K/S and K controlled element task appeared uniform. An analysis of variance of the differences due to the addition of the auditory task to the single axis tasks for all subjects and all controlled elements showed no significant effects from subjects, controlled elements or bandwidths. The overall average loss in single axis tracking from the addition of the auditory task was 0.18 bit/sec (0.01). Thus, it was concluded that the auditory task caused a small but significant loss.

Since the secondary task allowed a separate auditory perception input channel as compared to the tracking task shown in figure 1, and a separate response execution output channel (namely the other hand to activate the response microswitches), visual-motor interference was not likely to be the cause of this loss per tracking channel.

Figure 5, depicting total transinformation achieved for each experimental condition, verifies that the (S) to the (S+) loss was not due to a maximum transinformation limit in the recognition selection box of figure 1 since the (D) or the (D+) total transinformation measures were always higher than the

(S+) measures. It was thought that sampling at the recognition and response selection function might account for this loss when the secondary task was added. This hypothesis was explored briefly by examining estimates of changes in the subjects' reaction times. The phase angles of the open-loop transfer function for the two subjects operating the K controlled element with the 0.47 Hz forcing function were measured at 1 Hz (where changes in 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 subjected to an analysis of variance.

The results showed that Subjects C and D were somewhat different in their adaptations to the tasks for the K controlled element. Subject D showed no difference in apparent reaction time due to the addition of the auditory task, but he did show a small but significant (0.05) shift in average phase angle for the dual axis task with or without the auditory task. This average phase angle shift from -121° to -126° would occur with an increase of 0.014 sec in reaction time. The other subject, C, showed no change in average phase angle with the dual task, but he did show a consistent (0.01) shift from -127° to -136° when the auditory task was added to either the single or dual axis task. This difference would occur with an increase in reaction time of 0.024 sec.

These observations seemed promising, particularly since Subject D, who showed no reaction time effect from the addition of the secondary task with the K controlled element also showed no loss in tracking transinformation at that condition (see table III), while Subject C, who showed an apparent reaction time increase with the addition of the secondary task, at the same time showed a significant loss in tracking transinformation. Although these results are consistent with the notion that Subject D was not sampling between the secondary task and the tracking task while Subject C was sampling between these tasks, the early training data do not support this idea. When Subject D's early training data were examined, his apparent reaction time still showed no change with the addition of the secondary task, but at that time he did show a definite loss in tracking performance when the secondary task was present (fig. 3). Thus, it appeared that sampling alone would not account for the entire loss in tracking transinformation when the secondary task was added.

Effects of the controlled element.- The difference in ceilings noted between the K and the K/S controlled element tasks (note that Subject C showed different ceilings at each of these tasks - figs. 5(b) and 5(c)) suggest that the total transinformation limit for tracking is related to the order of the controlled element, and that the recognition and response selection box of figure 1 has restrictions in total transinformation capability that are related to the need for acting upon higher order derivatives of the input and output signals. Certainly there is a significant effect from the controlled element on the per channel transinformation of human trackers as emphasized in figure 7, with each change in the order of the controlled element producing a 1 bit/sec change in each tracking channel. This latter effect might be attributed solely to visual-motor noise resulting from the larger inherent error associated with higher order controlled elements; however, that would not explain the restriction in the total transinformation ceiling by the order of the controlled element. Further research is required to segregate and quantify these effects of the controlled element.

Effects of forcing function bandwidth.- The effect of signal bandwidth on transinformation in tracking tasks has been noted before (refs. 1 and 4), and the current results agree with the data of those studies when the forcing function spectral shape, motivation of subjects, and display presentation are taken into account. With allowances made for visual-motor interference, it appears that tracking information processing channels can be added as though they were parallel, at least until the total information processing rate reaches some ceiling. The important point is that the box of figure 1 labeled "recognition and response selection," through which it is presumed that all information must pass, appears to have no limitation for the amount of transinformation required by a single tracking channel once a particular controlled element is specified, otherwise the channels would not appear to be parallel. Hence, it is not unreasonable that the principal restrictions in transinformation noted at low and high bandwidths for a given controlled element may be due entirely to limitations in the perception and response execution boxes of figure 1.

Visual-Motor Interference

When the plans for Experiment II were established, it was intended that the results would apply toward explaining the (S) and (D) channel increase in remnant and related loss in per channel transinformation. The results of this brief experiment with two axes to control, but with an input in only one channel, are presented in table IV.

Though there appeared to be a linear relationship between the standard deviation of the no-input channel remnant and the standard deviation of the coherent error, it was not believed practicable to try to predict the increase in remnant due to the addition of a second axis and forcing function, particularly inasmuch as two of the subjects often showed a lower remnant in each of the dual-axis channels when the secondary task was not present. Table IV was included to support the conclusion that there is visual-motor interference, and that a portion of the remnant in a second channel will be related to the coherent error in the first channel, at least with an integrated display and a single controller for two-axis control.

Heterogeneous Test Conditions

The purpose of Experiment IV was to determine if the requirement for a different mode of responding to an additional tracking channel would place any special restrictions on the transinformation for each channel. Because display gain effects on transinformation are not understood, all the input signals (forcing functions) used in the experiments of this study were adjusted to have about the same standard deviation in amplitude. Thus, with different bandwidths or different controlled elements, the two-axis tracking error generally would not be equal in the horizontal and vertical axes. The channel with the largest error was considered to be the primary tracking channel, and the other, the secondary channel. Evidence for adjustment interaction would appear as a decrease in the transinformation of the primary channel, while it was anticipated that the secondary channel would be degraded by visual-motor interaction as well as adjustment interaction. If there were any effects at all from the heterogeneous conditions, it was expected that the least effect would occur with the heterogeneous bandwidths where only the values of the parameters of the assumed human transfer function need be different. It was expected that the most pronounced effect would accompany the heterogeneous controlled element conditions where the order of the response mode, as well as parameter values, would most likely be different.

Heterogeneous forcing function bandwidth.- Table V summarizes the results of the heterogeneous bandwidth data for each controlled element. The primary axis transinformation data were in almost every case higher than comparable Experiment I or III dual-axis data, indicating that there was no degrading effect from the different adaptations required between the channels. Instead there apparently was an improvement in performance on the higher bandwidth channel, probably in an effort to equalize the displayed error in the horizontal and vertical directions. The secondary axis showed losses as expected.

Levison and Elkind (ref. 5) noted similar results from dual-axis tracking with heterogeneous bandwidths, although the bandwidths studied were over a smaller range; namely, 0.24, 0.40, and 0.56 Hz (rectangular spectra achieved by summing sine waves).

Heterogeneous controlled elements.- Table VI presents the changes in transinformation for the heterogeneous controlled elements as compared to the dual axis homogeneous controlled element condition (Experiment I or III) for each effective bandwidth. The subjects apparently performed better than might be expected in the channel having the higher order controlled element and the larger displayed error. Thus with a large difference in controlled elements which required different modes of response in each of the two axes, there was no degradation in transinformation in the primary channel. Poorer performance on the secondary channel (the lower order controlled element channel) as compared to the comparable Experiment I or III dual axis performance was anticipated because of the visual-motor interference effect described before.

It is concluded from the results of these heterogeneous bandwidth and controlled element experiments that, at least for a low level of total transinformation, no measurable degradation in information processing rates was attributable to the subjects adopting different response modes for each axis of a two-axis integrated display and controller tracking task.

CONCLUSIONS

On the basis of the results of several experiments designed to study human information processing rates in manual control tasks of varying complexity, the following conclusions are indicated.

1. Dual-axis tracking as compared to single axis tracking with a K/S^2 controlled element evidenced a transinformation loss of 0.26 bit/sec in each channel. This loss was attributed to the visual-motor noise effect of one channel upon the other. With the K/S or K controlled elements, evidence of this effect was not consistent among the subjects.

2. The addition of an auditory secondary task, button pressing in response to one of two tones presented randomly at the rate of one per second, caused a transinformation degradation of about 0.2 bit/sec per tracking channel where a ceiling on total transinformation was not indicated. This effect was attributed to interference in a signal recognition and response selection function. Though there was some evidence for sampling at the recognition and response selection level, sampling alone did not seem to account for the effect.

3. There was evidence that a ceiling on total transinformation, the sum of the transinformation of all active data processing channels, existed and that it was influenced by the order of the controlled element, with the lower order controlled element allowing a higher ceiling.

4. The order of the controlled element imposed a limit on the amount of transinformation for each channel. A loss of about 1 bit/sec was noted as the order increased from K to K/S and from K/S to K/S^2.

5. When the dual-axis tracking task had either heterogeneous controlled elements or heterogeneous forcing function bandwidths, there was no evidence of a degradation in human transinformation performance that could not be accounted for by the visual-motor interference that one tracking axis had upon the other.

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TABLE I.- EXPERIMENTAL PLAN

Phase	Subject A		Subject B		Subject C		Subject D	
Initial training period	$\frac{K}{S^2}$	72 runs (6 days) at W_{eff} = 0.12 Hz, single and dual axis, with and without secondary task Three days with same conditions as Exp. I	$\frac{K}{S^2}$	Same as A	$\frac{K}{S}$	54 runs (3 days) at W_{eff} = 0.47 Hz, single and dual axis, with and without secondary task Three days with same conditions as Exp. I	K	90 runs (5 days) at W_{eff} = 0.47 Hz, single and dual axis, with and without secondary task Three days with same conditions as Exp. I
Experiment I	$\frac{K}{S^2}$	Three days, three sessions per day, seven randomly sequenced runs per session (See table II)	$\frac{K}{S^2}$	Same as A	$\frac{K}{S}$	See A	K	See A
Experiment II	$\frac{K}{S^2}$	5 runs. Dual-axis tracking, single axis input, Horiz. and Vert. at W_{eff} = 0.12, 0.47 and 1.88 Hz. (No secondary task)		Terminated	$\frac{K}{S}$	See A	K	See A
Second training period	$\frac{K}{S}$	Three days with same conditions as Exp. III		---	K	Two days with same conditions as Exp. III	$\frac{K}{S^2}$	Four days with same conditions as Exp. III
Experiment III	$\frac{K}{S}$	Same schedule as Exp. I (Similar Latin Sq. Design)		---	K	Same schedule as Exp. I	$\frac{K}{S^2}$	Same schedule as Exp. I

TABLE I.- EXPERIMENTAL PLAN - Concluded

Phase	Subject			
	A	B	C	D
Experiment IV	$\frac{K}{S^2}$ & $\frac{K}{S}$ All dual-axis tracking (No secondary task) 54 runs (3 days), heterogeneous, W_{eff} or controlled element, or both. (See table II)	---	$\frac{K}{S}$ & K See A	K & $\frac{K}{S^2}$ See A

TABLE II.- LATIN SQUARE DETAILS

Experiment I

[Numbers indicate W_{eff} of input]

Session	Subject A (K/S^2) Day 1	Day 2	Day 3	Subject B (K/S^2) Day 1	Day 2	Day 3	Subject C (K/S) Day 1	Day 2	Day 3	Subject D (K) Day 1	Day 2	Day 3
1	0.12	0.47	1.88	0.47	0.12	1.88	1.88	0.47	0.12	1.88	0.12	0.47
2	.47	1.88	.12	1.88	.47	.12	.12	1.88	.47	.12	.47	1.88
3	1.88	.12	.47	.12	1.88	.47	.47	.12	1.88	.47	1.88	.12

Note: Each recorded session consisted of six runs of the following conditions presented in random order: (S) vertical axis, (S) horizontal axis, (S+) vertical axis, (S+) horizontal axis, (D) and (D+).

Experiment III was similar to Experiment I with the subjects having different controlled elements and a different randomized Latin square.

TABLE II.- LATIN SQUARE DETAILS - Concluded

Experiment IV

Subject A

Session	Horiz.	Vert.	Day 1	Day 2	Day 3
1	$\frac{K}{S}$ 0.47	$\frac{K}{S}$ 1.88	m	l	n
	$\frac{K}{S}$ .12	$\frac{K}{S}$ 1.88			
	$\frac{K}{S}$ .12	$\frac{K}{S}$ .47			
2	$\frac{K}{S^2}$ .12	$\frac{K}{S}$ .12	n	m	l
	$\frac{K}{S^2}$ .47	$\frac{K}{S}$ .47			
	$\frac{K}{S^2}$ 1.88	$\frac{K}{S}$ 1.88			
3	$\frac{K}{S^2}$ .12	$\frac{K}{S}$ 1.88	l	n	m
	$\frac{K}{S^2}$ .12	$\frac{K}{S}$ .47			
	$\frac{K}{S^2}$ .47	$\frac{K}{S}$ .12			

Subject C

Session	Horiz.	Vert.	Day 1	Day 2	Day 3
1	$\frac{K}{S}$ 0.47	K 1.88	o	q	p
	$\frac{K}{S}$ .12	K .47			
	$\frac{K}{S}$ .12	K 1.88			
2	$\frac{K}{S}$ 1.88	K 1.88	p	o	q
	$\frac{K}{S}$ .12	K .12			
	$\frac{K}{S}$ .47	K .47			
3	K .47	K 1.88	q	p	o
	K .12	K 1.88			
	K .12	K .47			

Subject D

Session	Horiz.	Vert.	Day 1	Day 2	Day 3
1	$\frac{K}{S^2}$ 0.12	K 0.12	r	t	s
	$\frac{K}{S^2}$ .47	K .47			
	$\frac{K}{S^2}$ 1.88	K 1.88			
2	$\frac{K}{S^2}$ .47	$\frac{K}{S^2}$ 1.88	s	r	t
	$\frac{K}{S^2}$ .12	$\frac{K}{S^2}$ 1.88			
	$\frac{K}{S^2}$ .12	$\frac{K}{S^2}$ .47			
3	$\frac{K}{S^2}$ .12	K 1.88	t	s	r
	$\frac{K}{S^2}$ .47	K 1.88			
	$\frac{K}{S^2}$ .12	K .47			

Note: Lower case letters refer to the test conditions for each cell of the Latin squares above and are described in the cells for Day 1.

TABLE III.- CHANGES IN TRANSINFORMATION PER TRACKING CHANNEL DUE TO THE ADDITION OF A SECOND TRACKING AXIS OR A SECONDARY AUDITORY TASK

Controlled Element	Subjects	Condition	W_{eff}, Hz	Average per channel change, bits/sec
(a) Second axis added				
K/S^2	A,B,&D	(-) & (+)	All	-0.26**
K/S	A & C	(-) & (+)	0.12	.29*
			.47	.04
			1.88	-.23*
K	D	(-) & (+)	All	-.27*
	C	(-)	All	.57*
		(+)	All	-.14
(b) Secondary auditory task added				
K/S^2	A,B,&D	(S) & (D)	All	-.12**
K/S	A	(S) & (D)	.12	.03
			.47	-.49*
			1.88	-.72**
	C	(S)	All	-.13
		(D)	All	-.42*
K	D	(S) & (D)	All	.13
	C	(S)	All	-.29
		(D)	All	-.97**

(-) = no secondary auditory task
(+) = secondary auditory task present
(S) = single axis
(D) = dual axis
** = significant at 0.01 level
* = significant at 0.05 level
Overall average, second axis added = -0.11
Overall average, secondary auditory task added = -0.23

TABLE IV.- VISUAL-MOTOR INTERFERENCE IN TWO AXES TRACKING WITH AN INPUT IN ONLY ONE AXIS

Input W_{eff}, Hz	Controlled element					
	K/S^2		K/S		K	
	Axis with input Rel.(E-N)	Other axis Rel.N	Axis with input Rel.(E-N)	Other axis Rel.N	Axis with input Rel.(E-N)	Other axis Rel.N
0.12	0.28	0.47	0.14	0.07	0.12	0.06
.47	1.27	1.09	.57	.14	.41	.09
1.88	1.36	1.15	1.34	.39	.98	.13

Rel.(E-N) = RMS relative error with noise component removed.
Rel.N = RMS relative noise.

Note: There were two replications for each condition having forcing functions of 0.47 Hz and 1.88 Hz.

TABLE V.- DIFFERENCE IN TRANSINFORMATION BETWEEN HETEROGENEOUS INPUT BANDWIDTH TRACKING AND COMPARABLE HOMOGENEOUS DUAL AXES PERFORMANCE OF EXPERIMENTS I AND III

[Minus indicates that the heterogeneous bandwidth performance was lower]

Subject	Controlled element	W_{eff} each axis, Hz		
		0.12	0.47	1.88
D	K/S^2	-0.45 bits/sec	0.48 bits/sec	
		-0.32		0.76
			-0.31	0.22
A	K/S	-0.24	-0.73	
		-0.27		0.31
			-0.61	0.86
C	K	-0.19	0.64	
		-0.83		-0.29
			-0.33	0.13

Average higher bandwidth channels = 0.26 bits/sec.
Average lower bandwidth channels = -0.39 bits/sec.

Note: There were three replications of each heterogeneous bandwidth task.

TABLE VI.- DIFFERENCE IN TRANSINFORMATION BETWEEN HETEROGENEOUS CONTROLLED ELEMENT TRACKING AND COMPARABLE HOMOGENEOUS DUAL AXIS DATA OF EXPERIMENTS I AND III

[Minus indicates heterogeneous controlled element performance was lower]

Subject	W_{eff}, Hz	Controlled element		
		K/S^2	K/S	K
A	0.12	0.11	-0.71	
	.47	.58	-1.04	
	1.88	.20	-.70	
D	.12	-.45		-1.35
	.47	.65		-2.35
	1.88	1.00		-.20
C	.12		-.29	-.62
	.47		.54	-1.77
	1.88		1.17	-1.47

Average higher order controlled element = 0.39.
Average lower order controlled element = -1.13.

Note: There were three replications of each heterogeneous controlled element task.

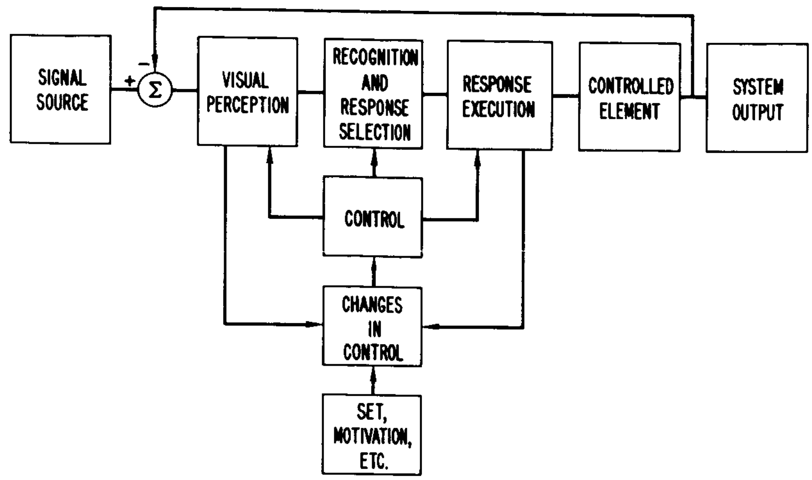


Figure 1.- Information processing model of single channel compensatory tracking.

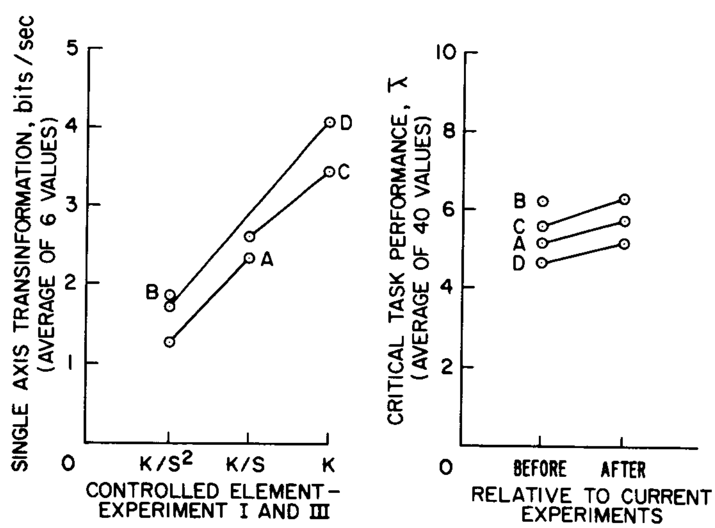


Figure 2.- Comparison of subjects' critical task performance and performance in Experiments I and III.

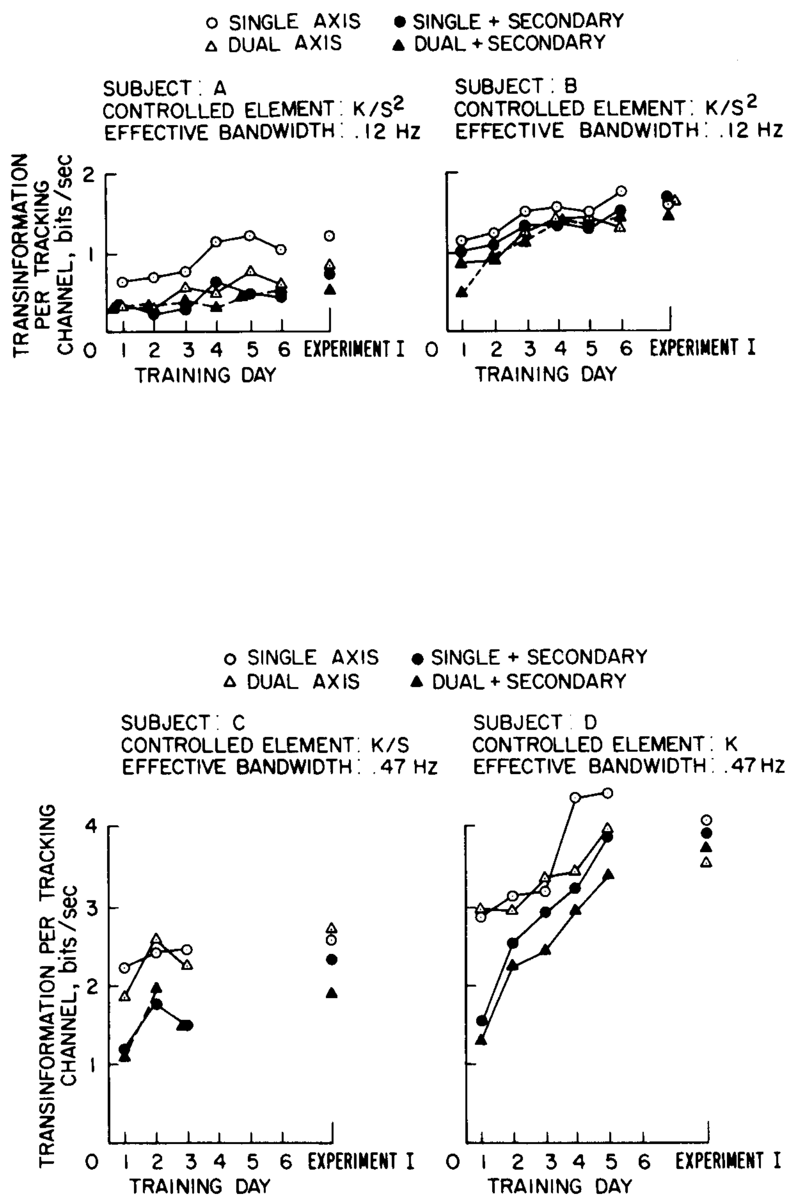
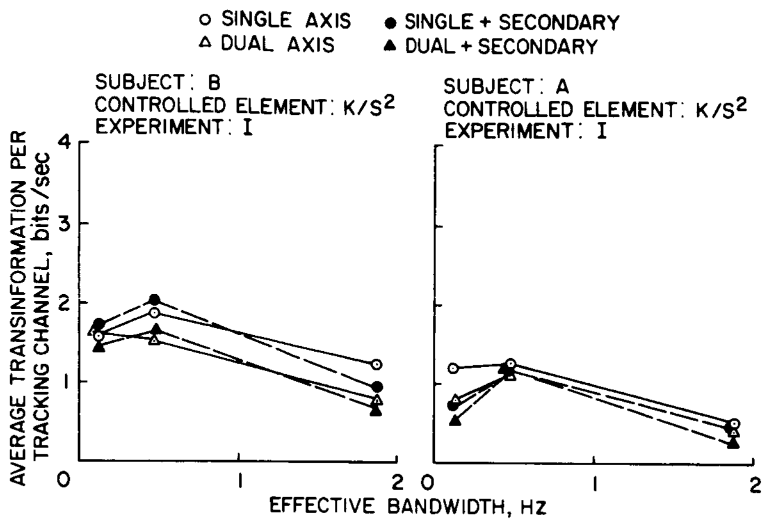


Figure 3.- Transinformation during early training and comparable data from Experiment I.



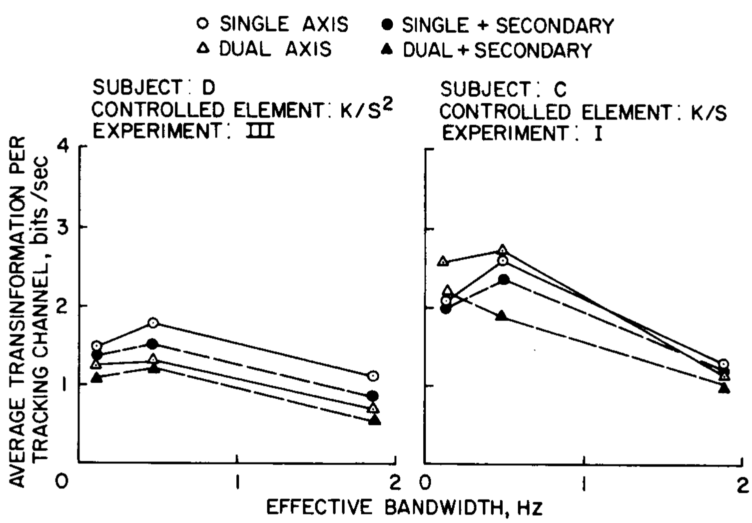
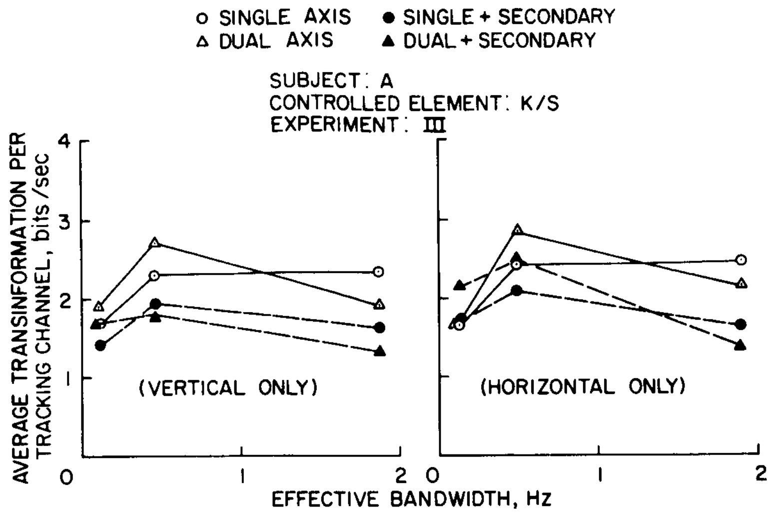


Figure 4.- Results of Experiments I and III (averages of six values per data point except where horizontal and vertical channels are separated).



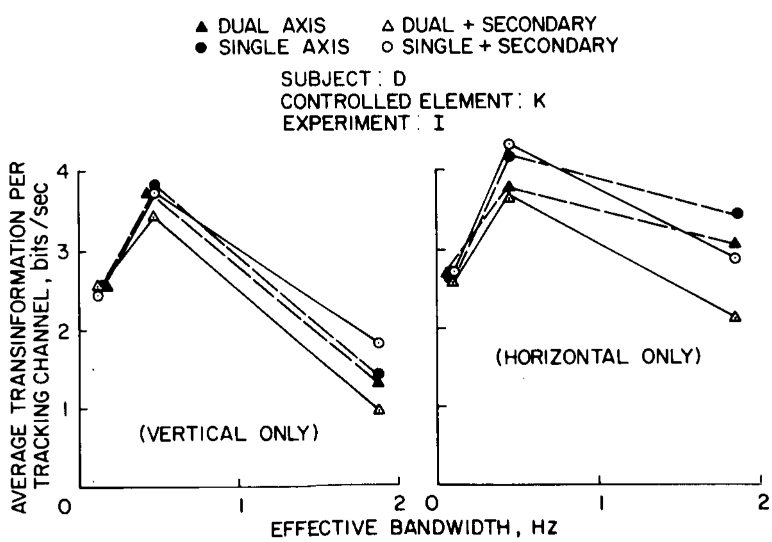


Figure 4.- Continued.

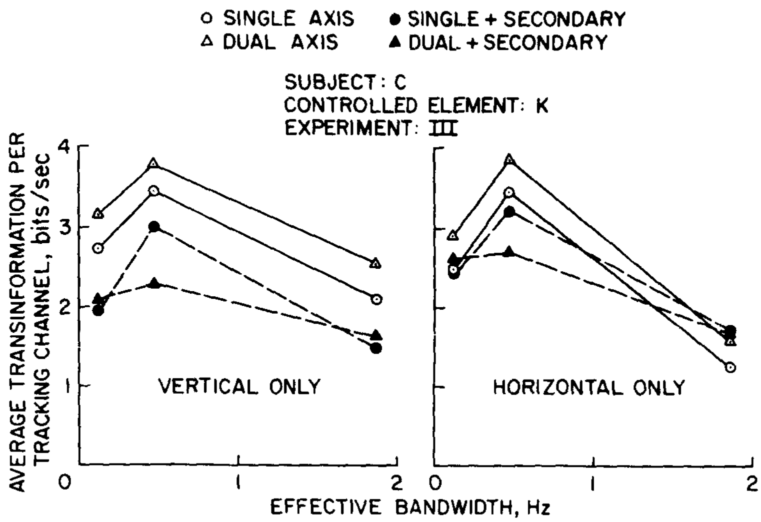
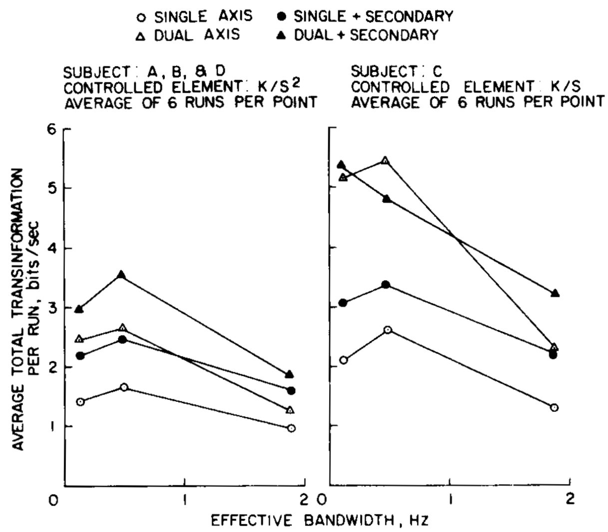


Figure 4.- Concluded.



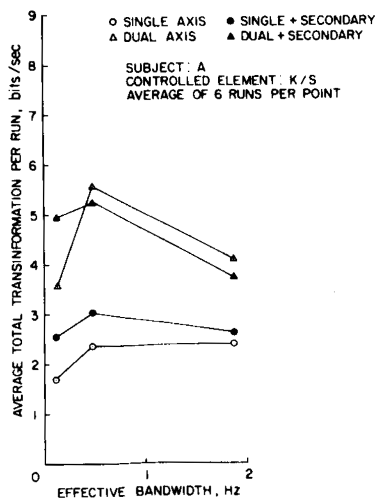
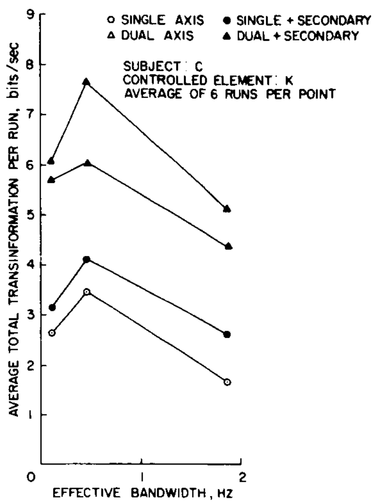


Figure 5.- Total transinformation per test condition - Experiments I and III.



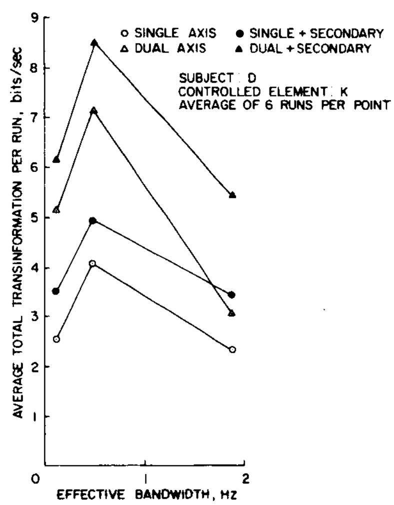


Figure 5.- Concluded.

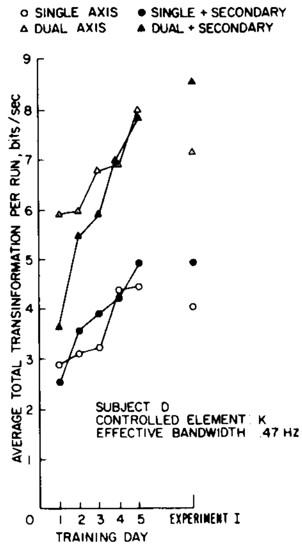


Figure 6.- Total transinformation during early training and Experiment I.

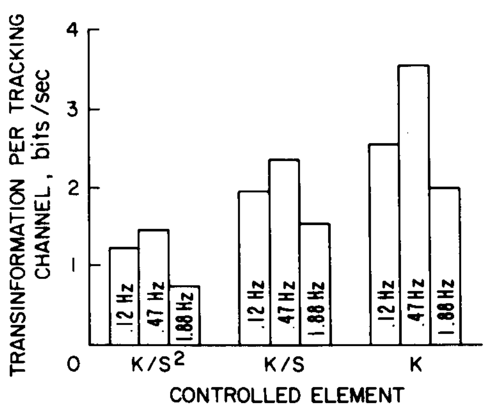


Figure 7.- The effect of controlled element on transinformation (averages of all subjects and all conditions from Experiments I and III).