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ATTENTION ALLOCATION IN DYNAMIC ENVIRONMENTS.(U)

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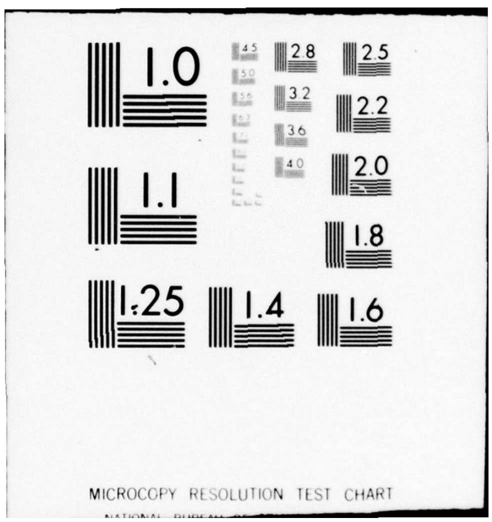
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ATTENTION ALLOCATION IN DYNAMIC ENVIRONMENTS

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Attention Allocation in Dynamic Environments

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ABSTRACT

Three policies of attention resource allocation between tasks of dynamically varying difficulty are described. These policies--optimal allocation, optimal resource expansion, and non-optimal allocation are distinguished analytically by the gain of the transfer function between task difficulty and primary and secondary task performance. Eight subjects time-shared two compensatory tracking tasks in which the control dynamics of the primary task fluctuated continuously between first and second order. Linear control analysis of the difficulty and filtered RMS error performance measures indicated that subjects were initially non-optimal in their allocation policy, failing to guard the primary task in the face of fluctuations in its difficulty. With practice, a trend toward more optimal performance was observed. This appeared to be related to greater automation of performance at the most difficult level. However, close analysis and comparison of the variable difficulty data with performance in constant difficulty dual task conditions indicated a persisting limitation in subjects' ability to reallocate resources from the secondary task when required by demand changes of the primary. The source of this limitation was postulated to reside in the difficulties operators encounter when maintaining two concurrent and dissimilar describing functions.

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INTRODUCTION

When two tasks of similar structure are performed concurrently, it may be assumed that the performance of each relies upon a common pool of processing resources [1,2,3,4,5]. When more resources are allocated to one task, as a consequence of either an increase in its difficulty, or of its required performance level, fewer are available to the concurrent task, and performance of the latter will deteriorate accordingly. The joint representation of concurrent performance of two tasks, as resources are traded off between them is presented in the Performance Operating Characteristic or POC, an example of which is shown in Figure 1a [1,2]. The vertical and horizontal axes represent performance measures on task A and B respectively, such that good performance corresponds to higher values. Single task performance is represented by the points falling on the axes, while the points within the space correspond to hypothetical performance measures in dual task conditions. Three such conditions are indicated: One in which resources are allocated equally between tasks, one in which the allocation policy favors task A, and one in which it favors task B. The smooth curve connecting the points--the Performance Operating Characteristic or POC--represents the hypothetical frontier of maximum joint performance, across the set of all possible allocation policies between tasks.

Gopher and Navon [1,2] have described how, as the difficulty of one task (task A in Figure 1) is varied, each difficulty level generates a different POC, with tasks of greater difficulty moving the POC closer to the origin. In the specific case of dual axis tracking when the difficulty manipulation employed is the order of the system transfer function (varied from first to second), Gopher and Navon [2] have shown that the set of POC's thus generated form the fan-like shape shown in Figure 1b. The influence of task difficulty on performance of both tasks grows as more resources are

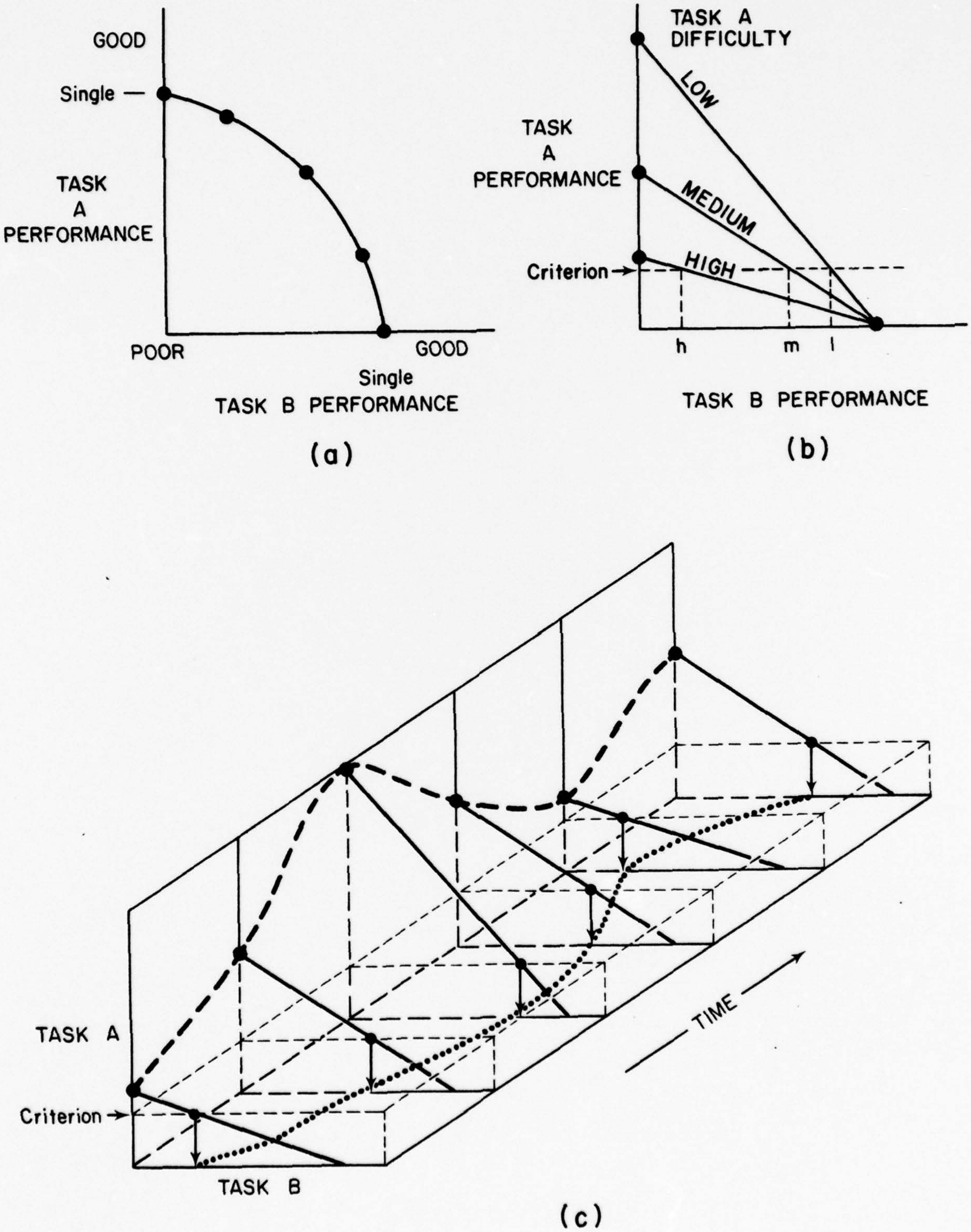

Figure 1

The performance operating characteristic in which task A difficulty is constant (a), variable (b), and time-varying (c).

allocated to the task whose difficulty varies.

Within the framework of Figure 1b, if task A is designated as primary--to be held at a criterion level of performance (indicated by the horizontal dotted line), then assuming an operator of fixed capacity, this performance can be achieved by trading off resources from task B, the performance of which would be indicated by the points h, m, and l in Figure 1b. Consider now the performance resulting when the difficulty level of the primary task is varied continuously within a trial, rather than discretely between trials. This would be represented by the POC of Figure 1b oscillating between the two extremes of difficulty. Alternatively, in Figure 1c, a time axis is incorporated and the POC now represents an undulating surface. Criterion performance is the horizontal plane that intersects this surface, and optimum secondary task performance, of a fixed capacity system with perfect allocation is represented by the intersection of this surface with the criterion plane projected onto the secondary task (task B) "floor" axis.

An alternative representation of this hypothetical data pattern is shown in the top panel of Figure 2. Wickens and Pierce [6,7] have argued that the transfer function of the inferred resource allocation system can be derived from linear time series analysis of the difficulty and the primary and secondary task performance signals in Figure 2. The pattern shown by the optimum allocator of the top panel would be reflected by a gain, or linear coherence value (between difficulty and performance) that is low for the primary task relative to the secondary. This pattern is referred to as Optimal Allocation. Alternatively, the optimal operator could maintain constant primary task performance by temporarily expanding the supply of available resources at the epochs of peak primary task difficulty (middle panel). Such expansion has been suggested by Kahneman [8] to be mediated via the role of feedback loops associated with mechanisms of physiological

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Predicted Gain Values (G) of Primary Task Difficulty (———) with performance of the :

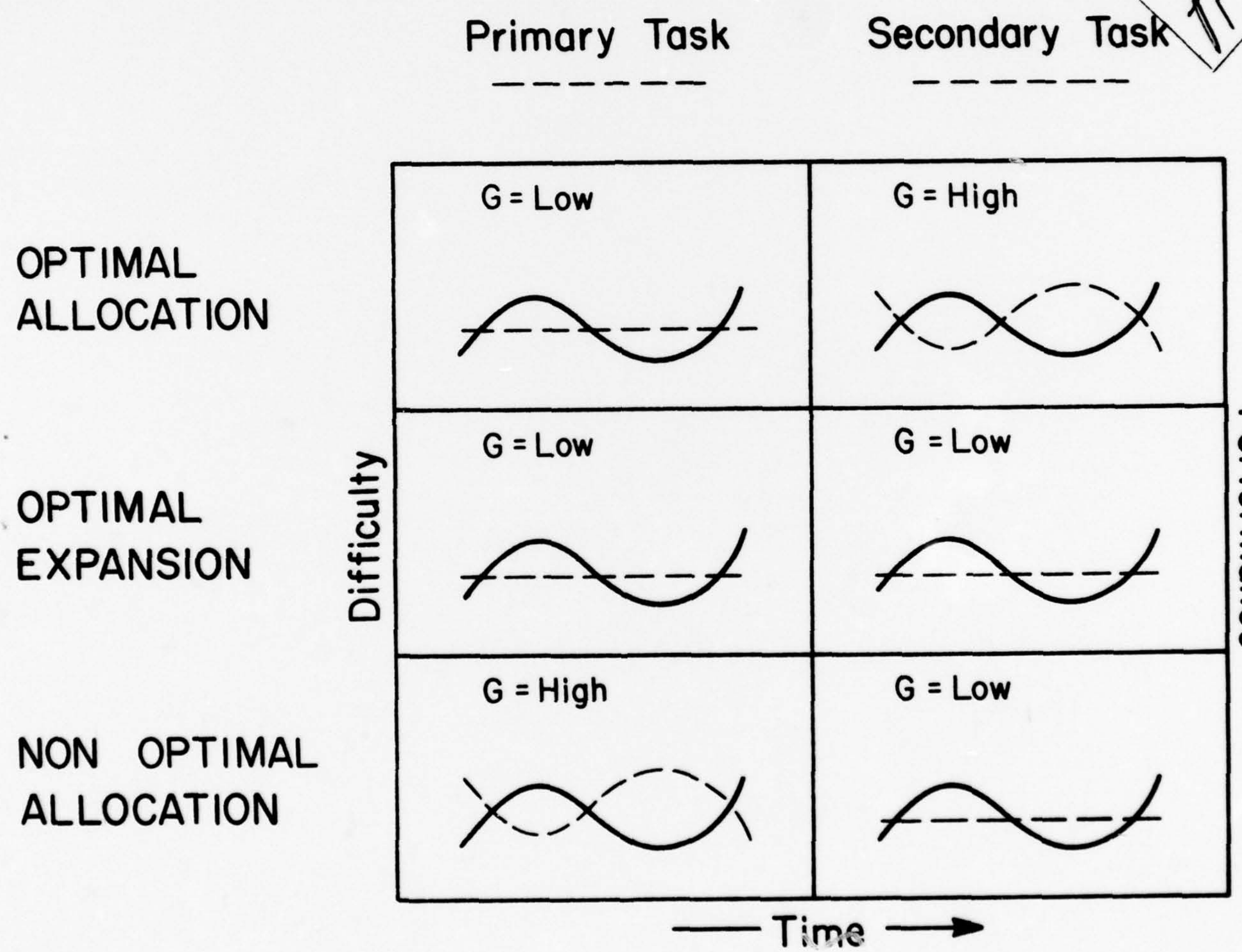


Figure 2

Gain of the difficulty-performance transfer functions (3 model predictions).

arousal. Such a policy, referred to as Optimal Expansion will, of course, be reflected by reduced values of gain and coherence on both tasks. Finally, a non-optimal response (bottom panel) is one in which a fixed supply of resources is maintained to both tasks, and primary task performance varies in coherence with its own difficulty fluctuations. This policy generates primary and secondary task gain values opposite from those of the optimum allocator. In summary, two dimensions of allocation policy may be identified. The degree of optimality is indexed by the difference (or ratio) of the primary and secondary task gain measures, and the degree of expansion indexed by the inverse of the sum of the two gains.

It should be emphasized that two other characteristics of the allocation process could also generate apparent, but spurious patterns of optimal expansion. If the task becomes more automated at the upper levels of the difficulty parameter, then the difference in resource demands between high and low levels is minimized, and only small differences in available resources to the secondary task will be expected. As a consequence, neither task should vary much with difficulty. Secondly, it is possible that full resources are not expended to either task throughout the entire period of difficulty variation, but only at the epochs of peak primary task difficulty. The resources thus made available as the difficulty of the primary task lessens are not allocated to the secondary task, but remain idle in an increasing pool of "residual capacity," to be depleted again as difficulty increases. Here again, task performance will tend to remain constant, but will on the whole be of less than maximum efficiency during the periods of reduced difficulty. Thus it should be noted that the distinction between this alternative, and the expanding capacity notion relates to the assumption of the steady state baseline from which capacity has expanded.

We assume in the current research that this baseline is represented by the level of performance achieved by well motivated subjects, financially rewarded for good performance (low RMS error) during trials of constant difficulty. Only if performance remains at, or exceeds this level during epochs of temporarily greater difficulty is expansion presumed to occur. If, during epochs of low difficulty, performance falls below the level obtained during the constant difficulty conditions then the assumption can be made that all resources were not expended during these epochs, and expanding resources cannot be assumed.

Wickens and Pierce [6,7] required subjects to time-share two tracking tasks as the difficulty (control order) of the primary task was varied in a series of steep spikes and ramps betwen first and second order. They observed that the behavior of operators engaged in dual axis tracking fell midway between the categories of optimal and non-optimal allocation. The difficulty-performance gains, and linear coherence measures for both tasks were relatively high and of approximately equal value. They also noted that the response did not appear to progress toward optimality across four days of training. This observation was somewhat surprising and served as one instigation for the present study.

A potential source of the non-optimal response observed by Wickens and Pierce is the severity of the difficulty changes. As a consequence, in the present investigation the difficulty "forcing function" was modified so that pure (non-truncated) sinusoidal components were employed, spanning the range between first and second order dynamics. In addition, the present investigation included a greater number of constant difficulty control conditions than did the prior study, incorporating conditions during which the primary task was maintained at the highest, the lowest, and the average level that is obtained under the variable condition. As indicated, these control conditions allow a more careful analysis of the source of apparent optimal expansion if this should be observed. More specifically, these allow a comparison of allocation behavior with task difficulty as difficulty is varied between trials, versus continuously within a trial.

Method

Subjects

Eight right-handed male students at the University of Illinois, age ranging from 19 to 28, were selected on the basis of tracking performance. Four of the subjects had some flying experience. All were paid for their participation on an hourly basis and received monetary bonus which was based on their tracking performance. See Appendix I.

Task

The tracking task employed a one-deminsional compensatory system which was displayed on a 10.2 by 7.6 cm screen of a Hewlett-Packard Model 1330a CRT. A vertical stationary reference line was centered in the middle and the cursor moved in the lateral direction. Two Measurement System Incorporated Model 435 spring-centered tracking sticks were employed for task control. Error indicators of the two tasks were displayed laterally on a CRT display with a vertical separation of 0.7 degrees of visual angle. The two displays had a small (1 degree) lateral offset; the right of center display was controlled by lateral deflections of a right hand control stick while the left set display was controlled by a manipulator held in the left hand. Both tasks were driven by a separate band-limited Gaussian disturbance input with an upper cutoff frequency of .32 Hz. The system control dynamics (governed by a Ratheon 704 computer) was composed of a linear combination of first and second order components. The system output, Y, was therefore represented by the following equation:

$$Y = [(\alpha) \iint u(\tau)\, dt\,] + [(1-\alpha) \int u(\tau)\, dt\,]$$

where u = control stick position

t = time

α = difficulty level

The difficulty level (α) of the tracking task was described by the percentage of the second order component in the control dynamics. α could take any value between 1 and 0 representing 100% and 0% of the second order component respectively. In the present experiment, under the constant difficulty conditions, α was maintained at values of 1, 0.5, or 0 throughout the trial for different trials. Under the time-varying conditions, α varied as a function of time but maintained an average of 0.5 within one trial. The time-varying function that determined the α level was:

$$\alpha = 0.5 + A\ [SIN(f_1t) + SIN(f_2t)]$$

where t = time

f_1 = frequency 1

f_2 = frequency 2

Two sets of frequency difficulty functions ($\{f_1 = 0.03$ Hz, $f_2 = 0.02$ Hz$\}$; and $\{f_1 = 0.03$ Hz, $f_2 = 0.01$ Hz$\}$) were employed on different trials to reduce the probability of the subjects recognizing the time-varying pattern of α. Each trial was 200 seconds in duration and this allowed a minimum of 2 complete cycles of the time-varying α function for the variable α trials.

Design

A within subject design was employed to reduce the effect of individual differences in time-sharing and tracking ability. To further control the subject heterogeniety, subjects were selected by a pretest described below. Following the pretest, each subject participated in four experimental sessions. Within each session, there were six experimental conditions including two variable and four constant tasks as shown in Table 1. Of the two variable conditions, one was single task (SV) and one was dual task (DV). Of the four constant difficulty conditions, one was a single task with α equal to 0.5 (S.5) and three were dual tasks with α set at 1, 0.5, or 0 (D1, D.5, D0). The primary task α values for the various experimental conditions are shown in Table 1. The secondary task α for all the dual conditions was set at a constant value of 0.5.

TABLE 1

TRIAL TYPES

	Trial Designation	Primary Task Difficulty (α)	Secondary Task Difficulty (α)	
	DV	Variable	0.5	Dual Task
Constant Difficulty	D1	1.0	0.5	Dual Task
Constant Difficulty	D.5	0.5	0.5	Dual Task
Constant Difficulty	D0	0	0.5	Dual Task
Constant Difficulty	S.5	0.5	None	
	SV	Variable	None	

There were two orders of presentation of the different experimental conditions:

Order 1: D0, SV, DV, D.5, S.5, D1

Order 2: D1, S.5, D.5, DV, SV, D0

Each order was presented once every session and the sequence of the two presentation orders was counterbalanced over subjects and over sessions. Each subject performed all six experimental conditions twice in every session separated by a 5-minute break and each session lasted about 60 minutes.

Procedure

Of the eleven subjects who participated in the pretest, the eight subjects with the lowest RMS error were selected to continue the experiment. The pretest consisted of 13 trials of tracking tasks which included six single tasks and seven dual tasks, all with constant α at various levels. In addition to its function of selection, the pretest also served the purpose of familiarizing the subjects with the nature of the different experimental conditions. Subjects were encouraged to experiment with different kinds of movement to maneuver the control stick that would give them the best results or the lowest RMS error.

At the beginning of the first experimental session, subjects were given three practice trials (two single tasks and one dual task, all with constant α at 0.5). At the beginning of the subsequent three sessions before receiving the experimental trials, subjects were given one D.5 condition for warmup.

Instructions

Subjects were instructed to pay full attention to the tracking task. Subjects were also instructed to keep their RMS error as low as possible in the single tasks and to divide attention equally between the primary and secondary tasks in the D.5 condition. During the other dual task conditions, subjects were instructed to pay special attention to the primary task so as to maintain primary task performance at the same level as obtained at the D.5 condition. Instructions thereby emphasized that when the primary task α was low (i.e., when the primary task was easy, as in the D0 condition) or high (i.e., when the primary task was hard, as in the D1 condition), subjects were to allocate more or less attention respectively to the secondary task as required to maintain consistent primary task performance. They were also reminded not to ignore the secondary task entirely at any point in time. The single task and the primary task in the dual task conditions were always performed with the right hand.

A monetary bonus system was employed to encourage the subjects to follow the instructions as precisely as possible. In addition to their hourly pay, subjects could earn extra bonus for every experimental condition in which their RMS error was lower than their previous average, when their primary task and secondary task performance were within 10% of the RMS error of each other in the D.5 condition, and/or when the primary task performance on the rest of the dual conditions was within 10% of the RMS error of that of the primary task performance in the D.5 condition. Verbal feedback (based upon the RMS error) was given to the subjects after each trial (see Appendix).

At the end of the experiment, subjects filled out a questionnaire in which they were asked to rate the difficulty of each experimental condition on a scale of 1 to 10 and to describe the strategy they adopted to deal with the different conditions.

Results

Global RMS Error. RMS error values for the primary and secondary tasks in the six conditions are shown in Figure 3. The figure indicates a decline in error on both tasks with practice, a greater error in dual as opposed to single task performance, and a reduction in this dual task decrement with practice.

The data were subjected to two ANOVAS. One ANOVA included only the dual task data (both primary and secondary task) for the four dual task conditions (DV, D1, D.5, and D0). The second included only the primary task data for the single task (SV and S.5) and dual task (DV and D.5) conditions. Both ANOVAS indicated reliable main effects of sessions ($F_{3,7} = 23.63$, $p < .01$, $F_{3,7} = 32.33$, $p < .01$ for the dual task and primary task ANOVAS respectively). The dual task ANOVA indicated reliable effects of conditions ($F_{3,7} = 15.6$, $p < .01$) and task (primary vs. secondary, $F_{1,7} = 6.7$, $p < .05$) as well. In the primary task ANOVA effects of constant vs. variable, dual vs. single, and the dual-single X sessions interactions were all statistically reliable ($F_{1,7} = 31.4$, $p < .01$; $F_{1,7} = 32.3$, $p < .01$; $F_{3,21} = 13.1$, $p < .01$, respectively).

Time-series analysis. To evaluate the allocation strategies, the raw sampled RMS error values were smoothed by computing the running average of these

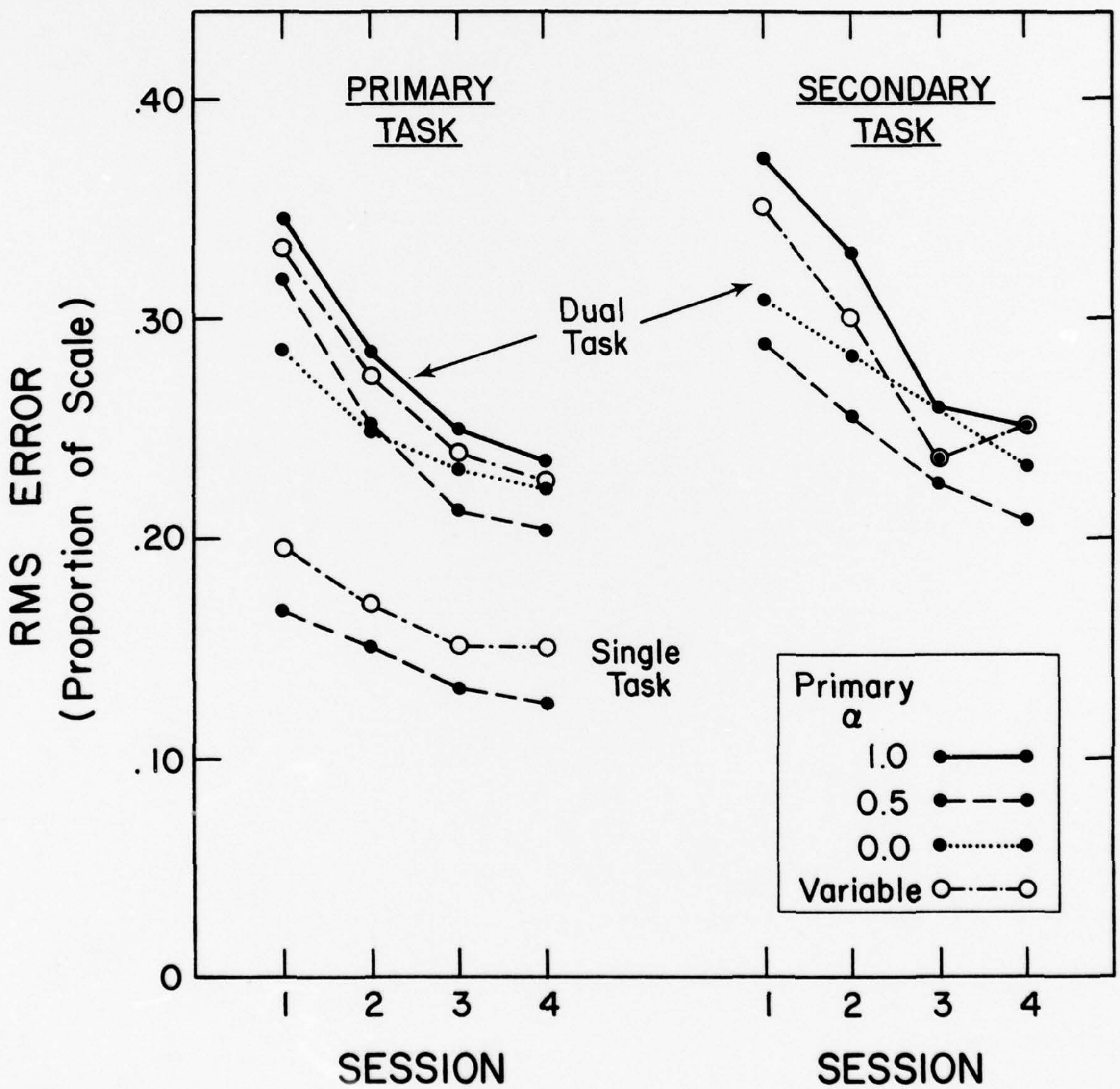


Figure 3
RMS tracking error in the various experimental conditions.

values within a 2 second sliding window. The 200 averages computed every second for a given trial were thus used as the performance (output) data in a time-series analysis (Biomed 02T). Separate transfer functions were computed between difficulty (α) and primary and secondary task performance for each subject, in each variable condition on days 1 and 4. Preliminary analyses of the data indicated that the amplitude-ratio measures provided the clearest differentiation between conditions, so only these measures will be described below. It should be noted, however, that the linear coherence measures obtained here were consistently lower than those observed by Wickens and Pierce [6,7], being of values generally less than 0.50 in the present study.

Figure 4a presents the ensemble average time-series of the primary task error measures, early (top) and late (bottom) in practice for one of the two difficulty forcing functions employed F=(.02 Hz, .03 Hz). Corresponding plots of the secondary task measures are shown in Figure 4b. Inspection of Figure 4 indicates that the apparent strategy employed early in practice is non-optimal, as primary task performance fluctuates with its own difficulty level. With practice (bottom panel) the primary task gain appears to decline; however, this reduction is not paralleled by a corresponding increase in secondary task gain, as would be predicted by adoption of a policy of optimal allocation.

The mean amplitude ratio values of the transfer function at each of the three input frequencies employed across both disturbance functions are shown in Figure 5. It is apparent that no monotonic trend with frequency is shown in the dual task conditions, suggesting that the allocation system does not behave as a strictly linear system. However, the single, orderly pattern that is observed in Figure 5 occurs with single task gain late in practice. Here there is a suggestion that the response is that of a first order lag, a finding that appears to be consistent with the results of Delp and Crossman [9] in a similar single task condition.

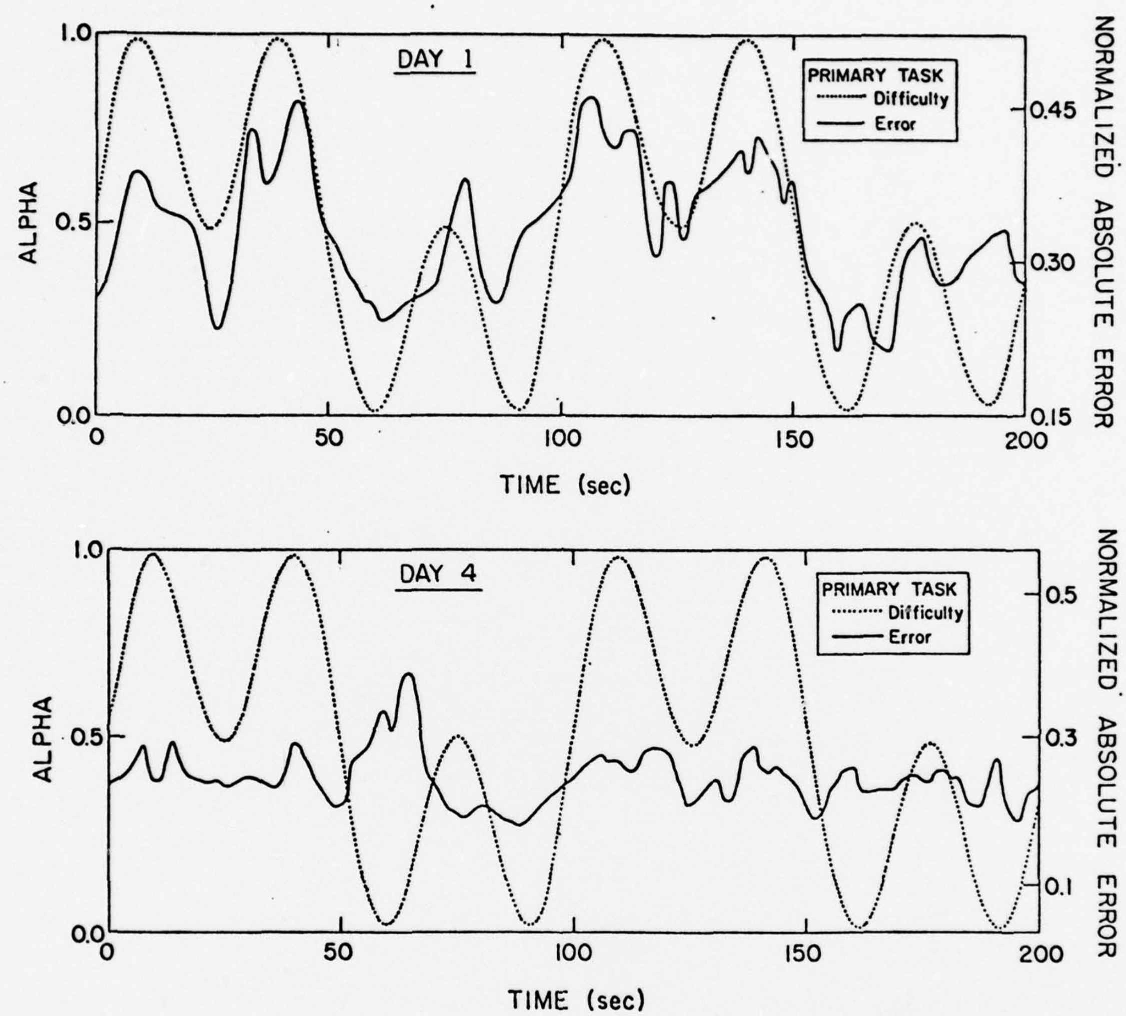
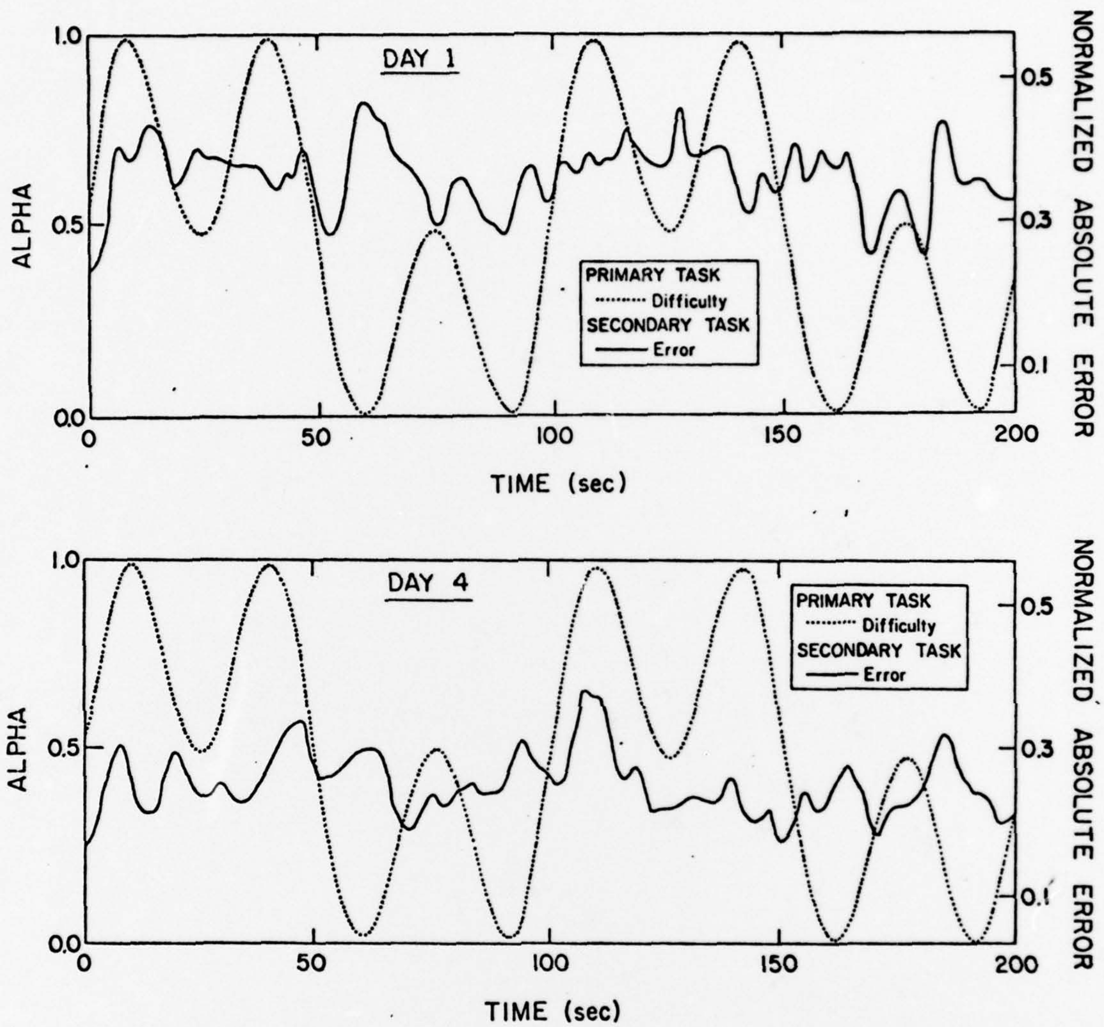


Figure 4

Ensemble average of task difficulty (alpha) and performance (tracking error) as a function of practice (day 1 vs. day 4).

(a) primary task



(b) secondary task

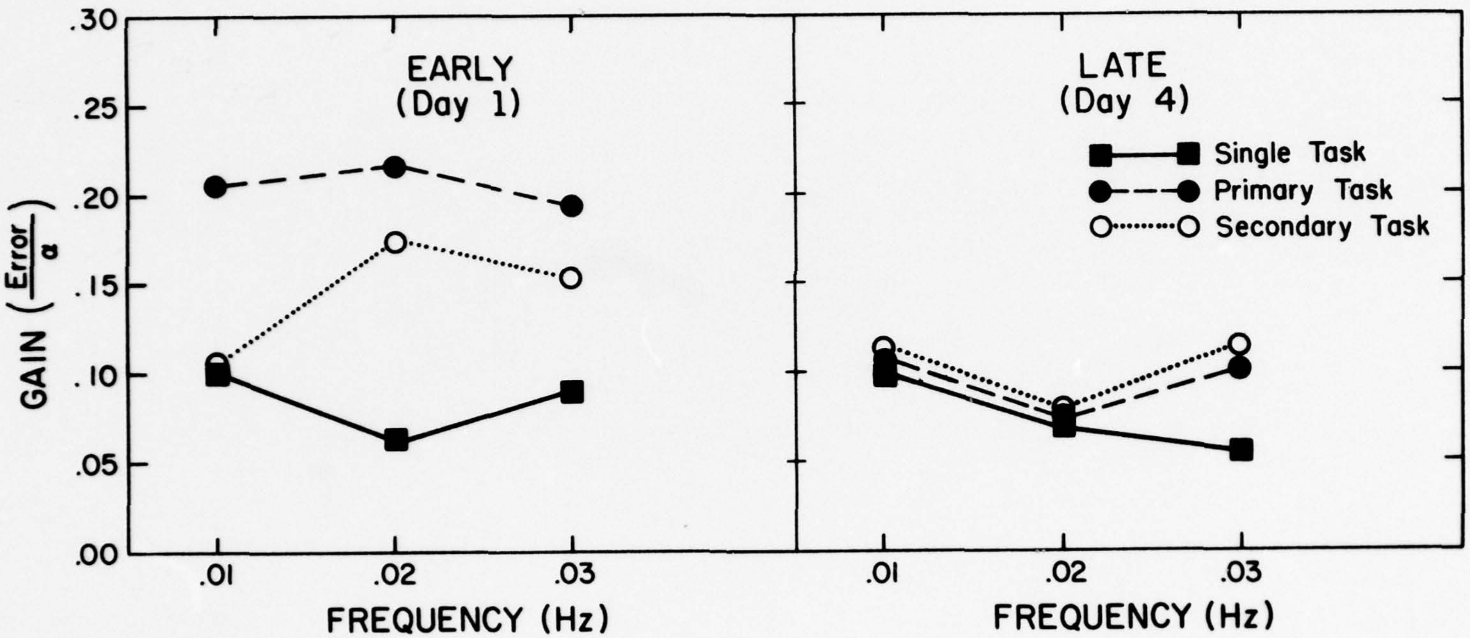


Figure 5

Gain of the performance-difficulty transfer function.

A 4-way repeated measures ANOVA was performed on the dual task gain measure. The ANOVA variables were task (primary and secondary), frequency (high-low), function (F_1 vs. F_2) and sessions (1 vs. 4). The results indicate that the apparent reduction in gain with practice, evident in Figures 4 and 5, was in fact statistically reliable ($\underline{F}_{1,7}$= 15.6, $\underline{p}$ < .01). A second ANOVA performed only on the primary task for both the single and dual task trials indicated a reliably greater gain in the dual than single task condition ($\underline{F}_{1,7}$= 41.68, $\underline{p}$ < .01), and a reliable task (dual-single) X sessions interaction ($\underline{F}_{3,7}$= 9.51, $\underline{p}$ < .05). Within the framework of the models presented above, evidence that the subjects were proceeding with practice toward more optimal allocation would be provided by a reliable task X sessions interaction, an indication that secondary task gain increased with practice while primary gain declined. Although this interaction is suggested by the data, its level was not found to be statistically reliable ($\underline{p}$ = .17). Thus the pattern of behavior demonstrated by the subjects can be described as one that is initially non-optimal, but manifests a reliable practice trend toward optimal expansion (reduction in both gains) and a non-reliable trend toward optimal allocation (reversal in gains, or change in their ratio).

Constant vs. variable difficulty comparisons. Further analysis was focussed upon the apparent trend toward optimal expansion. As outlined above, this policy was operationally defined in terms of the ability of the operator to mobilize temporarily more resources than are normally available, during the transient epochs of peak primary task demands. Such a strategy would yield the relatively constant performance on both tasks that was observed. In order to assess the contributions of the two spurious sources of constancy described in the Introduction--automation and resource withholding--comparison of performance with the constant difficulty conditions is imperative. To enable such a comparison, RMS error values were derived for each subject at the epochs of the DV conditions, when α reached values of 1 and 0, respectively. The difference between these values thereby provides a "gain" measure that has a direct correspondence to the constant difficulty D1 and D0 conditions. If the expansion policy underlies the practice trend and expansion is defined to be transient (thereby evident only in the variable condition), then the "gain" of the performance-difficulty relation (the difference in RMS error between $\alpha = 0$ and $\alpha = 1$) should be reduced only in the variable condition. However, if automation is the underlying variable, then a reduction in gain (change in performance with difficulty) that is equivalent in the constant and variable difficulty conditions should be observed. Finally, if "resource withholding" in the DV condition is occurring, then the DV error at the easiest level ($\alpha = 0$) should be greater (performance worse) than in the D0 condition, a manifestation of unutilized resources under the variable regime.

In order to evaluate these strategies, the RMS error values were extracted from each subject's ensemble at the instances of maximum ($\alpha = 1$) and minimum ($\alpha = 0$) difficulty. (In Figure 4a the $\alpha = 1$ points occurred at the 9th, 10th, 40th, 41st, 109th, 110th, 140th, and 141st second samples.) The average RMS error values at these points, along with those at the $\alpha = 0$ values and the constant difficulty errors in the D0 and D1 conditions, are presented in Figure 6. Performance on both the primary and secondary task, early and late in practice is represented. The data in the figure suggest that the expansion hypothesis can be rejected in favor of an automation explanation. Late in practice the "gain" in the DV condition is, if anything, greater than in the constant conditions. In a 3-way ANOVA performed only on the session 4 data, this apparent interaction between α and condition (variable-constant) was statistically reliable ($\underline{F}_{3,7} = 7.12$, $\underline{p} < .05$). In short, the decrease with practice in the performance difference between the $\alpha = 1$ and $\alpha = 0$ conditions is just as evident in the constant as in the variable conditions, if not more so. To the extent that this decrease in the constant condition results from automation of 2nd order tracking,

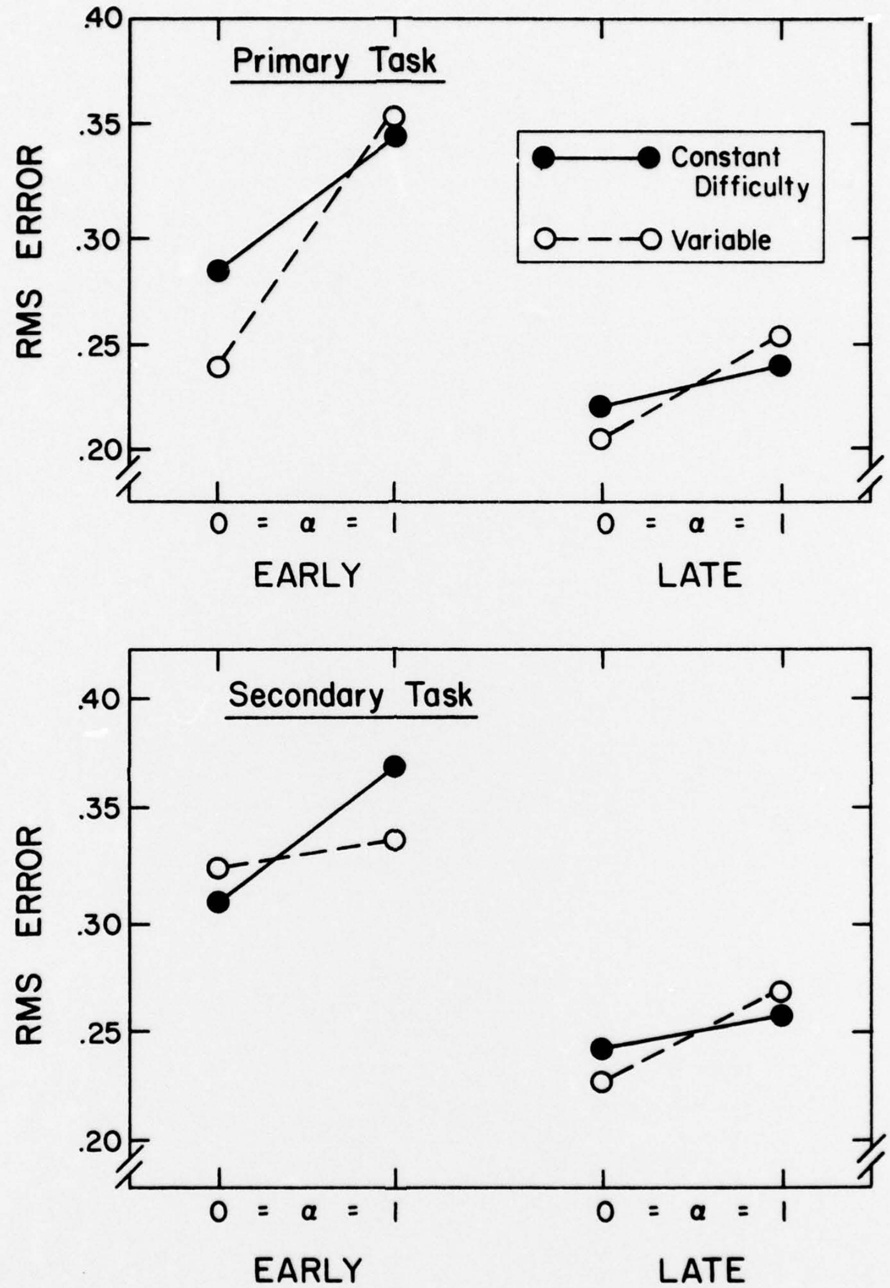


Figure 6

Tracking error in constant vs. variable conditions at low and high difficulty.

then the decrease in the DV condition may also be attributable to the same source, rather than to a change in characteristics of the processing resources themselves. While expansion therefore does not appear to be operating, the data also allow rejection of the possibility that resource withholding is occurring. Figure 6 indicates clearly that late in practice, RMS error is lower in the variable than in the constant difficulty conditions at the easiest ($\alpha = 0$) levels.

Discussion

In the present experimental analysis, the concept of "gain" has received two operational definitions: As the amplitude ratio, at specified frequencies of the performance-difficulty transfer function, and as the difference in RMS error between the highest and lowest levels of task difficulty, as operationally defined by α. The former definition, relying upon all of the performance data applies only to the DV and SV conditions, and the latter only to the high and low data points in either the constant or variable conditions. Using the two gain definitions, two alternative comparisons are of interest as they pertain to the underlying adaptive mechanisms employed.

Variable vs. constant gain. The reliable interaction described above between condition (variable constant) and α (0 vs. 1) suggested that the dual task gains (on both primary and secondary tasks) were greater in variable conditions. A plausible explanation for this finding is that in the constant difficulty conditions subjects were able to adopt a set for each dual task condition, generating the appropriate equalization that is compatable with the system dynamics on that trial and thereby reducing the extent to which performance varies with system order. On the DV trial, however, it is assumed that the lead equalization can be less easily modulated to the appropriate level demanded by the high α periods and so the relatively greater error is obtained.

Single vs. dual task primary gain. A separate ANOVA performed on these two gain measures for the primary task only, revealed the single task gains to be reliably less than the dual. A speculative source of this difference is the "pull" exerted by the constant ($\alpha = .5$) secondary task in the dual task condition. In the SV conditions subjects may be relatively free to adopt the lead-lag equalization appropriate to the high and low α values [10]. Under dual task (DV) conditions, however, the constant equalization required for the secondary task may have constrained the extent of equalization adjustment on the primary, thereby rendering the primary task describing function less optimal, at the extreme levels of α. This loss of optimality would increase the range of error spanned by the high and low α levels (the gain of the resource allocation system).

Further evidence substantiating this "pull" effect of the secondary task α is provided by the observation of consistently better performance in the D.5 than in the D0 conditions. The original selection of percent acceleration as a difficulty manipulation variable was predicated on the assumption that difficulty, and therefore performance, would vary monotonically with α. While the contrary result obtained here does not invalidate the other conclusions drawn--there clearly are large differences in performance between the extreme ranges ($\alpha = 0$, $\alpha = 1$)--it nevertheless requires explanation. In this regard, since the paired task dynamics were always constant at $\alpha = .5$, only in the D.5 condition is the subject able to control the same dynamics with both hands, and thereby employ a single internal describing function for both axes of control. Chernikoff, Duey, and Taylor [11] have provided evidence that a cost is associated with mixed dynamics tracking. In the present experiment this cost in the D0 condition apparently outweighed the benefit of the lower control order on the primary task. The non-optimal aspect of allocation was reflected in the fact that this cost was not born entirely by the secondary task. The extent to which it was shared by the primary task is revealed by the non-zero primary task gain values.

Questionnaire

The subjective rating of the difficulty level of each of the experimental conditions averaged over subjects was highly correlated with the primary task error ($r = 0.83$, $p < 0.05$) but very poorly correlated with the secondary error ($r = 0.07$, $p > 0.05$). In their reports of strategies adopted, five subjects reported that they attended to both tasks all the time but the amount of attention they gave to each hand varied. Two subjects reported that they switched their attention back and forth between the primary and secondary task. Four subjects reported that they tried to anticipate the movement of the cursor. Most used a combination of continuous and impulse-type movement depending on the difficulty level and how far away the cursor was from the center.

Conclusions

In conjunction with the previous investigation by Wickens and Pierce [6,7], the present study indicates that human resource allocation in dynamic environments can be far from optimal. If difficulty fluctuations are relatively smooth, as in the present study, then practice does influence the extent to which primary task performance can be maintained at a constant level. However, comparison of the variable with the constant difficulty control conditions suggested that the mechanism underlying this improvement was not related to an allocation skill, nor apparently to any properties of the resource system itself (e.g., expanded availability). Rather, the reduction in performance sensitivity to difficulty fluctuations seemed to result from an increased automation of primary task performance. This pattern of results casts some doubt on the extent to which resource allocation in dynamic environments may be modelled by a closed loop servomechanism, as Kahneman [8] has argued. Instead, as Galanter [12] has proposed, substantial portions of an operator's response strategies may be generated as ballistic, open loop commands, that are not continuously corrected according to performance feedback. Because of its implications to multi-task performance in dynamic environments, the extent to which this apparently non-optimal open loop behavior can be modified by training represents an important area of future research.

The results of the present investigation indicate also that considerable attention should be focussed upon the mechanisms by which resources are allocated (or are constrained from allocation). Specifically, in the present data the limiting constraint imposed by the secondary task describing function appeared to represent a potential source of non-optimal behavior. According to this interpretation, optimal allocation might have been achieved, to the extent that the appropriate lead-lag equalization of the primary task could be modulated in real time, in response to the changing system order. Under single task conditions (SV) this adjustment was performed reasonably well. Under dual task constant difficulty conditions (D0 and D1) the adjustment was somewhat constrained by the intermediate secondary task describing function. In the DV condition it was further constrained by the higher frequency of required modulation, and the "gain" measures were highest.

The implication of these results are that some of the limitations observed in this study and in the investigation of Wickens and Pierce [6,7] resulted from the structural incompatibility of the two different describing functions, rather than in the resource allocation process itself. Before therefore asserting the "open loop" or "ballistic" concept of resource allocation, generalized from Galanter's [12] observations, future research must establish whether similar limitations exist when manipulations that do not require a change in describing function are imposed (e.g., input bandwidth). These perhaps will place a more direct demand upon processing resources. In order, therefore, to validate that the assertion made by Galanter [12] concerning the ballistic aspects of task performance, apply to resource allocation, it is necessary to demonstrate similar failures of closed loop allocation when different difficulty parameters are employed. These parameters should represent those such as disturbance input bandwidth, whose value will not affect the form of the required describing function employed but only the frequency of corrective responses required of the parameters within that function.

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APPENDIX I

MONETARY BONUS SYSTEM

CONDITION	CRITERIA	BONUS
S.5*	Performance error lower than previous average.	5¢
SV*	Same as S.5	5¢
D.5*	Left and right hand error difference ≤ 5%	20¢
	Left and right hand error difference ≤ 10%	15¢
	Error for both left and right hand lower than previous average.	10¢
DV**	Right hand error and right hand error in D.5. condition difference ≤ 5%.	25¢
	Right hand error and right hand error in D.5. condition difference ≤ 10%.	15¢
	Right hand error lower than previous ave.	5¢
	Left hand error lower than previous ave.	5¢
D1**	Same as DV	
DO**	Same as DV	

Maximum Possible. . . $2.50

* bonus based on ave in 1 session

** bonus based on every trial

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Three policies of attention resource allocation between tasks of dynamically varying difficulty are described. These policies--optimal allocation, optimal resource expansion, and non-optimal allocation are distinguished analytically by the gain of the transfer function between task difficulty and primary and secondary task performance. Eight subjects time-shared two compensatory tracking tasks in which the control dynamics of the primary task fluctuated continuously between first and second order. Linear

control analysis of the difficulty and filtered RMS error performance measures indicated that subjects were initially non-optimal in their allocation policy, failing to guard the primary task in the face of fluctuations in its difficulty. With practice, a trend toward more optimal performance was observed. This appeared to be related to greater automation of performance at the most difficult level. However, close analysis and comparison of the variable difficulty data with performance in constant difficulty dual task conditions indicated a persisting limitation in subjects' ability to reallocate resources from the secondary task when required by demand changes of the primary. The source of this limitation was postulated to reside in the difficulties operators encounter when maintaining two concurrent and dissimilar describing functions.