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LINEAR MODELLING OF ATTENTIONAL RESOURCE ALLOCATION[1]

by Byron Pierce[2] and Christopher D. Wickens

University of Illinois Department of Psychology

SUMMARY

Eight subjects time-shared performance of two compensatory tracking tasks under conditions when both were of constant difficulty, and when the control order of one task (designated primary) was varied over time within a trial. On line performance feedback was presented on half of the trials. The data are interpreted in terms of a linear model of the operator's attention allocation system, and suggest that this allocation is strongly suboptimal. Furthermore the limitations in reallocating attentional resources between tasks, in response to difficulty fluctuations were not reduced by augmented performance feedback. Some characteristics of the allocation system are described, and reasons for its limitations suggested.

INTRODUCTION

A common requirement imposed upon the human operator engaged in time-sharing performance under time-varying environmental conditions results when changes occur in the difficulty of one of two concurrently performed tasks, as its performance constraints are held constant. Such changes thereby force a reallocation of attentional resources toward the task whose difficulty is increasing. Thus for example in precision flight, an increase in lateral air turbulence will require re-allocation of resources away from tasks of lesser demand (communications, pitch control) toward control along the lateral axis.

The entire process of task demand evaluation and resource allocation can be conceptualized as a two stage process. The operator must first evaluate the error, or discrepancy between desired and actual performance on the task or tasks required (error evaluation). If such an error is perceived to exist, the attention allocation system then must respond by shifting resources in a manner to restore the desired level of performance and nullify the original error (resource allocation). This closed feedback loop describing the resource allocation system is analogous in some respects to a compensatory tracking task, in which position error is evaluated and a manual control response is executed to nullify the error. Because of this similarity, modelling techniques borrowed from manual control will be utilized in

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[2] Now at Williams Air Force Base.

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the current investigation to describe and evaluate the human's attention allocation system.

Delp and Crossman (Reference 1) have provided an analytical framework for describing the linear relation between time-varying task parameters and single task performance in terms of a higher level "meta transfer function." The objective of the present research is to apply similar procedures to analyze the meta transfer function of the resource allocation system to task demand (difficulty) changes in the dual task environment. In the paradigm employed, subjects perform two concurrent tracking tasks. One task is designated as primary--a high priority task whose performance is to be maintained at or above some criterion for the duration of a trial. During the trial, the difficulty of the primary task is varied in a semi-periodic fashion. It is assumed that, to the extent that he is capable, the subject follows the priority instructions, and primary task performance remains constant in the face of varying primary task difficulty. To achieve this optimal allocation behavior, the subject is therefore required to withdraw processing resources from performance of the secondary task, and its performance should then vary, more or less phase-locked to the difficulty variations of the primary task.

An hypothetical example of this "optimum allocation response" to a ramp increase in primary task difficulty is depicted by the solid lines of Figure 1. The time-varying performance on both tasks is portrayed, along with the inferred allocation of processing resources between the tasks. Note the differential sensitivity of primary vs. secondary task performance to the increase in primary task difficulty, and the corresponding optimum allocation of resources. Naturally, other varieties of allocation responses may be observed as well. The dashed lines in Figure 1 depict that of a nonoptimum allocator in which resources are not at all redistributed, and primary task performance varies with its difficulty. Naturally a hybrid response between that of the optimal and nonoptimal allocator is possible, in which there is some reallocation of resources, but in insufficient degree to meet the new primary task demands.

The model that will be employed to describe the allocation system is portrayed in Figure 2. Here the allocation system is assumed to be a linear dynamic system in the sense that it receives inputs (task demands and subjectively assessed performance) and generates outputs in response (mobilized processing resources). While these outputs cannot be directly observed, they may be inferred from an appropriately filtered on-line performance measure. Thus in dual task performance, depicted in Figure 2, the dynamic relation between the four inputs to the allocation system (difficulty and performance demands on both tasks) and the two outputs (task performance on each task) can be evaluated to determine the extent to which these are described by a linear transfer function or orderly mathematical relation. Such a procedure is analogous to the analysis of dual axis tracking (Reference 2).

When analyzing dual task performance, one may examine for each task, the sensitivity of its allocated resources (inferred from performance) to changes in its own difficulty (D_1P_1 and D_2P_2 in Figure 2) and to changes in the difficulty or performance of the concurrent task (D_1P_2 and D_2P_1). In the

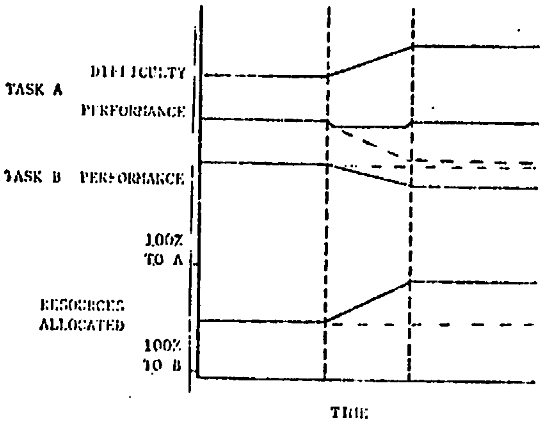

Figure 1. Hypothetical response depicting optimal allocation adjustment (solid lines) and nonoptimal allocation (dashed lines)

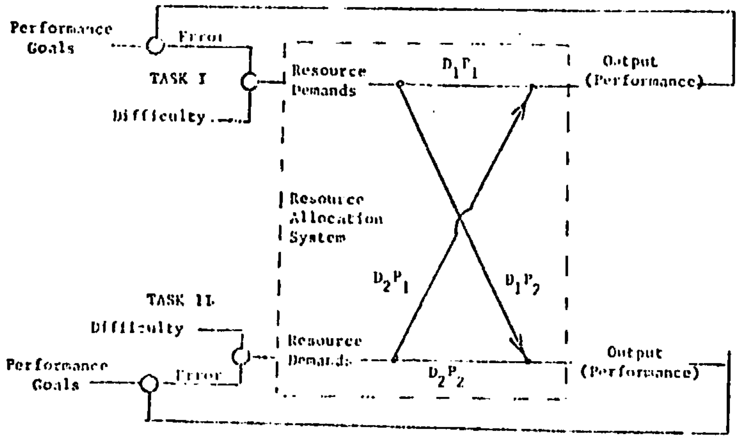

Figure 2. Schematic representation of dual task performance

current study Fourier analysis will be employed to determine the relations between time-varying inputs (tracking task difficulty) and time-varying outputs (filtered performance). To the extent that the resource allocation system is sensitive at all to these variations, the linear coherence measure, correlating variations over time between the input and output signals, should be non-zero. More specifically the cross-channel (D_1P_2 and D_2P_1) and like-channel (D_1P_1 and D_2P_2) coherence measure will be examined as a means of determining the optimality of the allocation system. For a highly optimal system, the like channel coherence (D_1P_1) should be a low (near 0), with the crosschannel coherence (D_1P_2) high (near 1.0). For the non-optimal allocator the values should be reversed, and for the hybrid case both coherence values should be relatively high.

If suboptimal allocation is observed in the present results, then an important question that can be asked relates to the source of the limitation in the allocation system. In terms of the two-phase description of the allocation process as shown in Figure 2, one may ask whether the limitation results from the operator's inability to perceive discrepancies between desired and actual performance (failure of error evaluation), or from the inability to reallocate resources in response to an accurately evaluated error. In an analogous manner it is possible to ask whether inadequate performance in a compensatory tracking task results from poor perceptual evaluation of the displayed error, or from an inability to execute an appropriate control response.

To investigate the source of potential limitations, a separate set of experimental conditions were included in which the conventional instantaneous tracking error display was supplemented by augmented performance feedback that displays the discrepancy between the desired level of primary task performance, and the running average of that performance (e.g., Reference 3). To the extent that limitations in the allocation system result from inadequate error evaluation, rather than limits of allocation, then the explicit display of the discrepancies in performance should produce a corresponding approach toward optimality of allocation (i.e., an increase in the cross-channel, and decrease in the like-channel coherence).

METHOD

<u>Tasks</u>. Subjects performed two compensatory tracking tasks, displayed one above the other with a slight horizontal offset. The left display was controlled by left-right manipulation of a spring loaded controller held in the left hand. The right display was similarly controlled with the right hand. The total visual angle subtended by both displays was 4^{o} (horizontal) x 1^{o} (vertical). Disturbance inputs consisted of band-limited white noise with an upper cutoff frequency of .32 Hz. Separate uncorrelated disturbances were employed on each task and were added to the output of the control dynamics. Control dynamics were of the form:

$$Y_c = K\left(\frac{1-\alpha}{s} + \frac{\alpha}{s^2}\right)$$

On trials of constant difficulty, the value of the difficulty parameter alpha was set at .50. On variable difficulty trials, the value of alpha on one task, designated primary, was driven by the function: $\alpha = .50 + \text{Sin}\ (.1884\ t) + \text{Sin}\ (.0628\ t),\ (0 < \alpha < 1)$. This produced a system that varied continuously between second order unstable dynamics, first order stable dynamics, and intermediate levels in a series of spikes and ramps (see Figures 3 and 4). Secondary task difficulty was always held constant with alpha = .50.

Supplementary performance feedback of the primary task, used in variable difficulty trials, appeared as a bar graph varying in height to reflect changes in performance (Reference 3). The performance bar represented integrated primary task error, averaged over a sliding 5-second window. The desired performance level, indicated by a short horizontal line positioned about half the distance from the zero point (no bar graph showing) to the top of the display, reflected the subject's average performance assessed for trials of constant difficulty. By tracking so that the bar graph remained at or above the desired performance line, the subject attained desired standards of primary task performance.

Root mean squared error (RMSE) was computed on line for each task and recorded at the end of each trial. Control stick and cursor error positions were sampled and recorded on tape every 120 msec. Experimental control was governed by a Raytheon 704 computer.

Design and Procedure. Eight right-handed male students at the University of Illinois participated in the experiment and were paid for participation. A within-subjects design was employed so that all subjects performed all experimental conditions. Following one day's session of practice on the dual axis tracking tasks, four experimental sessions were conducted. Within each session, subjects performed 24 two minute dual task trials. These consisted of 8 trials of constant difficulty, of which the final 4 were used for data analysis (Phase I), followed by 12 trials of variable difficulty, of which the final 8 were used for data analysis (Phase 2). Finally the subjects received four more trials of constant difficulty (Phase 3). During constant difficulty trials subjects were instructed that the two tasks were of equal priority, while in Phase 2, the task of variable difficulty was designated as primary--its performance to be held constant. On alternating Phase 2 trials, either the left hand task or the right hand task was primary (and was therefore variable). Similarly on alternating pairs of Phase 2 trials, supplemental feedback was either present or absent.

RESULTS

RMS Error. Two 1-way repeated measure analyses of variance were performed on the RMS tracking errors, one for primary and one for secondary task performance. The four levels of each ANOVA consisted of Phase 1, Phase 2 feedback, Phase 2 no-feedback, and Phase 3. The effect of condition on the performance measures in both ANOVAs was highly reliable (Primary Task, $F_{3,21} = 107.98$, $p < .001$; Secondary Task, $F_{3,21} = 54.93$, $p < .001$). The mean values of primary and secondary task error for the four conditions are shown in Table 1. It is apparent that large differences in both tasks

Table 1: RMS Error (Proportion of Scale

	Phase 1	Phase 2 Feedback	Phase 2 No Feedback	Phase 3
Primary Task	.1164	.1808	.1869	.1166
Secondary Task	.1206	.2058	.1806	.1147

were evident between the variable (Phase 2) and constant difficulty (Phases 1 and 3) trials, a difference substantiated by the experimental contrast of Phase 1 with Phase 3 no-feedback (Primary Task, $F_{1,7} = 153.0$, $p < .001$; Secondary Task, $F_{1,7} = 31.8$, $p < .001$). The effect of feedback, however, examined in the contrast between the two Phase 2 conditions, was only reliable for the Secondary Task ($F_{1,7} = 59.03$, $p < .001$).

Coherence Analysis. The response of performance to the time-varying changes in task difficulty is illustrated in Figures 3 (feedback) and 4 (no-feedback). The error measures were smoothed by averaging tracking RMS error within a sliding 2.4 second window. These smoothed performance records were then ensembled over trials and subjects to produce the data portrayed in Figures 3 and 4. It is evident in these figures that to some extent performance on both tasks "tracked" the time-varying difficulty parameter, an observation that was born out by the analysis of linear coherence.

The linear coherence analysis employed a Fast Fourier Transform algorithm (Reference 4) to transform time variations of primary task alpha and within trial error measures to power spectra in the frequency domain. From these transformed measures, linear coherence values (Reference 5) were computed correlating variations over time between Primary Task difficulty (alpha level) and the performance measures (within trial error averages) on both tasks.

Obtained linear coherence values, assessed at the six lowest frequency values that best account for variations of the task one alpha signal, are displayed in Figure 5. It is evident in Figure 5 that linear coherence is reasonably high in both conditions for both measures. However, primary task difficulty fluctuations seem to induce greater variation in primary task than in secondary task performance. Similarly feedback demonstrated little effect on primary task coherence but a small but consistent effect on the coherence with the secondary task.

DISCUSSION

The most striking aspect of the data relates to the marked deterioration in performance on both tasks that results when the difficulty of one is made variable. This was manifest in a 60-70% increase in RMS error, despite the fact that the average value of the difficulty parameter alpha (= .50) in the variable difficulty tasks was equivalent to its value in the constant condition.

A reasonable explanation for this difference can attribute the performance decrement to the higher level cognitive process required to deal with varying task demands, in an effort to meet performance requirements. In short, the operation of the attention allocation system itself requires processing resources in order to function in continuously reevaluating and responding to resource demand changes.

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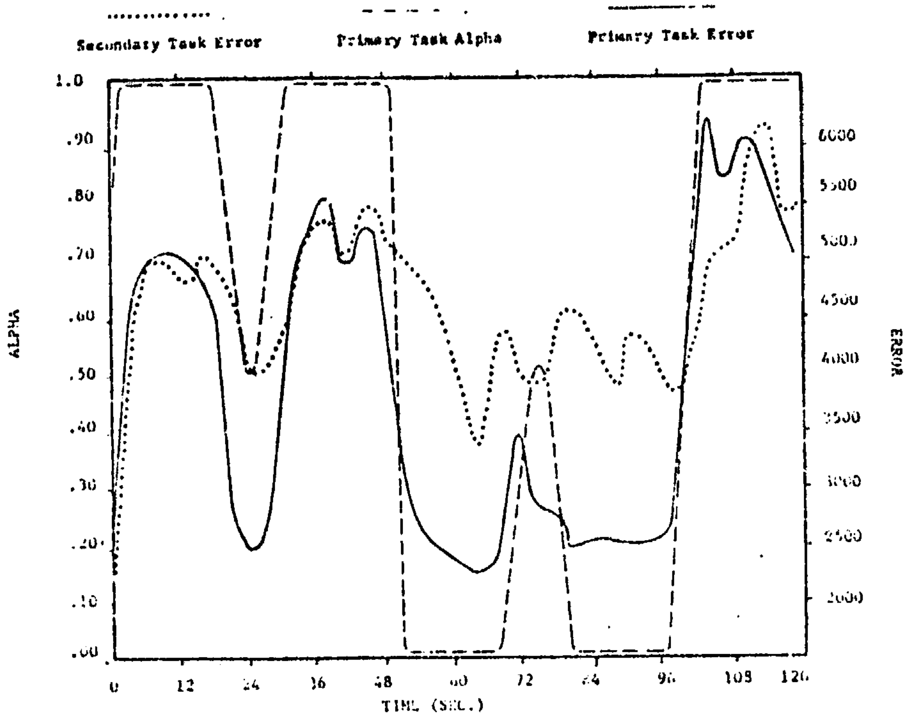

Figure 3. Average time history of within trial dual task error

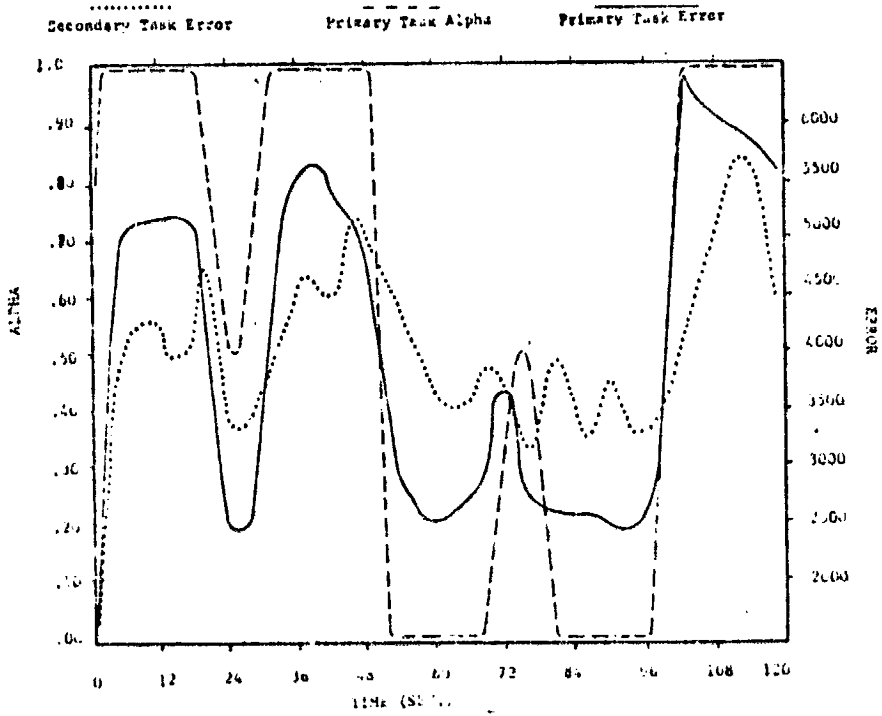

Figure 4. Average time history of within trial dual task error and primary task alpha--no-feedback condition

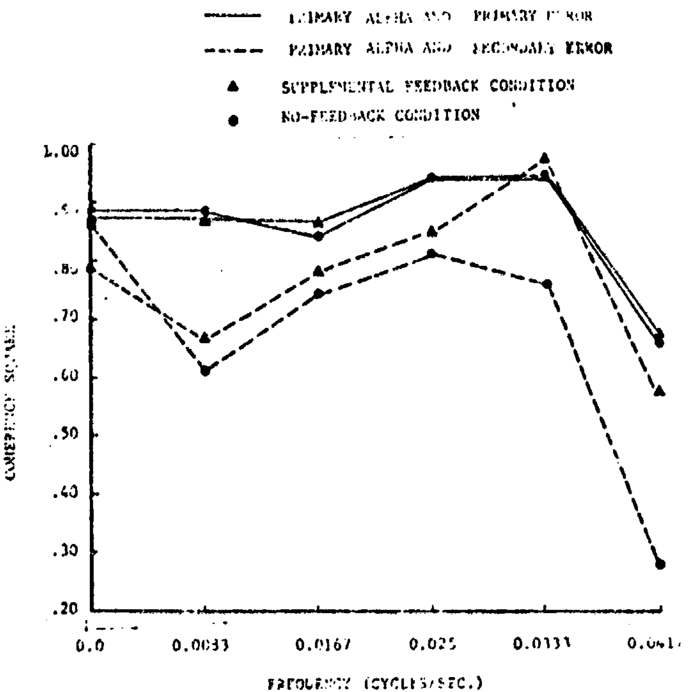

Figure 5. Linear coherence values between alpha and tracking error measures

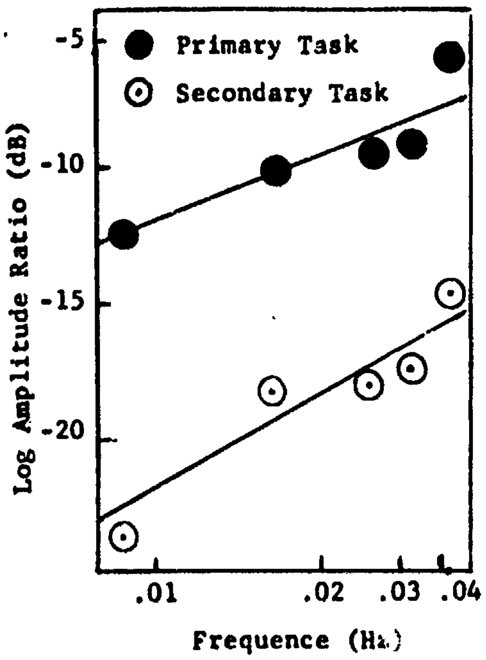

Figure 6. Gain plot of transfer function. Ratio of tracking error (range 0-1.0) to alpha.

Properties of the Allocation System. The proposition that the system may be modelled approximately as a linear dynamic system received some support in the current results, both from the relatively high linear coherence values obtained at the frequencies corresponding to difficulty variation, and on the basis of visual examination of Figures 3 and 4. In addition to the general responsiveness of performance on both tasks to the difficulty fluctuations described above, two additional characteristics of these figures that are not revealed by the coherence analysis are particularly relevant.

1. The transfer function of the alpha-performance data was computed, and the amplitude ratio data are plotted in the gain portion of the Bode plot shown in Figure 6. While the linear correlation of this slope is not high, and the number of points (6) is too few to allow any strong conclusions, the implication of these data is that the response of the allocation system, as inferred from subjects' performance is to lead the difficulty variation as a KS system. That is, performance is sensitive to the rate of change or first derivative of difficulty, rather than to the absolute level of difficulty itself. This behavior is graphically illustrated in the response of primary task performance to the spike increase in alpha at time t = 72 in Figures 3 and 4. This result is in contrast to that observed by Delp and Crossman (Reference 1), who modelled the performance response to difficulty changes (their "meta"-transfer function) as a first order, K/S, or integral system.

The source of this difference is not immediately apparent; it may be attributable to either the repeated nature of the difficulty function employed in the current study that allowed the subjects some degree of anticipation, to the discrete steplike changes of that function, or to the dual task environment used here.

2. Both figures indicate the presence of relatively high frequency oscillations in secondary task performance that do not correspond to variations in alpha. While these oscillations might at first be described as "noise," it should be noted that they correspond very closely, point-for-point in time between the separate and independent replications depicted in Figures 3 and 4. A close correspondance of this nature would not be predicted from random variability in the two replications. Instead, these oscillations bear a resemblance to the frequency response that a second order physical system with spring loading might show to a step or impulse input, approximating the nature of the difficulty changes presently employed. While the precise nature or source of these oscillations cannot be established, their presence nevertheless provides supportive evidence for the linearity, and invariant properties of the allocation mechanism, and encourages further investigation.

Optimality of the Allocation System. The coherence analysis performed indicated clearly that subjects did not behave as the optimum allocator of Figure 1. In marked contrast to the instructions delivered to the subjects, primary task performance was highly sensitive to primary task difficulty. It is therefore important to ask why, in the present results, subjects appeared unable to follow the imposed priority instructions. Wickens and Kessel (Reference 6) showed that when the difficulty of a task (instability tracking) is increased between sessions in a dual task environment, it is possible for subjects to hold that task performance constant--at the expense of secondary task performance. Why then, when difficulty was manipulated within a session in the current experiment, was the severe limitation observed?

It appears unlikely that subjects simply ignored the instructions, as resources clearly were withdrawn from the secondary task to deal with the difficulty increase and were returned when demands were lowered, thus producing the high secondary task coherence measure. Instead it appeared that either the resources withdrawn were not delivered to the primary task, or alternatively that the changes in difficulty were sufficiently abrupt that smooth resource modulation could not occur (i.e., resource adjustment did not have sufficient time to operate). This second hypothesis is supported by visual inspection of Figure 3. Note following the difficulty step increases at times t = 24-28 and t = 96 seconds that in both instances primary task error begins gradually to reduce as secondary task error undergoes a corresponding increase, as if at this point the subject begins a gradual and appropriate reallocation of processing resources away from the secondary task toward the primary, in accordance with instructions. In fact a rough estimate of the lag between difficulty increases and secondary task error increases places this lag at approximately 2-3 seconds, a value that corresponds reasonably well to the 2.8 second lag observed by Delp and Crossman.

The implication of this observation is that the appropriate resource mobilization might be within the capabilities of the operator to a greater extent, had the difficulty transitions been of the more gradual nature employed by Delp and Crossman.

Feedback. The contrast in performance measures between the augmented feedback and no-feedback conditions indicated further that the operator's limits were manifest in the second stage of the closed loop allocation system--the reallocation of resources--rather than in the first stage--the error evaluation process. When this evaluation process was presumably aided by explicit presentation of the discrepancy between desired and obtained performance, no reliable improvement in allocation behavior was observed, either in the form of a reduction of primary task error, or a reduction in its linear coherence function with alpha. In fact, the only effect of feedback that was observed was a reliable increase in secondary task error, and a corresponding increase in the secondary task coherence measure, as this task apparently became more responsive to the changes in primary task difficulty.

While augmented feedback did not prove to be useful in the current investigation, the conclusion drawn must of necessity be limited. It is quite likely that the difficulty changes were sufficiently dramatic that their presence, and the resulting performance changes, were easily observable by the subjects. Changes of a more subtle nature might have produced a sub-threshold deterioration in performance that could only be detected with the aid of the augmented feedback.

CONCLUSION

The major limitations of human performance in the variable difficulty paradigm, demonstrated in the present results, suggest that this area warrants further exploration. Research is needed to determine the effect on allocation ability of such variables as training, the nature of the difficulty time functions, and the qualitative similarity between the time-shared tasks. Through this research a better appreciation can be gained not only of the mechanism by which attentional resources are allocated, but of the fundamental nature of those resources themselves.

REFERENCES

1. Delp, P. and Crossman, E. Transfer Characteristics of Human Adaptive Response to Time-varying Plant Dynamics. Proceedings 8th Annual Conference on Manual Control. Wright Patterson Air Force Base. AFFDL-TR-72-92. June 1972.

2. Damos, D. and Wickens, C. A Quasi-linear Control Theory Analysis of Time-sharing Skills. Proceedings 13th Annual Conference on Manual

Control. U.S. Government Printing Office, 1977.

3. Wickens, C. and Gopher, D. Control Theory Measures of Tracking as Indices of Attention Allocation Strategies. Human Factors, 1977, 19, 349-366.

4. Shirley, R. Application of a Modified Fast Fourier Transform to Calculate Operator Describing Functions. Proceedings 5th Annual Conference on Manual Control, NASA, SP-215, 1969.

5. Sheridan, T. and Ferrell, L. Man-machine Systems. Cambridge, Mass.: MIT Press, 1974

6. Wickens, C. and Kessel, C. The Effect of Participatory Mode and Task Work-load on the Detection of Dynamic System Failures. Proceedings 13th Annual Conference on Manual Control. U.S. Government Printing Office, 1977.