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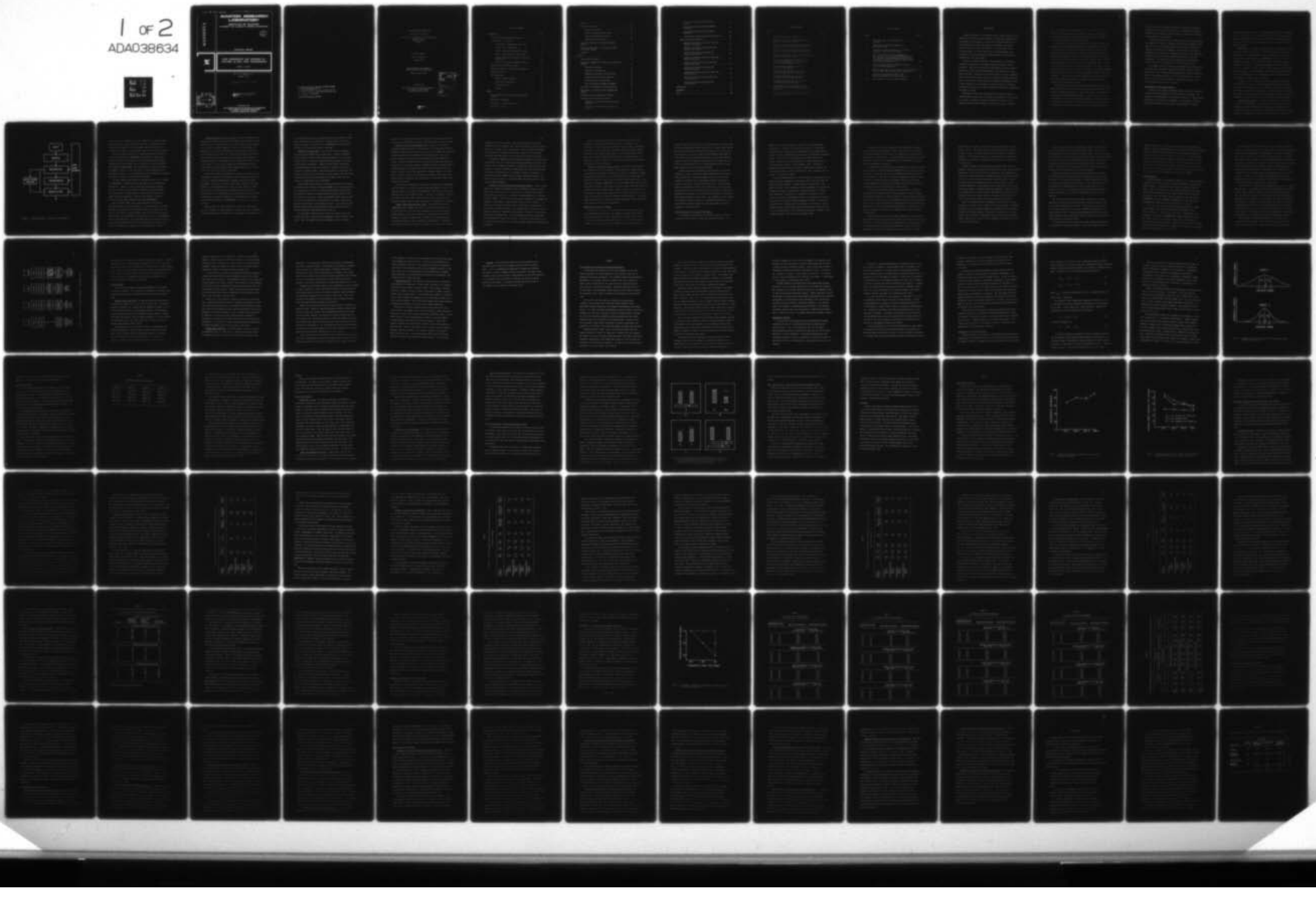

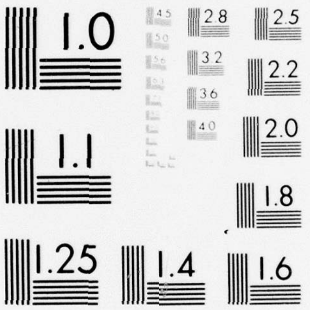

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TECHNICAL REPORT

TASK COMPONENTS AND DEMANDS AS FACTORS IN DUAL-TASK PERFORMANCE

ROBERT A. NORTH

ARL-77-2/AFOSR-77-2
JANUARY 1977

F44620-76-C-0009

PREPARED FOR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

AVIATION RESEARCH LABORATORY

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Technical Report

ARL-77-2/AFOSR-77-2

January 1977

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Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AIR FORCE SYSTEMS COMMAND
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INTRODUCTION

A common requirement of the human operator in complex systems is the performance of several tasks concurrently. In operational settings, such as airborne tactical maneuvers or air traffic control procedures, he is often called upon to gather and respond to information from several sources differing in quality and quantity. The development and use of future systems are highly dependent upon the understanding of the capabilities of man in time-sharing situations under a wide variety of representative task combinations.

The need for reliable methods for the estimation of time-sharing performance capabilities of the human operator has produced several techniques. Some have been directed at determining the precise workload imposition of selected primary system tasks. The general aim of these efforts has been to quantify and scale these tasks in terms of a workload index such as the performance level of a concurrently performed secondary task. An alternative and potentially more meaningful requirement related to this estimation is the assessment of specific aspects of concurrent performance with a variety of tasks and when these tasks vary in importance from moment to moment.

Experimental results have indicated that the pairing of specific tasks may produce interference or decrement in performance of one or both of the tasks. Additional decrement or disturbance may occur if the individual task priorities suddenly increase due to changes in mission goals. Consequently, information that must be obtained by investigators concerned with design improvement includes both indices of decrements in multiple-task performance vs single-task performance and an assessment of performance changes under varying task demands.

Investigators in psychology and human factors engineering have often attempted to study such problems using dual-task techniques. The results of such studies are inconclusive regarding performance prediction over concurrent task situations; however, several factors appear important as performance determinants. One factor is the task structure, in terms of the specific functional components of the tasks. Another factor influencing performance is the difficulty level of the individual tasks. A third factor is the skill level the operator has attained on the tasks, recognizing that learning may effect both the level of skill on the tasks individually and the skill involved in efficiently interweaving the tasks in concurrent performance. The subjective priorities between tasks in these studies have also been an important performance determinant, especially in studies employing the secondary-task technique.

Although other investigators of dual-task performance have noted the importance of these factors there have been few attempts to examine their interrelationships systematically. The present study is an investigation of three areas of time-sharing performance. These areas are: (1) the relationships of selected functional task components to observed dual-task performance, (2) the ability of the operator to respond differentially to two tasks in accordance with variation of levels of desired performance, and (3) the nature of individual differences in dual-task performance strategies in certain dual-task situations. Individual differences in performance were studied by comparing specific strategies for concurrent task performance across subjects.

To investigate the first area, tasks were chosen that have differential emphasis on functional components, and dual-task performance decrements relative to corresponding single-task performance levels were compared for different task pairings. The second area, allocation of performance in the presence of changing task priorities, was studied by varying the level of performance demand within specific dual-task combinations. The interaction of task components and time-sharing demands represents an integral part of the experimental results.

In accordance with the research goals described above, several areas of multiple-task performance literature are directly relevant to the present study. The following review organizes the literature around the areas of task component structure and priority manipulation. The relevance of several theoretical models of time-sharing performance will also be discussed and critically reviewed.

Task Components and Dual-Task Research

The scope of the present experimental design involves the selection of tasks representing emphases on various functional components. To facilitate the understanding of this selection rationale, a simple descriptive model of task functions is presented. At the simplest level, the processing and response functions could include SENSING of incoming stimuli, RECOGNIZING the stimuli, and MANIPULATING some control or response device. Within each of these components additional sub-components may be operating. RECOGNIZING, for example, is the result of combining contact with long-term memory and the transformation of neural activity from the SENSING component.

TRANSFORMING is an additional component which can take different forms. These might include determination of the direction, timing, speed, and amplitude of the correction needed to null a tracking error of a system having complex control dynamics, or TRANSFORMING may be in the form of a comparative judgment of the stimulus item against a standard, applying a mathematical operation, or categorizing stimuli based upon a specified rule. The operation of complex systems typically involves other functions. One such function, short-term STORING, will be investigated in this study. short-term STORING refers to the requirement to store information until the time that a response is to be initiated.

A composite of all of the above functional components is presented in the drawing in Figure 1. It must be emphasized that these functions are representative of some, but not all possible, functional requirements that might be encountered by the operator in complex systems. The following collection of dual-task and time-sharing studies focuses on the specific combination of tasks with one or more of the above functional components.

TRANSFORMING and STORING. Few dual-task studies have examined the combination of TRANSFORMING and STORING functional components. Shulman, Greenberg, and Martin (1971) provide an example of this combination in an experiment requiring the subject to judge which of two lines was longer and make a corresponding response choice while engaged in rehearsal of a

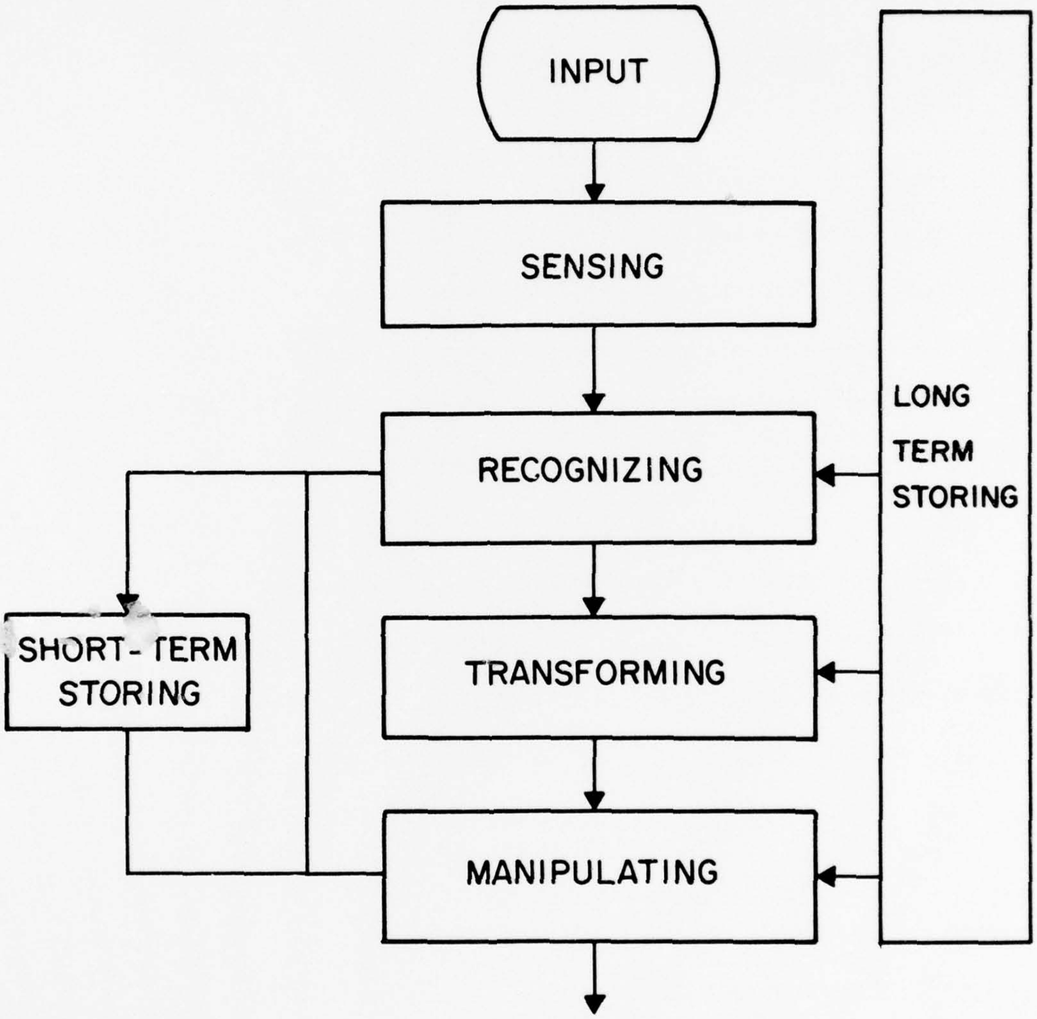

Figure 1. Descriptive model of functional task components.

series of letters presented prior to the judgment task. Results showed significant delay in dual-task reaction time for the judgment task over the single-task condition, and the judgment times were found to be a function of the number of items that the subject was required to rehearse.

Posner and Rossman (1965) used a single-task approach to study the concurrent involvement of TRANSFORMING and rehearsing. Subjects were required to perform transformations of varying complexity upon audibly presented letters which later were to be recalled, a task that required both STORING and TRANSFORMING. The transformation included categorizing the numbers as "high" or "low," and "odd" or "even," depending on the experimental condition. As the complexity of the transformations increased, the number of correctly recalled letters decreased.

The above studies suggest that the functional combinations of STORING and TRANSFORMING of stimulus inputs elicit high levels of time-sharing interference. However, it must be noted that these studies explored only the concurrency of the rehearsal component of short-term memory and transformation. Although studies of input and recall memory components have been conducted in concurrent task research, concurrent activities have included components other than TRANSFORMING.

Dillon and Reid (1969) used a similar approach to studying the rehearsal component of short-term memory. In their experiment, the subject performed an interpolated task during the retention of trigrams that consisted of (1) reading a two-digit number aloud, or (2) adding the digits, reporting their sum, and whether the sum was odd or even. The TRANSFORMING task was more disruptive of recall when performed early during the rehearsal period, and when the interpolated activity was reading the digits aloud the recall performance was superior to the transformation condition.

TRANSFORMING combined with other tasks. Several investigators have examined transformation tasks paired with simple reaction-time tasks and monitoring tasks. Kahneman, Beaty, and Pollack (1967) presented subjects with a series of four-digit numbers at a rate of one per second. The secondary task consisted of monitoring a visual display of letters for the presentation of the letter "K". Monitoring performance was superior when the subject only had to repeat the four-digit number instead of a transformed version of the number created by adding one or three to each of the digits. As in previous examples, the transformation activity produced more severe decrements in the secondary task than in a version of the task that did not include transforming.

Keele (1967) conducted an experiment in which the difficulty of the transformation necessary in choosing the correct response in turning off a series of lights was manipulated by changing the stimulus-response arrangement. Scores on the secondary task, which consisted of the time required to count backwards by one, three, or seven, showed a reliable increase when the stimulus-response compatability was most difficult. Although this sort of transformation is involved with the response choice component more than with the stimulus, it again demonstrates the interference producing quality of a TRANSFORMING activity prior to response execution.

Bahrick, Noble, and Fitts (1954) used a five-choice reaction time task with repetitive or random signals as a primary task and a transformation task consisting of the subtraction of two numbers as a secondary task.

The transformation task was performed better with the repetitive stimuli choice reaction-time task than with the random version, providing an additional example of interference of a TRANSFORMING activity when the difficulty of the interfering task is increased.

STORING and tracking tasks. There have been several experiments pairing short-term STORING with tracking tasks. Johnston, Greenberg, Fisher, and Martin (1970) showed tracking performance to be a function of memory load of a concurrent rehearsal task with longer list lengths producing poorer performance. Trumbo and Milone (1971) investigated tracking performance during the presentation, retention, and recall of a sequence of stimulus lights. The greatest amount of interference with tracking occurred at the recall stage of memory; however, the data failed to indicate that tracking performance had a reliable effect upon the quality of secondary-task recall performance.

Memory tasks without distinct phases have been devised for studying interfering effects between tracking and STORING. One such task involves the presentation of a series of stimuli during primary-task performance and requires the subject to respond with the previously presented item upon receipt of a new item. Zeitlin and Finkelman (1975) used this task as a task to investigate the susceptibility of tracking to interference when the control order of the tracking is varied. It was found that this STORING task differentiated between primary task conditions, whereas a task involving only random digit production did not.

The advantages a memory task such as the one used by Zeitlin and Finkelman are that it compresses the components of input, rehearsal, and recall. Thus, the demands on short-term STORING is more continuous.

Results of a similar study involving tracking and continuous retrieval were reported by Pew (1972) who used words in the memory task in place of digits.

STORING tasks paired with STORING tasks. Studies of concurrently performed STORING tasks have not been prevalent in the dual-task literature. Broadbent and Heron (1962) report one such study of a primary task consisting of digit cancellation in a 600-digit array requiring none or one of two memory components paired with a secondary memory task that required the subject to listen to spoken letters, one every five seconds, and report the one letter in ten that was repeated. Broadbent and Heron concluded that the subsidiary memory task disrupted the primary task with the more difficult memory condition, the one that required more frequent changes of the item to be cancelled. However, the concurrent performance of two memory tasks has not been fully explored, and a high degree of interference between such tasks may be expected.

The split-span technique used in auditory attention studies (Broadbent, 1954, and others) is a form of concurrent dual-task STORING. In this technique the subject is presented with simultaneous item strings dichotically, and then asked to recall what was heard. The recall is typically grouped by ear, rather than what stimuli occurred close in time, and items are also grouped according to modality when the modality of presentation is different.

STORING tasks paried with other tasks. As has been the case with TRANSFORMING tasks, STORING tasks have also been paired with tasks such as simple and choice reaction, free responding, and serial anticipation. Trumbo and Noble (1970) used a primary task involving learning nonsense syllables, and their secondary tasks included freely selecting buttons, learning the stochastic rules controlling a light sequence, responding to each light by pressing an appropriate button, or anticipating the lights by responding prior to their onset. The primary task was more severely disrupted by the two decision tasks, serial anticipation, and free responding, than by a simple choice reaction task. Thus, the authors concluded that the process of deciding what the next response was to be was more interfering with memory than a task in which no decision was involved.

The results of STORING tasks in dual-task performance have demonstrated that rehearsal and recall represent interference producing activities, and functions that are highly susceptable to interference from tasks with other functions. The major parameters of interference are material organization, list length, and, during recall, the number of items to be reported. A continuous "one-back" STORING task, involving continuous response to the previous item, represents an alternative memory task which produces a more constant STORING component.

Tracking paired with tracking in dual-task performance. Several investigators have compared performances on two concurrently performed tracking tasks using separate controls for each task. The tracking tasks used in these studies are variants of a "critical" task developed by Jex, McDonnell, and Phatac (1967). The difficulty of the task is manipulated by changing the parameter of instability, associated with the rate of error increase. In studies by Jex, Jewell, and Allen (1972), the parameter of instability, λ, was used as an adaptive variable on the secondary task, and the level of the adaptive variable was interpreted as a measure of the degree of interference produced by the primary task. In the experimental condition in which both visual displays were within foveal vision, a "critical" task decrement of 10 to 20 "percent" was found on the secondary task when compared with single-task performance.

Levison, Elkind, and Ward (1971) had operators perform up to four simultaneous tracking tasks (using two dual-axis controllers in one condition). Using mean square error (MSE) to compare single- and multiple-task conditions, they found that the multiple-task cases produced unequal performance scores between tasks; however, the total performance scores, were close to values predicted from single-task conditions measured on single-axis tracking. This study, then, indicates inter-task interference between multiple tracking tasks.

Summary of functional component studies. The studies reviewed above have included tasks involving memory, transformations of stimulus inputs, and complex motor responses, represented by tracking. Although the findings depend upon the difficulty of the tasks involved and the establishment of inter-task priorities, several conclusions may be drawn from the data. The components of STORING, TRANSFORMING, and complex MANIPULATING represent highly interfering functions in time-sharing situations compared with the functional components involved in simpler tasks. However, there is no conclusive evidence that one component may produce more interference than another, because tasks and conditions have been too variable across experiments. The present study provides a basis for making controlled comparisons between time-shared tasks involving these functional components.

Manipulation of Dual-task Demands

The ability of subjects to distribute performance between two tasks in accordance with instructions that emphasize one task over the other has been investigated by several experimenters. Murdock (1965) reports a reciprocal relationship between performance of a card sorting task and a memory task when he differentially emphasized them in instructions.

Woodhead (1966) found an asymetric relationship between concurrent task performances manipulated through instructions. Subjects showed improvement on a relatively difficult memory task, when told that it was the more important, but did not improve their performances appreciably on a less difficult search task when told that it was the more important. Johnston, Griffith, and Wagstaff (1972) successfully manipulated concurrent task performance levels by varying monetary payoffs between a memory task and a discrete reaction time task.

Another technique for manipulating task priorities in dual-task performance, recently developed by Gopher and North (1974), involves visually presenting a desired performance level for each task and continually indicating actual performance during the preceding few seconds on each task. A recent experimental test of this technique, using a one-dimensional tracking task paired with a digit-processing reaction-time task, has shown that subjects are capable of making fine adjustments in performance in accordance with increasing or decreasing task demands presented in this fashion. The technique provides a means for studying an important feature of time-sharing performances: the interaction between task demand levels and the specific functional components of the paired tasks.

Theoretical Models of Time-Shared Performance

In psychology, investigators have developed several theories of attention based on studies of human time-sharing performance. The definition of the term "attention," however, has varied among these investigators. Initially, it referred to the process of successfully selecting and processing stimuli from individual input channels and the ability to extract information from more than one simultaneously presented message. The results of these studies, mostly under the rubric of dichotic listening, led to the development of single-channel models of the human operator (Welford, 1952; Broadbent, 1959). According to Broadbent's interpretation of the single limited-capacity channel, one of two simultaneously presented stimuli must be held in storage until the channel is cleared of the other.

The single-channel approach to the description of information processing was severely challenged by investigators such as Triesman (1960) and Deutsch and Deutsch (1963). Triesman proposed a modification of this model to include a filter attenuator that was responsible for altering the perceptual threshold for nonselected, nonattended stimuli according to their importance or significance. Triesman also attributes certain parallel processing of simultaneous inputs to be contingent upon similarities in the processing and response components involved. This feature of the model offers an explanation of the ability of the subject to process stimuli presented in different modalities simultaneously, while presentation in the same modality causes substantial performance decrement in time sharing (Triesman, 1969; Karlin and Kestenbaum, 1968).

A criticism of the single-channel models of Broadbent and Triesman was offered by Deutsch and Deutsch (1963). They proposed that the locus of the single-channel bottleneck was at the response stage, rather than at the perceptual processing stage. Deutsch and Deutsch maintain that parallel processing of input may be accomplished but that production of responses must be accomplished sequentially.

The single-channel theorists view the information processor as one with limited capacity. Although some have proposed that the processing capacity is limited for different reasons and at different functional stages, the basic assumption is that time to perform two simultaneous tasks will equal or exceed the combined single-task performance times on the two tasks. Although supported by some studies of psychological refractory period, this prediction has not been substantiated in other studies.

Two alternative hypotheses provide for the possiblity of parallel processing and performance within a limited processing capacity framework. One hypothesis, known as the "limited capacity, central mechanism" hypothesis asserts that certain functional task components require the mechanism, while others do not. When simultaneously performed tasks both have elements that demand the use of the central mechanism, interference is predicted to occur. Thus, the component structures of the combined tasks dictate the presence of interference.

Posner and Keele (1970), the principal proponents of this hypothesis, have conducted experiments that have led them to the interpretation that such activities as complex responding and transformation of stimulus inputs prior to responding represent functional components that require the central mechanism. Most of these studies have used reaction time to aperiodic probe stimuli as a measure of the level of interference produced by the primary activity. The primary difficulty with this theoretical viewpoint is that the types of functions discussed by these authors are somewhat undefined. The hypothesis also does not explain changes in time-sharing performance with changes in individual task difficulty or the skill level of the operator.

Another alternative has been offered by Kahneman (1970, 1973), who proposes a limited-capacity model of the human operator that allows unimpaired performance on two or more activities as long as the total demands of the tasks do not exceed his capacity. Kahneman refers to this limited capacity as a "pool of effort" which is drawn upon by different tasks. The major difference between this hypothesis and the "limited capacity, central mechanism" hypothesis is that Kahneman does not specifically refer to the "processing demands" of different functional components. Capacity, according to Kahneman, does vary with operator dispositions, arousal level, and momentary intentions. Another aspect of the model is the "allocation of effort" policy that distributes effort among individual activities.

Again the problems with such a hypothetical structure are its loose definition of concepts such as "effort" and "allocation policy." Although allowance is made for momentary changes in performance due to increases or decreases in available capacity, the sources of variance are not clearly stated. The provision for changing skill level, for instance, represents another missing aspect of such a model, although it does provide for variation in available capacity.

A more promising approach to describing the limited capacity concept has recently been discussed by Norman and Bobrow (1975). These authors have proposed that the operator must draw upon a limited resource for processing information and that processes may be "data-limited" or "resource-limited." Processes become data-limited under conditions that produce either high or low quality input data that make the task extremely easy or difficult to perform. Thus increases or decreases in the use of resources under these conditions will neither improve nor derogate performance.

Between these extremes, processes become resource-limited, in which case performance varies depending upon the manipulation of external task variables. For a signal detection task, the resource-limited region might be dependent upon the signal-to-noise ratio. At very high noise levels, performance may be impossible, while it may be nearly perfect in the presence of low noise. Intermediate values of noise may define a region where the efficiency of the operator is dependent upon application of resources.

The dual-task situation is seen by Norman and Bobrow as a special application of resources in which an operator actually may have to trade off his limited resources between tasks. The structure of the tasks, as well as their difficulty, are discussed as possible determinants of the resource-limited region. Norman and Bobrow suggest that the major experimental problem is the determination of resource tradeoff functions between tasks differing in functional demands.

The viewpoints of these theorists have several important implications to the student of time-sharing behavior. One is the viewpoint that the region of interest on a task is the resource-limited region and that it should be isolated through manipulation of the proper task-related variables. The second implication is that structures of tasks should be varied to exercise different functional component combinations, because the mutual interference among different component combinations may result in vastly different resource-allocation tradeoffs. The third implication is that practice has an effect upon the resources available for a task and that, as a result of training, the region of resource allocation may shift resulting in different resource tradeoff functions in time sharing.

Experimental Plan

The investigation of time-sharing performance is of special significance considering the variety of concurrent tasks encountered in operating man-machine systems. The diversity of the functional components shown in Figure 1 does not represent all of the possible components found in man-machine systems operation but does sample several important components. As previously noted the present study concentrates on the comparison of TRANSFORMING, short-term STORING, and MANIPULATING. This comparison is accomplished by studying dual-task combinations of four tasks.

One of the selected tasks involves stimulus recognition and simple choice response. The second introduces short-term STORING, but is otherwise identical. The third and fourth involve TRANSFORMING prior to response: the third, a two-dimensional stimulus classification task; the fourth, estimation of direction, timing, speed, and amplitude of error correction required in tracking. Three of the four involve the simple selection of an appropriate key on a keyboard; in one-dimensional tracking, the lateral displacement of a control stick.

and make a corresponding response choice while engaged in rehearsal of a

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The functional descriptions of these tasks are presented in Figure 2. The first task, Immediate Digit Cancelling, requires no intervening functional components between RECOGNIZING and MANIPULATING. The subject is presented with a numeral that he must cancel with the appropriate key. The second task, Delayed Digit Cancelling, requires the continual STORING and retrieving of numerals. In this task, the subject must work "one back" in the sequence. The third keyboard task, Classification, requires the application of a transformation rule that involves classifying a pair of numbers on size and physical name and responding with the key appropriate to the correct category. All three of these tasks are self-paced, which allows the investigation of particular strategies of interweaving two time-shared Keyboard tasks by examining response times for each task.

The fourth task is compensatory one-dimensional Tracking of a random-appearing input. In compensatory tracking, the human operator is required to make a motor movement as response to a perceived difference between input and output on the display. At relatively low input frequencies and with simple control dynamics, this task remains well within the capability of the operator. Increases in the difficulty of the task can be achieved by adapting the control order of the system, and the level of instability coped with successfully can be considered to approximate the capability of the tracker. The adaptive logic provides advantages that become evident upon examination of the problems encountered in time-sharing research.

Before turning to background information on the tasks, several clarifications are necessary. These tasks constitute a specifically chosen set for the purpose of comparing concurrent task performances

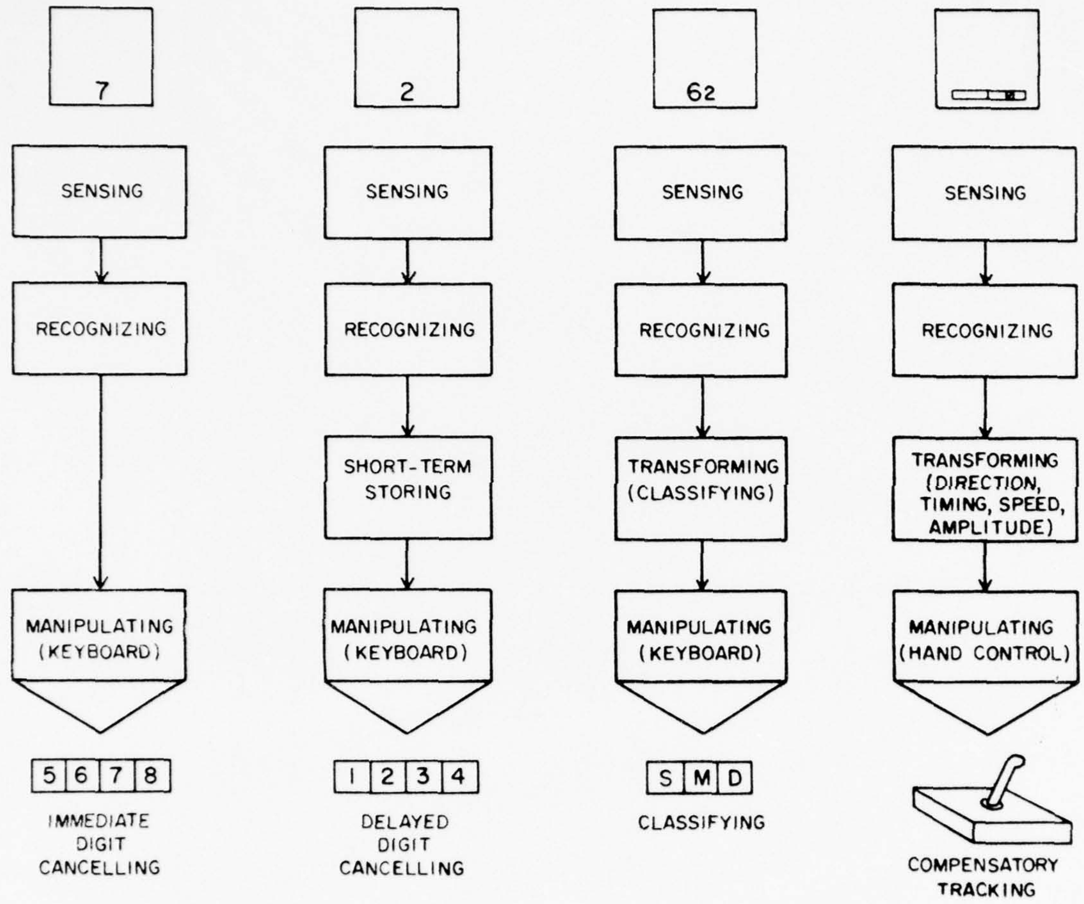

Figure 2. Comparison of functional components of experimental tasks.

involving various combinations of different functional components. Therefore, individual levels of task interference between any two of these tasks has little meaning until they are compared with levels obtained on other combinations. All of the visual stimuli in the four tasks are presented within the foveal field of a single fixation to assure that any interference is of a central rather than a peripheral nature and can be attributed to the functional component properties of the tasks.

Task Backgrounds

The four selected tasks have been used previously in both single- and dual-task research. The following is a description of the prior usage of the keyboard tasks and the tracking task to be used in the proposed study.

Immediate Digit Cancelling. The Immediate Digit Cancelling task is representative of many used to study choice reaction time. The number of response alternatives has commonly been an independent variable, as has the inter-stimulus interval in forced-paced versions. The development of models predicting reaction time dependent upon the number of response alternatives has produced fairly reliable predictions for a given number of alternatives (Hick, 1952; Hyman, 1953) and for different stimulus-response compatabilities (Fitts, 1964).

This particular type of task has been used as a time-sharing task in several experiments. Bahrick, Noble, and Fitts (1954) used a five-choice, visual reaction time task with manual repsonses as a primary task and a subtraction task as a secondary task. A repetitive sequence of stimuli on the primary task produced reliably superior secondary performance to that produced by a completely random primary sequence. Bahrick and Shelly (1958) also employed a forced-paced light cancellation task as primary and a similar task in the auditory mode as secondary. Again the randomly occurring condition of primary stimuli produced the highest interference with the secondary task.

A third experiment in which two reaction-time tasks were paired was conducted by Dimond (1966) who used two keypress tasks, both of which were visual and forced-paced. The independent variable was the regularity at which primary task signals occurred. With regularly occurring signals, the two tasks could be performed with less reaction-time delay than with the randomly occurring signals. Similar reaction-time tasks have been used as secondary tasks in several experiments (Kraus and Roscoe, 1972; Damos, 1972; and Gopher and North, 1974).

Results of the last study are of special importance to the present work. Subjects consistently learned to interweave performance of a self-paced digit-cancelling task with an externally paced continuous tracking task, but increasing demands on digit-cancelling performance caused large decrements in tracking performance. Thus, it appears that subjects may be expected to have more difficulty adjusting their allocation of attention on a concurrently performed task when the self-paced task has high demand. This question is further examined through the manipulation of desired performance levels in Phase Three of this study.

Delayed Digit Cancelling. The running memory task used by Zeitlin and Finkelman (1975) is a variation of a task developed by Kay (1953) to determine the limits of retrieval from memory under constant input conditions. It was originally conceived for the purpose of determining the effects of ageing on memory. The original task consisted of responding to a series of 12 lights by depressing a compatibly arranged key underneath each light. Kay required subjects to respond to the current stimuli in one condition and to lights occurring previously in the sequence in a set of conditions including 1-back, 2-back, 3-back, and 4-back responses. The task was forced-paced at presentation intervals of 1.5 sec.

Although the only measure reported is the percentage of correct responses for these conditions, it can be seen from his results that the 0-back and 1-back tasks produced virtually no incorrect responses, while performance was significantly degraded in the 2-back and 3-back tasks. The 4-back task was nearly impossible for most subjects, unless a highly developed short-term memory rehearsal strategy was practiced.

Similar results using this task were found by Kirchner (1958) and by Mackworth (1959). Kirchner, comparing age groups on memory ability, found that the further back responses were performed with much less efficiency by older subjects; however, the one-back task could be handled easily by both young and old. Mackworth found that a longer ISI enhanced performance in the higher-order memory situations and that even the 4-back task could be handled by some subjects. The interesting result of this study, however, was that the reaction-time averages for the 1-back condition were actually shorter than the zero-back condition (1.1 sec. vs 1.2 sec.).

This result becomes less surprising if one considers that the subject, due to the forced-pacing of the task, has adequate time to prepare his next response and needs only to perceive the next signal to trigger the output of his response. Two factors that may prevent the one-back reaction times from becoming pure reflex times are: (1) the fact that Mackworth gave subjects substantial practice on the zero-back task first to familiarize them with the S-R arrangement but did not give comparable practice on the other tasks, and (2) the possibility that the response may be slightly delayed following a new stimulus while the subject is recognizing it and storing his next response selection.

Classification task. The stimulus Classification task, requiring a two-dimensional discrimination of number pairs, is similar to an original task used by Morin, Forrin, and Archer (1961). Morin, *et al.*, required subjects to classify circles or squares on the basis of number of objects present and on stimulus shape. In the condition most similar to the present task, a unique response was assigned to each of the stimuli (either one or two circles or squares). This condition was compared with others requiring categorization according to only one of the stimulus attributes.

With practice, subjects improved their reaction times on the four-choice tasks to an asymptotic value of around 550 msec., which corresponds favorably to values found in simple four-choice alternative tasks. In other words, subjects in this condition merely acquired a one-to-one mapping strategy pairing each stimulus with a unique response. Still, these reaction times were well above Morin's two-choice cases which improved to about 311 msec. Thus, the four-choice cases, even with an easily acquired strategy, appeared to present a more difficult cognitive task than the simple two-choice cases. Fitts and Biederman (1965) replicated Morin's four-choice condition and found similar relationships in reaction times.

Tracking. The Tracking task selected for this experiment is one previously used in dual-task performance studies by Gopher and North (1974). It is a one-dimensional compensatory tracking task requiring the subject to center a randomly moving circle within a horizontal track. An adaptive logic system was used to bring subjects to their best capability in a relatively short time period by increasing the difficulty during single-task performance. The adaptive variable used was the ratio of acceleration to rate control in the control stick.

METHOD

The Secondary-Task Technique and Time-Sharing Research

The secondary-task technique has been used frequently in the inferential measurement of workload imposed by various primary tasks and for assessing time-sharing performance. The technique requires the simultaneous performance of a secondary task with a primary task, and the subject is usually told to devote most of his attention to the primary and use any spare capacity to perform the secondary. Secondary tasks have been used in both single- and dual-primary task situations, and the workload imposed by the primary task or tasks is inferred by the decrement in the secondary task.

Various tasks have been used as secondaries, including manual tracking, choice reaction time, monitoring, manual dexterity tests, spontaneous response production, and arithmetic transformation and problem-solving. The common aim among investigators has been to isolate a standardized secondary task that may be used with a variety of primary tasks. Although the use of the technique frequently involves the assumption that primary performance will not be affected by the secondary task, secondary tasks, if not extremely simple and/or overlearned, do produce interference with primaries, as is evident in the following examples from dual-task literature.

Bahrick and Shelly (1958), using a reaction-time primary task that required response to a series of lights and a secondary task that required key presses to a series of aurally presented digits, found that differential sequential complexities of the primary task caused it to interact with the secondaries in more difficult conditions. In these cases it was the primary performance, not the secondary, that suffered.

Other examples include experiments by Schouten, Kalsbeek, and Leopold (1962) who measured the value of alternative secondary tasks paired with a primary. The primary task, pressing pedals in response to digits presented aurally, was first measured at its maximum performance level for each subject and then paired with one of several secondary tasks. The secondary tasks showed differential performance decrements as performance on the primary task improved, and even at peak primary efficiency, some of the secondary tasks could be interwoven to allow nearly unimpaired performance.

Additional studies showing secondary-task interference with primary performance include those by Brown (1966), Briggs and Shulman (1971), McLeod (1973), Trumbo and Milone (1971), and Kraus and Roscoe (1972; also Roscoe and Kraus, 1973). The Kraus study measured information processing rate (keypress response to a set of randomly presented digital stimuli) while the subject performed complex navigation and flight tasks in a flight simulator. The secondary task was found to elevate error rates in the dual-primary flight and navigation tasks, and secondary task performance itself was differentially affected by different sets of primary task pairings.

One of the major problems with the secondary-task technique concerns its failure to provide unbiased estimates of operator workload because of the derogation of primary performance. A contributing factor to this problem has been the subjective interpretation of task priorities by the subject, although the studies of priority manipulation have been partially successful in controlling this problem.

An additional problem surrounding the study of workload through secondary tasks is that the summation of performance demands of the primary task and the secondary task may or may not saturate the subject's capacity. This may mean that two primary tasks widely differing in performance demands may not be correctly assessed if the addition of the secondary task with each does not cause the ensuing dual-task situation to exceed available performance capacity. Thus, caution must be taken in interpreting secondary-task results, especially if either the primary or the secondary task imposes a small demand on the subject. This problem calls for precise determination of individual task demands. A development of this argument is presented by Rolfe (1971).

Although findings from studies using the secondary-task technique include the fact that certain tasks interact in the dual-task situation, the technique is not the most attractive vehicle for the systematic study of task interaction and interference effects. Several additional controls are desirable, including precise measurement and manipulation of performance requirements of tasks performed alone, measurement of the time-sharing decrement within each subject's individual capability on the selected tasks, and techniques for manipulating task priorities and presenting performance feedback that allow the operator to compare his performance with a standard and adjust it accordingly within his performance capacity.

Experimental Technique

The unresolved issues emanating from the secondary-task studies underscore the need for a controlled procedure for assessing dual-task performance. One of the problems has been that the demands upon processing resources of the selected tasks have not been precisely known prior to their combination. By obtaining maximum single-task performance estimates as bases for comparison, unconfounded estimates of dual-task interference and degradation in time-sharing conditions may be obtained.

One method of obtaining maximum operator performance levels is the use of adaptive techniques. Through adaptive logic, the demand of the task may be increased, as the subject keeps some performance measure within a specified range, by manipulating the adaptive variable until an asymptotic level of performance is reached. At this level, the operator is considered to be at his momentary maximum efficiency level. Examples of adaptive variables that have been manipulated successfully in tracking tasks are forcing function frequency and complexity, amplitude, control order, and control gain (Damos, 1972; Crooks and Roscoe, 1973; Gopher, Williges, Williges, and Damos, 1974; Gopher and North, 1974).

A second consideration in the assessment of performance is related to variability across subjects and within the same subject. If time-sharing demands can be assumed to introduce additional variability in the performance of complex tasks as well as a reduction in mean performance, analysis of performance distribution characteristics will yield additional information. Performance distributions in both single-task and time-sharing situations may be compared within the same operator to assess both his central tendency and variability of performance on one task due to time-shared performance with another.

A third consideration is the effective presentation of task demands. The presentation of priorities between tasks must be accomplished in a meaningful manner that allows the subject to adjust momentary performance in accordance with desired task demands throughout the performance session.

The ability to manipulate priorities enhances the investigator's power to assess performance across various demand levels and measure the disturbance of performance on one task caused by increases in demand on the other.

An experimental technique developed by Gopher and North (1974) is designed to handle the above problems in performance measurement. The technique includes three separate performance phases. In the first phase, tasks are performed separately, and automatic adjustment of task variables is used to establish maximum performance estimates for each subject on each of the chosen tasks. In the second phase, the two tasks are presented concurrently with equal priority, and in the third phase, both equal and various unequal task demands are introduced. The task demand levels and momentary performance outputs are displayed to the subject by vertically moving goal lines and bar graphs, respectively. A graph is used for each task, and the goal lines are positioned to represent absolute demands and, by inference, relative priorities.

Experimental results using the technique have shown a wide range of individual differences in performance and have demonstrated that, within each subject's time-sharing capacity, consistent estimates may be obtained of his ability to change performance in accordance with demands. These results have also shown that some subjects are able to make much finer adjustments in allocation policy than others.

Manipulation of Task Demand Levels

Several techniques are involved in investigating task interactions by manipulation of performance priorities of tasks in time-sharing situations. By explicit indication of demands on each task, variable levels of priority may be conveyed to the operator. Thus, comparisons between performance outputs and desired levels may be made and a standardized multiple-regression equation derived that predicts performance as a function of demands on both tasks. A possible form of this prediction equation would be:

$$\hat{Y}_{i/_{i,j}} = \beta_i d_i + \beta_j d_j \quad (1)$$

$$\hat{Y}_{j/_{i,j}} = \beta_i d_i + \beta_j d_j \quad (2)$$

where $\hat{Y}_{j/_{i,j}}$ is predicted performance on task j, at demands d_i and d_j for tasks i and j, respectively.

The strength of these standardized regression coefficients, β_i and β_j represents the relative strength of task demands on the performance of each task. A brief example will clarify this point. Suppose that performance on task i were predicted by the equation:

$$\hat{Y}_i = -0.7d_i + 0.2d_j \quad (3)$$

and task j performance by:

$$\hat{Y}_j = 0.6d_i - 0.5d_j \quad (4)$$

In the first equation, performance on task i is largely affected by its own demands, and not degraded by high demand on the other task. In the second example, performance on task j is found to be nearly equally affected by a high demand on task j or a high demand on task i. (Negative weights correspond to decreasing tracking error or reaction times.)

The proper assessment of performance changes within the dual-task situation caused by increase of demand levels must be accomplished within the performance capabilities of the operator. Standardization across subjects can be achieved by considering the performance distribution of each subject to be independent, and assuming a normal distribution of performances, any level of performance above or below the mean of this distribution may be expressed as a percentage in a cumulative probability function.

Figure 3 illustrates differences in distributions of tracking performance for each of two subjects. For Subject 1, 20 percent above his average dual-task performance ($+.53\sigma$) is at the 32 percent point on the error scale, and 20 percent below his average ($-.53\sigma$) is at the 48 percent point. Subject 2 exhibits less variable performance than Subject 1, as reflected by his smaller standard deviation. Plus and minus 20 percent ($\pm 53\sigma$) from his mean performance cover a range of only 8 percent of scale error, from .36 to .44.

This interpretation implies that variability in performance, as well as its average level, is an important characteristic. Similar arguments have been proposed in time-sharing contexts by Wickens (1974) regarding addition of channel noise in dual-task performance and by Lager (1974) in a recent study of pilot reliability expectancy in complex flight tasks. By manipulating the levels of demand between a compensatory tracking task and a concurrent 10-alternative digit-cancelling task, Gopher and North (1974) showed that many subjects were capable of conforming to demand changes corresponding to increases or decreases of 20 percent around their average

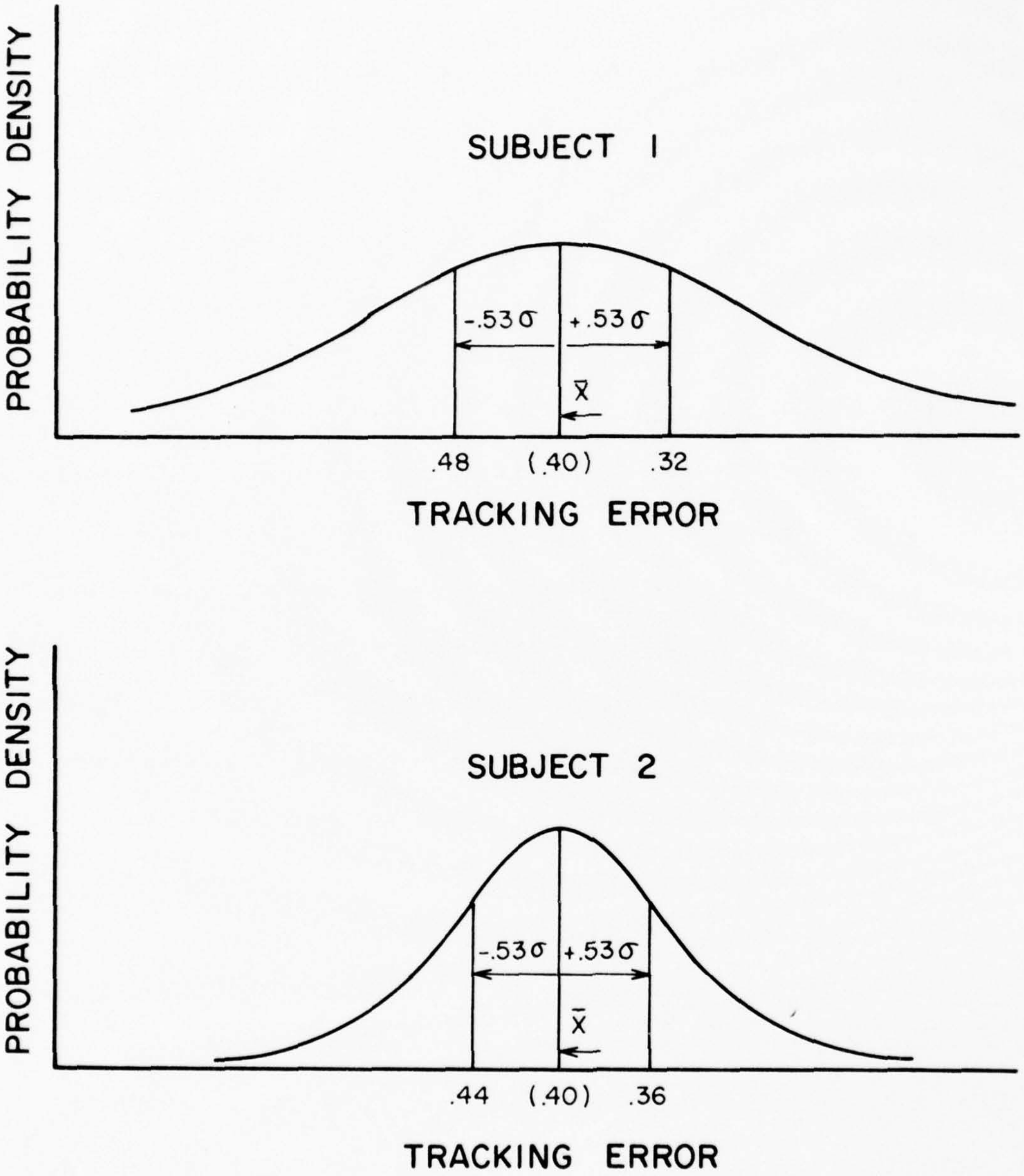

Figure 3. Examples of subject distributions of tracking performance with different variance.

performance levels, but there were wide individual differences among subjects in their abilities to conform to these demands.

Experimental Design

The four tasks discussed above were combined in pairwise fashion using a 4 x 4 mixed-factor design with one between-subjects and one within-subject variable. The between-subjects variable was the task assigned to each subject as the repeated, or "home-task," for all four days of dual-task performance. The task that was paired with this home-task on each day of performance was the within-subject variable. The design matrix is shown in Table 1.

This experimental design includes the pairing of each task with itself and with all others. Furthermore, these conditions may be grouped by the between-subjects factor, each column representing a group of subjects receiving dual-task pairings of one task with the other three. Any individual pair may be compared in two contexts, that is, it occurs in two groups. The order of experimental combinations within columns was counterbalanced to ensure that each combination was preceded and followed equally often by every other.

Eight subjects were assigned to each group defined by a column in Table 1. Two identical partial Latin squares were used with four subjects assigned to each. Each condition is followed and preceded once by every other condition in each square. One group of four subjects performed the home task with the left hand on all four days of the experiment, while the other four performed this task with the right hand. The paried task was assigned to the opposite hand.

TABLE 1

Dual-Task Experimental Conditions

Group 1	Group 2	Group 3	Group 4
Task A & A	Task B & A	Task C & A	Task D & A
Task A & B	Task B & B	Task C & B	Task D & B
Task A & C	Task B & C	Task C & C	Task D & C
Task A & D	Task B & D	Task C & D	Task D & D

Within each day of the experiment (one cell of the matrix in Table 1) three performance phases were used. Phase One was single-task testing on the two tasks assigned for that day. Phase Two consisted of two dual-task trials of four-minutes' duration in which the tasks were of equal importance. Phase Three included six dual-task trials of three-minutes' duration in which relative task demands were varied from trial to trial.

One potential problem with the use of certain within-subject designs is the possibility of asymmetric transfer from one condition to the next. Specifically, the effect may occur when performance in a previous condition either facilitates or inhibits performance in a subsequent condition. Poulton (1966; 1969) has examined and outlined the various transfer effects from a large number of studies representing tracking, vigilance, and information-processing tasks and discusses the general disregard for control of transfer in these experiments, or the use of alternative designs.

With the regard for the potentiality of asymmetric transfer in the proposed design, it could be possible for dual-task combinations (in the within-subject portion) to facilitate or inhibit performance in other sessions. The primary control for this effect is the measurement of single-task ability levels at the beginning of each dual-task session, and the use of adaptive techniques. In this fashion, the subject is readapted to his highest momentary level of performance on each individual task before performing the tasks together. The proportion score, or comparative index of single- and dual-task performance, is the major score of interest because it is continually recalibrated for the comparison between single- and dual-task performance levels.

Subjects

Thirty-two male subjects between the ages of 18 and 26 served in the experiment. All subjects were university students selected from either upper-level psychology courses or the primary flight training class at the Institute of Aviation. Subjects were paid for their participation at the end of the fourth day of performance.

Phase One Procedures

Single-task Tracking. The subject performed a one-dimensional compensatory tracking task with band-limited random noise added to joystick outputs (see Appendix A) for a six-minute period during which the control dynamics of the controller were changed from a pure rate control (easy task) to acceleration control (difficult task) according to the error output of the subject (Crooks and Roscoe, 1973). The task required the subject to keep a moving circle in the center of a horizontal track by appropriate left-right movements of the control stick. The acceleration percentage of the stick output increased adaptively in ten-percent steps from zero to 100 percent. When the subject's error level was within an area of ten percent of the scale on either side of the center line, the task continued to adapt. When the error level was outside of these limits, the acceleration percentage began decreasing in the same manner. The adaptive portion of the task continued for the first four minutes and remained fixed for the final two minutes during which root mean square error (RMSE) was calculated over ten-second intervals (see Appendix B).

Single-task Immediate Cancelling. Random single numerals from the sets 1, 2, 3, 4 or 5, 6, 7, 8 were presented on the CRT display and cancelled by the subject by pressing the corresponding key on the keyboard.

(Two sets of stimuli are desirable when this task is paired with itself in dual-task performance.) A new number was presented immediately following a correct response. To ensure maximum compatibility and minimum interference from extraneous factors related to response selection and execution, the keyboards were arranged 1-2-3-4 or 5-6-7-8 and could be adjusted to the most convenient distance and position for each subject.

During single-task performance, the subject was brought to a consistent level of performance. Average response latency for correct responses was computed for ten-trial blocks. After receiving a minimum of 50 trials, the subject continued until the difference between two successive ten-trial blocks was less than ten percent. The mean correct response time was computed for the final two blocks (20 responses). If the subject had not performed the task previously during the experiment, two such single-task sessions were administered. The better performance during these two sessions was chosen to represent the subject's single-task capability for the task.

Single-task Delayed Cancelling. The format for the presentation of stimuli for the Delayed Cancelling task was the same as in the Immediate Cancelling task; however, the appropriate response corresponded to the previously presented digit in the sequence. At the beginning of each session of Delayed Cancelling,the subject began the task by pressing the leftmost key on the keyboard which erased the first number appearing on the screen. After this initial response, the subject was required to remember the last number in the sequence. Logic for bringing the subject to consistent performance was identical to the Immediate Cancelling task, and the performance measure was also the mean correct response time.

Single-task Classification. The subject was presented with a digit pair whose elements differed in numerical name and/or physical size. Based upon the classification scheme discussed earlier, the stimulus item is cancelled by pressing the key assigned to one of three categories. As in the previously described Keyboard tasks, a new item was immediately shown when a correct response was made. To maximize stimulus-response compatibility of the task, and ensure that the reaction times produced were only the product of Classification and simple responding, the keyboard consisted of three keys. The left key was assigned to all stimulus pairs that were the same in both name and size, right key to pairs differing in both name and size, and the middle key to those that had one attribute in common and differed on the other. The logic for bringing the subject to consistency in single-task performance and the performance measure recorded were the same as for the other two Keyboard tasks.

Phase Two Procedure: Dual-Tasks with Equal Demands

Two dual-task performance trials (Phases 2A and 2B) followed single-task testing. Each lasted four minutes with a three-minute rest period intervening. In the first trial (Phase 2A), the acceleration percentage of the hand control output for the Tracking task and the generation rate of Keyboard-task stimuli were based on values obtained during single-task performances.

The Keyboard tasks were self-paced as in single-task performance, with one important change: if the time that an item were displayed exceeded the 95th percentile of the subject's previous reaction-time distribution plus the average of the previous trial, a new stimulus was generated. (This method was tested in previous studies by Gopher and North, 1973, and found to be an effective method of keeping constant reaction time pressure on the subject.) For the first dual-task trial this time was based upon single-task performance values, and for the second trial (Phase 2B) it was recalculated using averages and standard deviations obtained for the first dual-task trial.

In addition to the individual-task displays, a performance indicator for each task appeared as a moving bar graph varying in height with the momentary performance of the subject (Figure 4). The desired level of performance was indicated by a short horizontal line positioned about half the distance from the graph starting point to the top of the screen. In Phase 2A, this line represented average performance in the single-task trial, while in the second dual-task trial, it represented averages obtained in Phase 2A. The distance on the display from the zero point (no bar graph showing) to the desired line represented 2.5 standardized performance units computed by subtracting 2.5 standard deviations from the appropriate average. Thus, if the subject's performance were very poor, the bar graph was below the desired average or no graph was showing.

The height from moment to moment was calculated by subtracting the subject's momentary average from the desired average and computing a standardized level of performance transformed into the height of the graph. Thus, the graphs moved within the standard score space of individual subjects. For the Tracking task, the performance score used was RMS error calculated over ten-second intervals, and the bar graphs' heights were updated every second. For Keyboard tasks, the score used was the average time for the last ten correct responses. Thus, if a subject were either

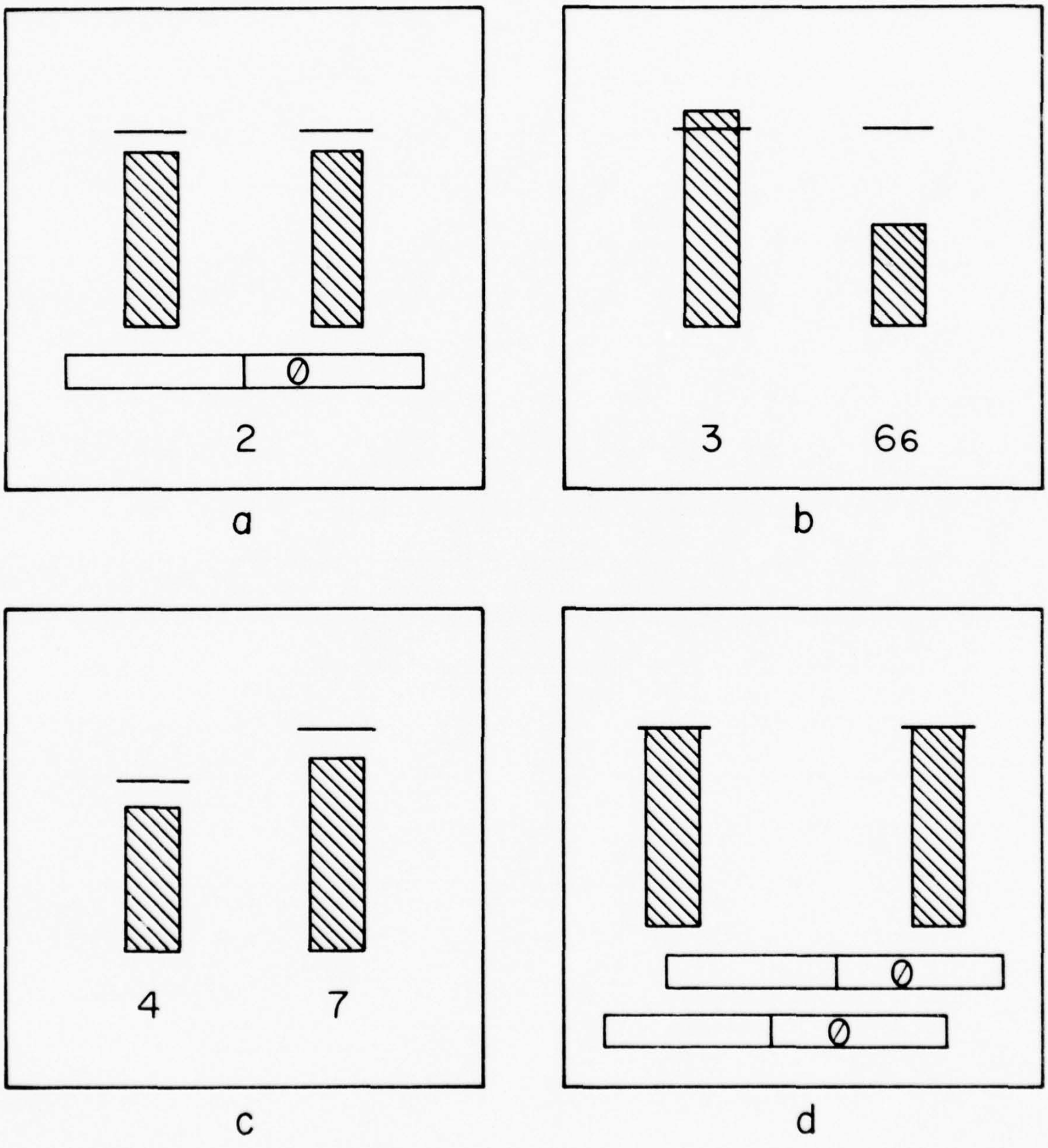

Figure 4. Dual-task displays for Tracking/Immediate Cancelling (a), Delayed Cancelling/Classification (b), Immediate Cancelling/ Delayed Cancelling (c), and Tracking/Tracking (d) showing feedback graphs and desired performance lines.

slow or inaccurate, the bar graph began moving toward the bottom of the display.

Phase Three Procedure: Dual-Tasks with Equal and Unequal Demands

Phase Three consisted of six dual-task performance trials. Each trial lasted three minutes with one minute of rest intervening between trials. The six trials represented six experimental conditions in which the desired performance lines could appear at one of three levels for each task. Increased performance requirements were indicated by a higher desired line, while decreased requirements were represented by a lower line. Subjects were instructed to attempt to perform at or above these performance lines.

The three levels used were those corresponding to the subject's 25th percentile (low requirement), 50th percentile (medium requirement), or 75th percentile (high requirement) calculated from the performance of the subject in Phase 2B. The 50th percentile actually was the average performance of the subject in Phase 2B. The demands for the six tasks used in Phase Three were: 3A, .50/.50; 3B, .50/.75; 3C, .75/.50; 3D, .25/.75; 3E, .75/.25; 3F, .75/.75. Three of these combinations called for combined demands greater than 1.00 (Trials 3B, 3C, and 3F) while the other three called for total combined demands of 1.00 (Trials 3A, 3D, and 3E).

The use of a counterbalanced within-subject experimental design, involving the six experimental conditions in Phase Three, presents an opportunity for asymmetric transfer between conditions. The particular manipulation in this phase is task demand, defined by the height of the desired performance lines. Poulton (1966) examples were plagued by asymmetric transfer in which variables such as stimulus-response arrangement or display-control relationships were changed from condition to condition in within-subject designs. Although the present experimental manipulation does not include these categories, this does not preclude the possibility of the effect. A test of asymmetric transfer was performed on data from 24 subjects of a recent dual-task experiment using the above technique for manipulating priority.

Apparatus

The basic experimental equipment included a Hewlett-Packard 10.8 x 7.6-cm Model 1300A cathode ray tube (CRT) for the displays for all tasks. A Raytheon 704 digital computer generated inputs to the CRT and processed signals from the keyboards and control sticks. The computer provided digital signals to a symbol generator that converted them to analog onputs for the CRT display. The keyboard keys were arranged linearly and conformed to the average position of the male fingers. The tilt and distance of the keyboard from the subject could be adjusted for convenience. The controller used in Tracking was a spring centered dual-axis manual control of which only the lateral control motion was used. Performance information, stored by the digital computer, was printed on a Gould 4800 line printer in the form of tables, Tracking graphs, and record of individual Keyboard responses. The experiment was conducted in a light and sound attenuated room.

RESULTS

Single-Task Performance

Subjects were tested on each task separately at the beginning of each day's performance. The home-task mean performance curves across four days of testing are shown in Figures 5 and 6 for Tracking and Keyboard tasks, respectively. The dependent measure for Tracking was acceleration percentage level attained during the adaptive period of performance, while average latency for the final 20 correct responses was used for the three Keyboard tasks. The effects of practice on each home task during the four test days were assessed by analyses of variance.

For Tracking, the level of the adaptive variable, as shown in Figure 5, increased reliably over trials ($p < .05$). An additional test of single-task RMS error means for the final two minutes of single-task performance yielded means of 14.9, 14.9, 13.5, and 14.2 percent of scale error for the four test days, respectively. These values do not differ reliably, and there is no indication that the adaptive technique failed to compensate completely for the acquisition of Tracking skill over the four test days.

Although performances improved reliably on all Keyboard tasks ($p < .05$), the comparative ranges of improvement between tasks were quite different. Immediate Cancelling improved very little; Classification performances improved greatly between Day 1 and Day 2 and little thereafter; and Delayed Cancelling continued to improve over all four days of testing. Although performances on neither of the two more difficult tasks reached the speed of Immediate Cancelling, the differences between tasks were relatively small by the fourth day.

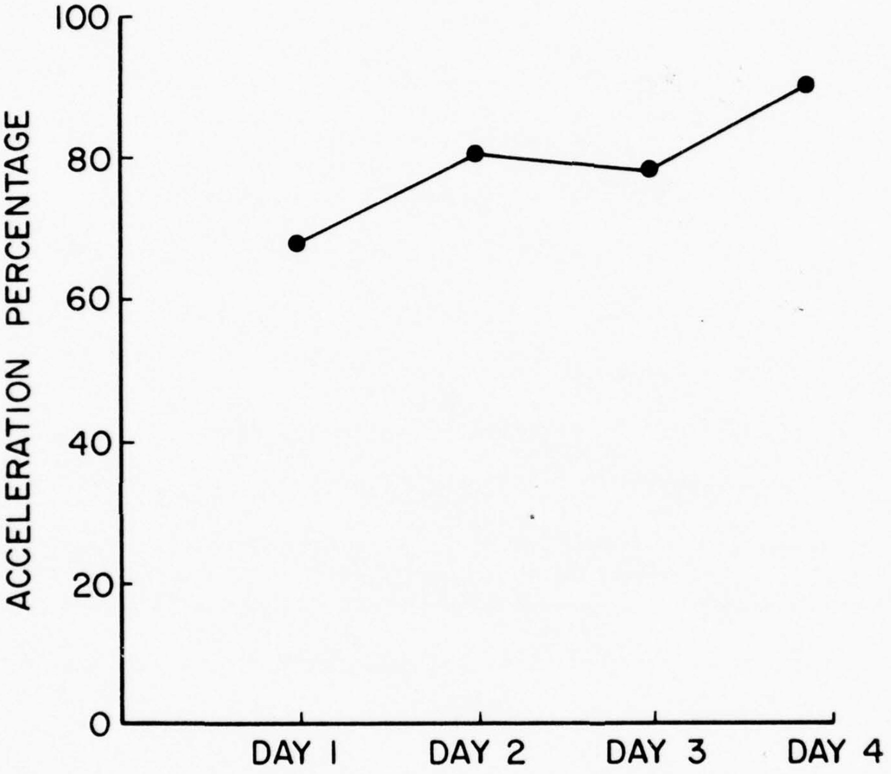

Figure 5. Acceleration percentage in Phase One over four days of Tracking performance.

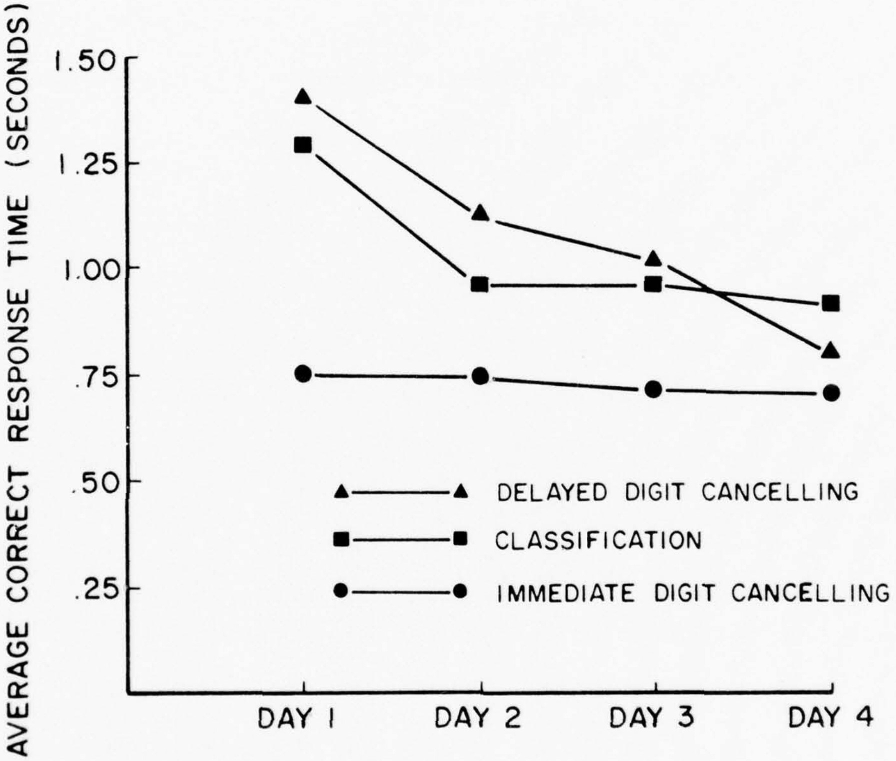

Figure 6. Average single-task correct response time for Keyboard tasks in Phase One over four days of performance.

Improvement in single-task skill for all tasks may be attributable to both single-task practice and repeated dual-task experience between single-task tests. Isolating the sources of improvement on each task was not a major goal of this study; however, the evidence of improvement emphasizes the importance of the repeated measurement of single-task skill level before each day's dual-task session.

Performance Comparisons in Phase Two: Equal Task Demands

The two dual-task trials in Phase Two served as the basis for intertask comparisons of performance decrements from single- to dual-task conditions and thereby allowed assessment of degree of interference each produces. Separate analyses of variance were conducted for each set of home-task scores to test the effects of Task Pairings, Trials, and Hand Assignments. The following section describes and discusses analyses of these data for each home task using the dependent measures discussed above.

Performance measures. Dependent scores used for Tracking were RMS error expressed as a percentage of scale and within-subject deviation (WSD). RMS error for each trial was the mean of the RMS values computed over ten-second intervals, and WSD was the standard deviation of these sample points, reflecting the consistency of Tracking for that trial.

Dependent scores for the three Keyboard tasks were average response time (ART), response interval (RI), correct response interval (CRI), and WSD, in this case computed from average response times rather than RMS errors. ART differs from RI and CRI because it includes reaction times only to items that were cancelled and excludes time lost due to missed items. RI is the average time between emitted responses which did include time lost due to missed items. CRI is the average time between correct responses. Therefore, differences between RI and CRI scores represent time lost due to errors in responding.

Because distributions of variable error scores and reaction or response times are known to be positively skewed, and their variances positively correlated with their means, all such scores were transformed to their common logarithms to correct both effects prior to any statistical analysis.

As previously mentioned, a proportion score for each task represented the performance decrement from single- to dual-task trials. Proportions were quotients formed by dividing single-task by dual-task scores using appropriate performance measures for each task. For Tracking with varying control dynamics, this computation is not the simple division of RMS error under single-task and dual-task conditions but requires a transformation to a time relation because of the individual differences in acceleration percentages attained during the adaptive portion of single-task performance. (For a more detailed description of this conversion see Appendix B.) For the three Keyboard tasks, the proportion score was formed by dividing single-task correct response intervals by dual-task correct response intervals.

The proportion scores reflect the relative decrement in each subject's single-task capability demonstrated in Phase One. The higher the proportion, the better the subject's retention of this capability. The advantage of this score is that it reduces the biasing effect of individual differences found in the raw score measures discussed above. Because proportion scores reflect decrements or increments in an individual subject's performance relative to his own earlier performances, they are relatively independent of skill levels of the subjects on the individual tasks.

One additional score computed for the dual-task trials was the combined score, formed by adding the proportion scores for the two tasks. This score provides an overall index of dual-task efficiency. Neither the individual nor the combined proportion scores can be considered to form form equal-interval scales; a score of 0.50 does not necessarily represent twice as great a decrement as a score of 0.75.

Tracking as the home task. Scores for the five dependent tracking variables are given in Table 2. The variuos task pairings caused reliable differences ($\underline{p} < .05$) for each of the five dependent variables, and consequently the specific condition differences were assessed pairwise using the Newman-Keuls post hoc comparison techniques. Home-task Tracking was poorer when it was paired with a second Tracking task than when paired with any of the three Keyboard tasks. The pairwise comparisons revealed reliable differences between the Tracking/Tracking condition and each of the Tracking/Keyboard conditions for combined scores ($\underline{p} < .05$), and differences approached reliability for RMS errors, WSDs, and proportion scores ($\underline{p} > .05 < .10$).

An additional method of conducting comparisons of within-subject means is the use of a planned comparison technique especially designed for within-subject data (Scheffé, 1959). With this technique, scores formed by linear combinations of means may be tested against scores formed from other linear combinations. In the planned comparison home-task Tracking scores in the Keyboard conditions were averaged to test the difference between the Tracking condition and the mean of these three conditions. A score was generated for each subject on each dependent variable by

TABLE 2

Phase Two: Home-Task Tracking Performances with Equal Paired-Task Demands

Pairing Condition	RMS Error (pct scale)	WSD (pct scale)	Home-Task Proportion	Paired-Task Proportion	Combined Score
Tracking					
Trial 1	34.5	11.9	.57	(.65)	1.22
Trial 2	29.9	10.4	.67	(.70)	1.37
Immediate Cancelling					
Trial 1	25.3	7.2	.76	(.82)	1.58
Trial 2	24.3	7.2	.78	(.91)	1.69
Classification					
Trial 1	21.9	7.2	.79	(.82)	1.61
Trial 2	20.8	6.0	.81	(.95)	1.76
Delayed Cancelling					
Trial 1	24.8	7.5	.78	(.72)	1.50
Trial 2	23.1	6.9	.82	(.88)	1.70

subtracting the score for the Tracking condition from the mean of the three scores of the Keyboard conditions to form a single difference score.

Eight scores were generated in this fashion, one for each subject. These scores were then treated as difference scores in a dependent t-test for reliable differences from zero. For RMS errors (log transformed scores), this analysis produced a t of 3.10 ($p > .05 < .10$); for proportion scores, the t value was 6.18 ($p < .05$). These findings are in general agreement with the Newman-Keuls comparisons between Tracking and each individual Keyboard mean.

Recalling the previously described functional component task model, Classification and Delayed Cancelling were chosen to represent tasks that involve TRANSFORMING and STORING, respectively. The Immediate Cancelling task includes neither of these components. Comparisons of interference levels in dual-task performance, therefore, should reflect any additional decrement in home-task performance produced by paired tasks with additional functions. The relevant comparisons are between home-task performances when paired with Immediate Cancelling and when paired with either Classification or Delayed Cancelling. As the means in Table 2 indicate, home-task Tracking was not differentially affected by paired tasks that required either TRANSFORMING or STORING. Tracking performances were not reliably different when paired with Immediate Cancelling, Delayed Cancelling, and Classification.

RMS error and proportion scores showed unreliable trends for improvement over trials, and no evident dependence upon hand assignment. The condition with the largest improvement in tracking error and proportion was the tracking pair condition. Paired task proportions and combined scores did improve reliably from the first to the second trial, and this improvement in combined score is especially prominent in the paired Keyboard conditions. Thus, it appears that interweaving skills develop more rapidly when the combined tasks are dissimilar in the MANIPULATING component.

Immediate Cancelling as the home-task. Table 3 summarizes the results for the seven dependent measures for Immediate Cancelling home-task performance in Phase Two. As in other cases, log transformations were performed on the ART, RI, CRI, and WSD scores to provide distributions more suitable for analysis of variance.

There was reliable improvement in scores from the first to the second trial for all dependent measures except ART and WSD, both of which increased in the three conditions pairing two Keyboard tasks. In the second dual-task trial, the presentation time for each item was lengthened to allow a longer interval in which to make a response. This was the consequence of the recalibration of the desired performance criteria from the subject's single task means and standard deviations from Phase One to his first dual-task trial in Phase Two. A reliable trials x tasks interaction ($p < .01$) was reflected in the large increase in ART and WSD for the three Immediate Cancelling/Keyboard conditions and no increase in the Immediate Cancelling/Tracking conditions.

Tracking produced the smallest decrement from single-task scores, followed by Immediate Digit Cancelling, Classification, and Delayed Cancelling conditions. Comparing these condition means using a Newman-Keuls test for pairwise differences, it was found that the

TABLE 3

Phase Two: Home-Task Immediate Digit Cancelling Performances with Equal Paired-Task Demands

Pairing Condition	ART (sec)	RI (sec)	CRI (sec)	WSD (sec)	Home-Task Proportion	Paired-Task Proportion	Combined Score
Tracking							
Trial 1	.87	1.00	1.14	.28	.67	(.66)	1.33
Trial 2	.85	.88	.93	.32	.81	(.71)	1.52
Immediate Cancelling							
Trial 1	1.00	1.50	1.97	.40	.39	(.38)	.77
Trial 2	1.28	1.40	1.50	.62	.51	(.47)	.98
Classification							
Trial 1	.87	1.94	2.63	.39	.28	(.55)	.83
Trial 2	1.59	1.71	1.87	.73	.38	(.63)	1.01
Delayed Cancelling							
Trial 1	.84	2.51	3.42	.38	.24	(.44)	.68
Trial 2	1.43	2.19	2.44	1.38	.31	(.52)	.83

Immediate Cancelling task was performed best when Tracking was the paired task relative to performances with Classification, Delayed Cancelling, and Immediate Cancelling as the paired tasks for RI, CRI, and Proportion scores ($\underline{p} < .05$).

These results are consistent with the results for home-task Tracking performance in that the three Tracking/Keyboard combinations produced the highest performances in dual-task conditions. Pairing the Immediate Cancelling Keyboard task with the other Keyboard tasks led to larger decrements. This result is further supported by the combined scores, which showed reliable differences between Tracking and the three Keyboard means, indicating the overall performance compatibility of the Tracking/ Keyboard combinations.

The comparisons among the three Keyboard pairing conditions produced reliable differences in home-task performances. Pairing Immediate Cancelling with Immediate Cancelling produced reliably higher home-task proportion scores than pairing with either the Classification or the Delayed Cancelling task. Pairing the home-task with itself also produced reliably better RI and CRI performance than pairing with Delayed Cancelling ($\underline{p} < .05$) and nearly reliably better than pairing with Classification ($\underline{p} > .05 < .10$). In each case, the performance of the home task deteriorates when paired with a more complex task.

Also it should be noted that there was a larger difference between ART scores and RI scores with Delayed Cancelling as the paired task than with either of the cther two Keyboard tasks. This is attributed to the increase in number of missed digits on the home task when paired with Delayed Cancelling and can be explained by differences in response strategies to be discussed. These results suggest that the STORING component present in the Delayed Cancelling task is highly disruptive of Immediate Cancelling performance, and that TRANSFORMING (Classification) is moderately disruptive.

Table 3 reveals several important features concerning Keyboard/ Keyboard performances. In no case does the combined score reach 1.00 for the first trial, and in only one case, Immediate Cancelling paired with Classificaiton, does the combined score exceed 1.00 in Trial 2. Home-task proportions were well below .50 for the first trial and reached .51 only for Immediate Cancelling paired with itself in Trial 2. The low combined scores suggest that subjects adopt response strategies that do not favor parallel operation on the two tasks. An examination of response patterns was conducted for both dual-task trials, and it was found that during first trials, subjects attempted several strategies before deciding upon one method. By the second trial, one of three response strategies was adopted.

One strategy was highly segmented operation on the tasks, that is, working on one task for several responses and then switching to the other task for several responses. A second method was a strict alternation between tasks, responding in a left-right-left-right manner. A third, and rarely observed method was simultaneous response to the left and right tasks. This technique usually was combined with the second strategy of alternation throughout a performance trial. The matter of response strategies will be quantified and discussed in a later section, including its relationship to interfering properties of the Keyboard tasks.

Delayed Cancelling as the home task. Table 4 summarizes results for the Delayed Cancelling task in Phase Two. The improvement between trials was reliable ($p < .05$) for all dependent measures except ART ($p > .05 < .10$). Although Hand Assignment did not affect performances reliably for any of the dependent variables, the interaction between Hand Assignment and Task Pairing for home-task Delayed Cancelling proportion scores was reliable due to the superiority of one particular condition: left-hand Tracking paired with right-hand Delayed Cancelling. This combination produced proportions of .60 for Tracking and .79 for Delayed Cancelling, while the opposite hand assignment yielded .60 and .62 for Tracking and Delayed Cancelling, respectively. All three of the other task combinations produced nearly equal proportions for alternate hand assignment, suggesting that this specific task set produced better performance on the Delayed Cancelling task.

This result agrees favorably with recent research by Hicks (1975) who reported differential interference in concurrent performance of a balancing task with a verbalization task according to left-right assignment of the balancing task. The motor task showed less interference from verbalization when performed with the left hand than with the right. Hicks interprets his interaction as support for current theories of cerebral hemispheric dominance, suggesting that the motor command portion of the brain, centered in the right hemisphere (controlling left-hand performance) and the verbalization control portion, centered in the left hemisphere, incur less mutual interference when tasks are assigned motor-left, verbal-right than vice versa.

TABLE 4

Phase Two: Home-Task Delayed Digit Cancelling Performances with Equal Paired-Task Demands

Pairing Condition	ART (sec)	RI (sec)	CRI (sec)	WSD (sec)	Home-Task Proportion	Paired-Task Proportion	Combined Score
Tracking							
Trial 1	1.05	1.31	1.84	.48	.62	(.61)	1.23
Trial 2	1.09	1.19	1.40	.61	.80	(.58)	1.33
Immediate Cancelling							
Trial 1	1.09	1.75	2.38	.54	.48	(.31)	.79
Trial 2	1.21	1.60	2.01	.88	.56	(.41)	.97
Classification							
Trial 1	1.09	2.00	2.64	.58	.42	(.45)	.87
Trial 2	1.17	1.68	2.26	.98	.49	(.52)	1.01
Delayed Cancelling							
Trial 1	1.15	2.33	3.53	.59	.33	(.33)	.66
Trial 2	1.30	1.99	2.72	1.25	.41	(.40)	.81

Performance of Delayed Cancelling with different task pairings produced similar differences between conditions as in the results for Immediate Cancelling as the home task. The best performance occurred when Tracking was the paired task, followed by the Immediate Cancelling, Classification, and Delayed Cancelling conditions. Home-task Delayed Cancelling performance with Tracking was reliably better than when paired with Delayed Cancelling for RI ($\underline{p} < .05$), CRI ($\underline{p} < .05$), home-task proportion ($\underline{p} < .05$), and combined score ($\underline{p} < .01$). Home-task performance was also reliably superior when paired with Tracking as opposed to Immediate Cancelling and Classification Conditions for proportion ($\underline{p} < .05$) and combined score ($\underline{p} < .05$).

Among conditions in which Delayed Cancelling was paired with another Keyboard task, performance with Immediate Cancelling was reliably superior to performance with the Delayed Cancelling task for the home-task proportion scores ($\underline{p} < .05$), and differences between these two conditions for RI and CRI scores approached reliability ($\underline{p} < .10$). Note also that there is indication of lost time due to missed items in all three pairing conditions (difference between RI and ART) and that this loss is greatest for the Delayed Cancelling condition.

Again, there is a consistent pattern within task combinations that favors combining Tracking with the Keyboard tasks. These results demonstrate the consistency of rank order of decrements in home-task performance when the four task pairings are compared to the Immediate Cancelling home-task results. Clearly the STORING/STORING dual-task combination presents the most difficult pairing as demonstrated by the longest response intervals for Keyboard tasks with which Delayed Cancelling was paired.

Classification as the home task. Table 5 summarizes results for the home-task Classification performances in Phase Two. ART, WSD, proportions, and combined scores increased reliably from Trial 1 to Trial 2 ($p < .01$). The ART and WSD increases from the first to the second trials were probably caused by a shift in subject strategies to eliminate missed items and interweave the tasks more efficiently. Both proportion and combined scores increased from the first to the second trials indicating general improvement in dual-task efficiency.

The effect of Hand Assignment of the home-task was not reliable for any of the dependent measures; however, the Task Pairing x Hand Assignment interaction was reliable ($p < .01$) for combined scores. When Classification was paired with Delayed Cancelling, performance was slightly better when the home-task was assigned to the left hand. For Immediate Cancelling, the assignments produced about equal combined scores, but for Classification/Tracking, right-hand Classification combined with left-hand Tracking produced a combined score of 1.66 compared to 1.34 with the opposite hand assignment.

The proportion scores in this combination reveal that although there is little difference between left-hand and right-hand performances on the Classification task, the left-hand Tracking proportion was .87, compared to .60 with the right hand. These results are consistent with the Delayed Cancelling home-task results in that this interaction produced similar superiority when Tracking was assigned to the left and Keyboard tasks to the right hand.

TABLE 5

Phase Two: Home-Task Classification Performances with Equal Paired-Task Demands

Pairing Condition	ART (sec)	RI (sec)	CRI (sec)	WSD (sec)	Home-Task Proportion	Paired-Task Proportion	Combined Score
Tracking							
Trial 1	1.06	1.20	1.34	.41	.68	(.72)	1.40
Trial 2	1.07	1.10	1.19	.43	.79	(.81)	1.60
Immediate Cancelling							
Trial 1	1.19	1.58	1.97	.56	.54	(.34)	.88
Trial 2	1.45	1.51	1.70	.83	.63	(.41)	1.04
Classification							
Trial 1	1.25	2.09	2.51	.58	.44	(.44)	.88
Trial 2	2.03	2.08	2.32	.93	.47	(.50)	.97
Delayed Cancelling							
Trial 1	1.07	2.30	2.64	.50	.42	(.40)	.82
Trial 2	1.79	2.42	2.63	1.29	.40	(.48)	.88

Similar performance decrement patterns were observed across the pairing conditions for home-task Classification as demonstrated for the Immediate Cancelling and Delayed Cancelling home tasks. Table 5 shows the same order of decrement for RI, CRI, and home-task proportion, with Tracking producing the least decrement, followed in order by Immediate Cancelling, Classification, and Delayed Cancelling pairings. Individual comparisons between conditions showed that home-task Classification performance when paired with the Tracking task was reliably superior to performance when paired with any of the three Keyboard tasks for CRI, proportion, and combined scores ($\underline{p} < .01$ for all). Again the Keyboard/Tracking combination allowed the best performance of a Keyboard task compared to any of the Keyboard/Keyboard pairings, demonstrating complete agreement with the results of similar condition comparisons for the other two Keyboard home tasks.

The Keyboard task comparisons yielded only one reliable difference and this was between the Immediate and Delayed Cancelling pairings for RI ($\underline{p} < .05$). This difference approached reliability for CRI and proportion scores ($\underline{p} > .05 < .10$). Note again, for the Delayed Cancelling condition, that there is a large difference between ART and RI scores, reflecting the lost time on the home task due to missed items. These data show the same order of dual-task decrement between conditions that was evident in both of the other Keyboard home-task performance scores for the three Keyboard conditions. These results strongly support the contention that the STORING task is most disruptive of home-task performance.

The raw performance scores presented are not reflective of interference magnitudes of the TRANSFORMING and STORING components unless combined meaningfully with individual subject strategies. The following section reports the incidence of different response strategies in dual-task performance and discusses their possible relationship to dual-task interference.

Dual-task Keyboard response strategies. Individual subject response strategies in dual-task conditions involving two Keyboard tasks have been previously discussed as falling into one of three categories: simultaneous responding; alternation of responses between tasks; and segmented responding in which the subject makes a group of responses to one task and then shifts to the other. A close examination of strategies adopted during first trials revealed that most subjects adopt the segmented pattern. By the end of the second trial, there are individual differences in choice of a response strategy.

To quantify these strategy types, the responses to each task were classified as being "alternating" or "segmented" by looking at preceding and following responses. If the immediately surrounding responses were made to the other task, then the response was classified as "alternating." Table 6 presents the results of this categorization of responses in percentages of alternating responses on each task combination for each of the eight subjects tested in that condition.

These results show clearly that the presence of the STORING task leads to the adoption of a segmented pattern of response in which attention is shifted from task to task in blocks of more than one response. For combinations not including the STORING task, the incidence

TABLE 6

Percentage of Alternating Responses by Each Subject during Second Trials of Phase Two on Each Keyboard/Keyboard Pairing

	PERCENT OF ALTERNATING RESPONSES		
Subject	Paired With Immediate Cancelling	Paired With Delayed Cancelling	Paired With Classification
	Immediate Cancelling as Home Task		
1	0	0	0
2	100	75	100
3	100	100	100
4	100	0	100
5	0	0	0
6	100*	0	5
7	100	0	95
8	0	0	100
	Delayed Cancelling as Home Task		
1	0	0	0
2	95*	95*	95*
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	90*	0
8	0	0	0
	Classification as Home Task		
1	70	0	85
2	100	0	95
3	0	0	80
4	95*	100*	100*
5	95	0	100
6	10	0	100
7	5	0	33
8	10	0	5

*Indicates simultaneous response strategy of alternating strategies increases, and they are used by about one-half of the subjects. Thus, the TRANSFORMATION task shows some evidence of smooth integration both with an identical task and with the Immediate Digit Cancelling task which does not require either STORING nor TRANSFORMING.

Individual subject consistency within strategy choice was evident for most subjects. In the Immediate Cancelling home-task group, Subjects 1 and 5 both adopted a segmented response strategy in all three Keyboard task pairings. Subjects 2 and 3 show consistency with the alternating response method throughout all conditions. Although the other subjects varied in strategies adopted across conditions, Subjects 4 and 7 were consistent in adoption of alternating strategies for the Immediate Cancelling and Classification pairings.

In the Delayed Cancelling home-task group, most subjects preferred segmented response strategies, although Subject 2 consistently made simultaneous responses. Subject 7 also adopted simultaneity in response in the same-task pairing case. In the Classification home-task group, consistency of the alternating strategy in the Immediate Cancelling and Classification pairings only was evident for Subjects 1, 2, and 5. Subject 4 consistently made simultaneous responses in all three conditions.

The presence of the Delayed Cancelling task not only produced the higher incidence of segmented response strategies but also produced <u>more responses</u> than the task with which it was paired. For the Immediate Cancelling home-task subjects who adopted the segmented strategy, an average of 75.3 responses were made to the home-task compared to 101.7 responses to the Delayed Cancelling task ($\underline{p} < .05 > .10$). For the

Delayed Cancelling group, the seven subjects who adopted the segmented response strategy averaged 123.3 Delayed Cancelling responses while making only 99.4 on the paired Immediate Cancelling task ($p < .01$). In the Classification pairing condition, the seven subjects who responded in segmented patterns averaged 111.1 Delayed Cancelling responses and only 79.6 Classification responses during second trials ($p < .05$). The same pairing of these tasks in the Classification home-task group did not produce the same preference toward the Delayed Cancelling task for the seven sequential responders in this condition.

These comparisons for the segmented strategy subjects suggest that the Delayed Cancelling task becomes the dominant or compelling task with regard to the attention it is given over a simpler Keyboard task that does not involve short-term STORING. It is apparent that STORING is more difficult to stop once started, and switching between tasks is difficult. Once the subject begins work on this task, reaction times are very similar to single-task scores as demonstrated by comparing the range of single-task performance averages in Figure 2 with ART for any of the Delayed Cancelling/Keyboard conditions in Table 4.

In the pairings that did not include a Delayed Cancelling task, more subjects adopted an alternating pattern of response. As expected, the total number of responses to each task in these cases was nearly equal. Correlations between total responses to each task in the second Phase Two trial for those subjects who alternated responses in the Immediate Cancelling/Immediate Cancelling, Immediate Cancelling/Classification, Classification/Classification, and Classification/Immediate Cancelling pairing conditions were all .90 and above and reliable ($p < .05$).

Phase Two Keyboard/Keyboard condition results clearly indicate a higher level of dual-task decrement compared to the Tracking-Keyboard combinations. Subjects required to perform two Keyboard tasks concurrently must develop efficient strategies that yield the maximum number of correct responses and provide approximately equal attention between tasks, as per the instructions. The self-paced nature of the tasks leads to the development of switching strategies that suit the component structures of the tasks in each pairing condition. An alternating response strategy provides a firm control over the number of responses to each task, keeping the number about equal.

If the task includes short-term STORING, the majority of subjects will adopt a segmented response strategy in which groups of responses are made to each task, and typically they will not make an equal number to each task. This strategy is actually representative of alternating sequences of single-task performance as reaction times during each response string are approximately the same as the measured single-task reaction times in Phase One. Thus, subjects prefer to operate in a segmented responding fashion with no evidence of integration of tasks in dual-task performance.

Strategies and Combined Dual-Task Efficiency

Response strategies in concurrent Keyboard task combinations are an important part of understanding the interfering properties of the three Keyboard tasks. Subjects who demonstrate the segmented strategy are most likely making completely independent processing-response cycles to each task, that is, time-sharing is of a completely on/off nature.

The choice of a regularly alternating response pattern in the four conditions not including a Delayed Cancelling task did not produce a reliable increase in the number of correct responses; that is, there was no evidence of increased efficiency using the alternating technique. Individual cases in which responses were evenly alternated did show high dual-task proportion scores in the equal-demand conditions of Phase Three. However, the number of cases and small sample sizes for the comparison of the efficiency of the two techniques make it speculative to argue for the advantage of regular alternation over the segmented strategy.

The alternating strategy may be more reflective of parallel operation provided the subject makes more responses than could be predicted from adding single-task reaction times of the two tasks. The overall dual-task efficiency for each task combination can be assessed by the combined score, which is the addition of the proportion scores for each task. If the subject worked independently between tasks with no lost time due to switching, his combined score would equal 1.00. A combined score less than 1.00 would indicate that the subject is losing time between switches. Reviewing the scores in Phase Two for the nine Keyboard combinations shows that for the combined scores computed from correct response intervals, there are only three cases in which the combined score exceeded 1.00, and these cases all occurred in Trial 2.

If the same combined score is computed using the sums of response interval proportions (dual-task RI/single-task RI) instead of the correct response interval proportions, several of the scores do exceed 1.00 for these Keyboard combinations. The interpretation of this result is that subjects may indeed respond more often than would be expected; however, their accuracy may suffer. Thus, the difference between the two combined scores is a direct reflection of the amount of performance time lost due to errors in responding.

Phase Three: Performance under Changing Task Demands

Phase Three included six performance sessions in which task demands were varied over three levels shown in the matrix in Figure 7. Tables 7, 8, 9, and 10 present RMS error and CRI for Tracking and Keyboard tasks, respectively, and are organized by home-task groups. Three analyses of variance (ANOVAs) were conducted on the appropriate dependent measures for each task. The first ANOVA compared the diagonal conditions (E, A, and D), all of which had a total task demand of 1.00 (.25/.75, .50/.50, and .75/.25). A second ANOVA on conditions D, B, and F tested the effect of holding the home-task demand at .75 and varying the paired task demand from .25 to .50 to .75. A third ANOVA on conditions C, E, and F tested the effect of holding the paired task demand at .75 while varying the home-task demands.

A regression analysis, based on the mean scores presented in Tables 7, 8, 9, and 10 and summarized in Table 11, shows the effeciveness of varying demand on each task. The predictor scores for this analysis were the standardized task demands (X_h and X_p), and the criterion scores were the task performance means across the eight subjects for that condition. The regression equation resulting from regressing the demand levels on the mean performance levels is of the form:

$$\hat{P} = \beta_h X_h + \beta_p X_p$$

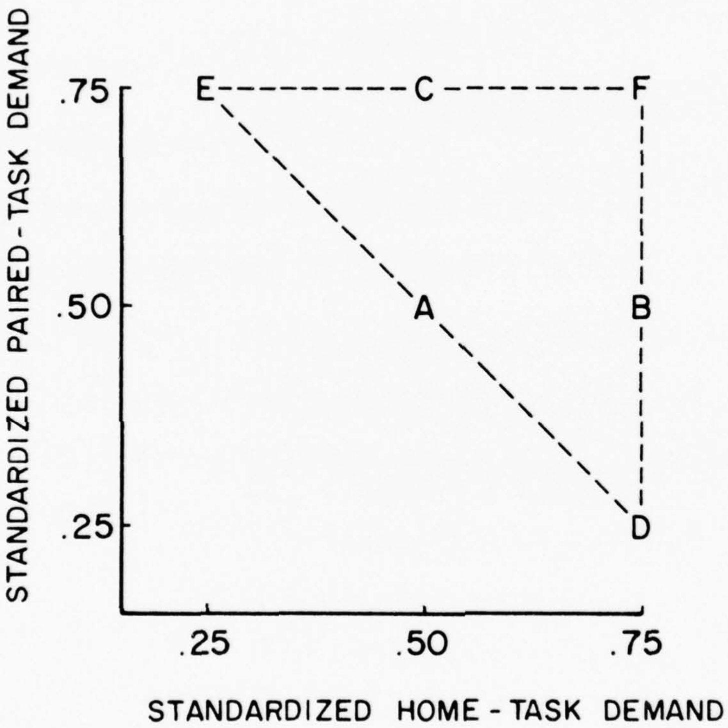

Figure 7. Performance comparisons in Phase Three between conditions E-C-F, D-B-F, and E-A-D.

TABLE 7

Performance under Changing Demands
with Tracking as the Home Task

Standardized Demand			
Home (X_h)	Pair (X_p)	Home-Task Performance	Paired-Task Performance
		Tracking as the Paired Task	
		(Mean RMS error)	(Mean RMS error)
.25	.75	28.0	20.0
.50	.50	20.9	20.7
.75	.25	20.5	26.2
.50	.75	24.9	22.0
.75	.50	20.9	23.1
.75	.75	24.7	23.9
		Immediate Cancelling as the Paired Task	
		(Mean RMS error)	(Mean CRI)
.25	.75	24.9	.84
.50	.50	24.2	.84
.75	.25	22.5	.86
.50	.75	24.2	.81
.75	.50	22.5	.85
.75	.75	23.6	.83
		Delayed Cancelling as the Paired Task	
		(Mean RMS error)	(Mean CRI)
.25	.75	22.7	1.46
.50	.50	22.8	1.55
.75	.25	22.8	1.56
.50	.75	23.7	1.50
.75	.50	22.1	1.49
.75	.75	21.9	1.50
		Classification as the Paired Task	
		(Mean RMS error)	(Mean CRI)
.25	.75	22.1	1.10
.50	.50	21.5	1.11
.75	.25	20.6	1.15
.50	.75	21.5	1.11
.75	.50	19.4	1.13
.75	.75	20.6	1.12

TABLE 8

Performance under Changing Demands
with Immediate Cancelling as the Home Task

Standardized Demand Home (X_h)	Standardized Demand Pair (X_p)	Home-Task Performance	Paired-Task Performance
		Tracking as the Paired Task	
		(Mean CRI)	(Mean RMS error)
.25	.75	.96	22.7
.50	.50	.95	22.8
.75	.25	.86	26.1
.50	.75	.93	24.6
.75	.50	.87	29.4
.75	.75	.89	26.5
		Immediate Cancelling as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	1.69	1.33
.50	.50	1.47	1.43
.75	.25	1.32	1.49
.50	.75	1.49	1.35
.75	.50	1.32	1.54
.75	.75	1.45	1.50
		Delayed Cancelling as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	2.49	2.04
.50	.50	2.17	2.21
.75	.25	1.93	2.38
.50	.75	2.64	2.11
.75	.50	2.06	2.36
.75	.75	2.14	2.12
		Classification as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	1.88	1.73
.50	.50	1.76	1.83
.75	.25	1.62	1.84
.50	.75	1.79	1.67
.75	.50	1.75	1.94
.75	.75	1.78	1.75

TABLE 9

Performance under Changing Demands with Delayed Cancelling as the Home Task

Standardized Demand		Home-Task Performance	Paired-Task Performance
Home (X_h)	Pair (X_p)		
		Tracking as the Paired Task	
		(Mean CRI)	(Mean RMS error)
.25	.75	1.37	37.1
.50	.50	1.38	36.5
.75	.25	1.31	39.8
.50	.75	1.41	35.6
.75	.50	1.30	39.5
.75	.75	1.34	37.0
		Immediate Cancelling as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	2.35	1.61
.50	.50	1.89	1.87
.75	.25	1.76	2.20
.50	.75	2.05	1.67
.75	.50	1.82	2.14
.75	.75	1.98	1.87
		Delayed Cancelling as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	2.93	2.08
.50	.50	2.51	2.21
.75	.25	2.27	2.80
.50	.75	2.82	2.21
.75	.50	2.14	2.56
.75	.75	2.63	2.39
		Classification as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	2.20	2.03
.50	.50	1.92	2.26
.75	.25	1.96	2.79
.50	.75	2.24	1.64
.75	.50	2.18	1.90
.75	.75	2.21	1.78

TABLE 10

Performance under Changing Demands with Classification as the Home Task

Standardized Demand			
Home (X_h)	Pair (X_p)	Home-Task Performance	Paired-Task Performance
		Tracking as the Paired Task	
		(Mean CRI)	(Mean RMS error)
.25	.75	1.20	23.8
.50	.50	1.11	25.0
.75	.25	1.09	26.0
.50	.75	1.17	23.9
.75	.50	1.13	27.4
.75	.75	1.15	25.1
		Immediate Cancelling as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	1.75	1.44
.50	.50	1.57	1.52
.75	.25	1.49	2.17
.50	.75	1.63	1.45
.75	.50	1.56	1.74
.75	.75	1.57	1.46
		Delayed Cancelling as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	2.51	1.92
.50	.50	2.61	2.30
.75	.25	2.29	2.35
.50	.75	2.26	2.29
.75	.50	2.46	2.50
.75	.75	2.50	2.23
		Classification as the Paired Task	
		(Mean CRI)	(Mean CRI)
.25	.75	2.19	1.90
.50	.50	2.08	1.88
.75	.25	2.07	1.88
.50	.75	2.15	2.04
.75	.50	2.06	2.07
.75	.75	2.09	1.88

TABLE 11

Standardized Regression Weights (β) and Coefficients (R) for Phase Three Performance Prediction

	HOME TASK											
	Tracking			Immediate Cancelling			Delayed Cancelling			Classification		
	REGRESSION MEASURES											
TASK	β_h	β_p	R	β_h	β_p	R	β_h	β_p	R	β_h	β_p	R
Tracking as the Paired Task												
Home	-.29	+.73	.92	-.84*	+.15	.92	-.76	+.19	.87	-.31	+.74	.94*
Paired	+.83	-.10	.89	+.81	+.01	.80	+.49	-.36	.74	+.49	-.51	.87
Immediate Cancelling as the Paired Task												
Home	-.71	+.39	.97	-.76*	+.33	.97*	-.72*	+.39	.97*	-.67*	+.43	.96*
Paired	-.12	-.86	.80	+.87*	-.13	.95*	+.55*	-.58*	.98*	+.16	-.85*	.94*
Delayed Cancelling as the Paired Task												
Home	-.59	+.23	.52	-.51	+.56	.92*	-.59	+.50	.95*	-.29	+.12	.37
Paired	+.09	-.73	.78	+.44	-.70*	.97*	+.51	-.56	.93	+.05	-.14	.17
Classification as the Paired Task												
Home	-.09	+.82	.88	-.39	+.65	.91	+.11	+.94*	.89	-.99*	-.22	.90
Paired	+.57	-.50	.95*	+.21	-.60	.74	+.35*	-.77*	.99*	-.34	+.24	.30

*Reliable at $p < .05$ level.

where $\hat{P}$ is a standardized predicted performance score, β_h is the standardized regression weight for home-task demand, β_p the standardized regression weight for the paired-task demand, and X_h and X_p are the standardized task demands.

The β_h and β_p scores are the important products of this regression analysis, because they are estimators of the impact that the demands of each task had on actual performance. A higher weighting indicates higher impact on performance. Negative weights indicate improvement in performance (lower RMS error scores or CRIs) and positive weights indicate performance decrements.

Results of the analyses of variance and regression are discussed below and are organized into three major types of pairing situations: Tracking paired with Tracking, Tracking paired with Keyboard tasks, and Keyboard tasks paired with other Keyboard tasks.

Tracking Paired with Home-Task Tracking

Within the Phase Three Tracking/Tracking conditions that had a combined task demand of 1.00 (conditions E, A, and D), performance on home-task Tracking showed reliable improvement in RMS error when the demand on the home task was raised from .25 to .50 but no further performance improvement when the demand was raised from .50 to .75. The performance of the paired Tracking task demonstrated this same pattern, although the difference between conditions was not reliable ($p > .05 < .10$).

When home-task Tracking demand was held at a constant level of .75 and the paired-task Tracking demand varied, a reliable change occurred in the home-task Tracking performance. RMS error, WSD, and proportion scores improved reliably when the demand on paired-task Tracking was reduced from .75 to .50, although no further improvement was shown when the demand was reduced to .25. A similar result was found for paired-task Tracking performance when the demand was held at .75 and the home-task demand was varied. Paired-task Tracking RMS error and proportion scores improved reliably when the home-task demand was reduced from .75 to .50, and a similar improvement occurred when the demand was reduced to .25 on the home-task.

The results of the regrssion analysis agree favorably with the above findings. For each task, a high positive weight was found for the strength of the opposing task demand, while the tasks' own demands did not appear to affect their performance; as the demand on one tracking task is reduced, the other benefits. High demands on both tracking tasks, (.75/.75) lowers performance efficiency on both tasks, and the best performance was observed under the .50/.50 demand condition, a realistic and readily attainable requirement.

Tracking Paired with Keyboard Tasks

Immediate Cancelling paired with home-task Tracking. When Tracking demand was increased in the three conditions with a combined workload of 1.00 (conditions E, A, and D) an improvement was found in RMS error, WSD, and proportion scores. This improvement approached reliability ($p > .05 < .10$). The performance of Immediate Cancelling was not reliably different over these three conditions. Neither task showed reliable differences over conditions B, D, and F, or E, C, and F.

The regression analysis on the six condition means for Tracking RMS error was consistent with the above results. The regression weight for the effect of Tracking demand on RMS error was reliable and negative, indicating improvement with increased demand on its own task. The regression weights for Immediate Cancelling CRI mean performances indicated a large, but not reliable, negative weight for the effect of its own demand on performance. In light of the fact that the analyses of variance on CRI performances showed no reliable change, it is speculative to infer that Keyboard-task priority had any actual effect on performance.

Delayed Cancelling paired with home-task Tracking. No reliable differences between condition means on Tracking or Delayed Cancelling performances were observed for this task combination. Thus, it appears that the combination of Tracking with the short-term STORING task is not conducive to performance adjustment in accordance with increasing or decreasing task demands.

Classification paired with home-task Tracking. Tracking errors and proportion scores differed reliably when the Tracking demand was held at .75 and the Classification demand was varied. Tracking performance decreased when the Classification demand was raised to .75 from .50 and .25, which produced about the same levels of Tracking performance. Tracking performance on the three conditions with combined demand of 1.00 showed variations generally responsive to changing demands, but the differences were not reliable for any of the dependent measures. Classification performance was not reliably affected by changes in task demands for either.

The regression analysis for Tracking was consistent with the analysis of variance as indicated by the high, positive weight for the influence of Classification task demand on Tracking performance. The overall regression equation for Classification performance was also reliable, but the individual condition comparisons were not. Although the influence of changing task priorities was suggested by the negative weight for Classification and the positive weight for Tracking demand, the range of the Classification means across the six conditions was small (1.11 seconds to 1.15 seconds) and might easily be due to chance rather than changing priorities.

Tracking paired with home-task Immediate Cancelling. Immediate Cancelling performance showed reliable changes in RI ($p < .05$) and barely not reliable changes in proportion scores ($p > .05 < .10$) with changes in combined task demands. The performance improvement was in the direction called for showing superior performance in the .75 demand condition and about equal performances in the .25 and .50 demand conditions. The other comparisons between conditions for Immediate Cancelling performance were not reliable. For Tracking, performances in the three conditions with a 1.00 combined demand did not differ reliably, but the means decreased in the expected direction, with the .25 demand showing the highest RMS error and the .50 and .75 lower levels of error.

The comparison across conditions in which Tracking demand was held at .75 and Immediate Cancelling demand was varied showed reliable increases in RMS errors and decreases in proportion scores when the priority on Immediate Cancelling was raised from .25 to .50 to .75. Regression analyses for this dual-task combination support these findings, as indicated by the large negative weight for the influence of Immediate Cancelling demand on its performance, and also a large positive weight for the influence of Immediate Cancelling demand on Tracking performance. The influence of Tracking demand levels was almost zero for both tasks.

These findings are consistent with those for the identical task pairing in the Tracking home-task group in that a large regression weight was obtained for the influence of Immediate Cancelling demands on its own performance, whereas Tracking performance was dominated by home-task demands, whatever the home task might be. Thus it appears that Immediate Cancelling performance is relatively independent of Tracking demand levels, whereas Tracking performance is influenced mainly by home-task demands whether or not it is the home task.

Tracking paired with home-task Delayed Cancelling. This dual-task pairing also showed no reliable difference for any experimental combination of demands on the two tasks, although there was a trend toward a decrease in Tracking efficiency at the reduced demand of .25 relative to the .50 and .75 demand levels when the combined demands were 1.00. Although the .25 demand on Tracking produced the best Delayed Cancelling performance in RI and CRI, compared to the .50 and .75 demand levels, the differences were not statistically reliable. The regression analysis did not show reliability for overall regression or for individual weights, although the weight for Delayed Cancelling performance was negative, indicating some degree of control by its own task demands.

Tracking paried with home-task Classification. Classification performance in the three 1.00 combined-demand conditions was affected by changing task demands (RI, $p < .05$; CRI, $p > .05 < .10$; and proportion, $p > .05 < .10$). No other condition comparison showed a reliable change in performance of either task. However, the regression analysis indicated that Classification was more strongly affected by Tracking demands than by its own demands and that Tracking was about equally affected by the demands of the two tasks, although these regression weights were not reliable.

Keyboard/Keyboard Conditions

Immediate Cancelling with home-task Immediate Cancelling. The task pairing of Immediate Cancelling with itself produced reliable changes in home-task performances (RI, $p < .05$; CRI, $p < .05$; and proportions, $p < .01$) across the three conditions in which the combined demand was 1.00. Differences in performance were in the expected direction with respect to demands. Home-task Immediate Cancelling performance was also reliably affected (CRI, $p < .05$; proportions, $p < .05$) by changing its own demand in the three conditions in which the paired-task demand was .75. This improvement in performance as demand was raised in these three conditions was accompanied by a decrease in the RI and CRI performance of the paired task approaching reliability ($p < .05 < .10$ for both). Thus, it appears that Immediate Cancelling as the home-task was considered the more important task by subjects whose responsiveness to changing home-task demands affected their performance of the paired Immediate Cancelling task as well.

The regression analysis on the means of the six conditions showed strong agreement with the above results. The highest regression weights were found for the home-task demand for predicting performance of both tasks. These weights indicate that improvement in home-task Immediate

Cancelling may be expected when demands on that task are raised (large negative weight), while raising home-task demands also causes a decrease in paired-task performance (large positive weight).

These findings suggest that the demands of the more practiced home-task dominated the overall dual-task performance level of subjects. Phase Two data on individual subject strategies revealed that there were individual differences in response strategy. Some subjects preferred segmented operation on the two tasks, while others operated in an alternating pattern. The unequal demand conditions present the subject with the task of distributing his responses to each task such that the individual task demands are met. The conditions with equal task demand are best suited to the alternating strategy which assures equality of response intervals to the two tasks. The unequal priority conditions, however, are not well suited to this strategy and are better handled by the segmented approach.

The latter approach allows the subject to make a different number of responses to each task in series according to task demands. Segmental responders merely varied the number of responses per sequence on each task, leaving one task once the bar graph reached the height of the desired performance line and switching to the other. Subjects who adopted the alternating strategy occasionally inserted more than one response per alternation, generally making two or more responses to the task with higher priority before making another response to the less demanding task.

The data from the Immediate Cancelling/Immediate Cancelling task combination indicate that subjects generally preferred to make a sufficient number of responses to the home-task to match the performance demand and apply their remaining attention to the paired task. As the home-task demand increased, the time allocated to the other task decreased, and hence, performance suffered. The two Immediate Cancelling tasks, therefore, do not appear to be performed independently of each other.

Delayed Cancelling paired with home-task Immediate Cancelling. Manipulation of Immediate Cancelling demands reliably affected its own performance in the three conditions with a combined demand of 1.00 (RI, $p < .05$; CRI, $p < .05$; proportion score, $p = .06$). The Delayed Cancelling task also showed reliable changes in performance over these three conditions (RI, $p < .05$; proportion, $p < .05$). None of the other conditional comparisons elicited reliable changes in performance with changing demands.

The regression analysis showed that Immediate Cancelling performance was influenced about equally by the demands of both tasks. Delayed Cancelling performance was strongly controlled by its own demands (large negative weight) and influenced little by the Immediate Cancelling demands. Thus, it appears that Delayed Cancelling demands influence performance more than Immediate Cancelling demands, and subjects appear to set performance levels on both tasks according to Delayed Cancelling demand levels.

Classification paired with home-task Immediate Cancelling. The performance of the Immediate Cancelling task in this task combination showed reliable changes with changes in demand over the three 1.00 combined-demand conditions (RI, CRI, and proportions $p < .05$). None of the other conditional comparisons produced reliable changes in the performance of either task. The overall regression analysis showed that Immediate Cancelling was affected more by the Classification demand than by its own demands, although support for this dominance is weak in light of the low and non-reliable regression coefficients. Classification performance appears to be somewhat affected by its own task demands; however, the overall effect of regression was not reliable. From these data, it is indeterminate whether the manipulation of task demands between Immediate Cancelling and Classification influenced performance on either task.

Immediate Cancelling paired with home-task Delayed Cancelling. Performance demand changes were generally effective in manipulating performance of both the Delayed and Immediate Cancelling tasks in this dual-task combination. Delayed Cancelling performance was increased by raising demands in the three 1.00 combined-demand conditions (RI, $p < .05$; CRI, $p = .06$, and proportion, $p = .05$), and Immediate Cancelling was improved by raising its demand (RI, $p < .01$; CRI, $p < .05$; proportions, $p < .05$). In addition to these changes in performance, Immediate Cancelling proportion scores were sensitive to changes of its own demands across the three conditions which had a constant .75 demand on Delayed Cancelling ($p < .05$).

The overall regression analysis was supportive of these findings in that Delayed Cancelling demand had a much stronger influence on its own performance (high reliable negative weight) than did Immediate Cancelling demand. The weights for determining Delayed Cancelling performance showed equally strong effects on performance by the demands of each task. These regression weights are consistent with the regression analysis results for the home-task Immediate Cancelling combination in which Delayed Cancelling was the paired task.

The effectiveness of desired performance manipulation in both cases may be due primarily to the selection of the segmented response strategy, which was chosen by nearly all subjects. As previously mentioned, this strategy is well suited to unequal priority situations, because subjects can merely adjust the number of responses per segment to achieve the desired performance levels.

Delayed Cancelling paired with home-task Delayed Cancelling. The combination of Delayed Cancelling tasks also produced reliable changes in performance for both tasks in the 1.0 combined-demand conditions. For home-task performance, this finding was reflected in RI ($p < .01$) and CRI ($p < .05$) scores and in RI ($p < .05$), CRI ($p < .01$), and proportions ($p < .01$) scores for the paired task. Differences between conditions were only reliable across the 1.00 combined-demand conditions, although the means in Table 10 indicate a decrease in performance efficiency in both tasks when the demand on the opposing task is increased. This indication is supported by the regression analysis which showed about equal influence for the demands of both tasks. Again, this dual-task combination was one in which subjects chose the segmented response strategy.

Classification paired with home-task Delayed Cancelling. No reliable performance effects were found for this task combinations over the six Phase Three conditions involving Delayed Cancelling. A trend toward improved performance on Classification occurred in the 1.00 combined-demand conditions (RI, $p < .01$; CRI, $p = .11$, proportions $p = .07$). The accompanying regression analysis indicated that Delayed Cancelling was controlled by the demands on the Classification task (large positive weight) and not by its own demand. Classification performance was controlled mainly by its own demand levels and to a lesser degree by the demands on Delayed Cancelling, although both weights were reliable in the regression analysis.

Immediate Cancelling paired with home-task Classification. Home-task Classification performance improved with increasing demand in the three 1.00 combined-demand conditions (RI, $p < .05$; CRI, $p < .05$; proportions, $p < .05$) and across the three conditions in which Immediate Cancelling demand was a constant .75 (RI, $p = .07$; CRI, $p = .08$). Immediate Cancelling performance also showed an improving trend with increasing demand in the 1.00 combined-demand conditions (RI, $p = .12$; CRI, $p = .15$; proportions $p < .05$), and proportion scores increased reliably with increased demand in the conditions in which Classification demand was a constant .75 ($p < .05$).

The regression weights for prediction of Classification performance showed that Classification demands had a stronger influence on performance than Immediate Cancelling demands, although the regression weights are both relatively large. The regression analysis on Immediate Cancelling indicated that performance was almost completely determined by its own task demand (large negative weight). The effective manipulation of Immediate Cancelling in this task combination is consistent with the results in the analogous home-task Immediate Cancelling condition, and the regression weights indicating that Classification demands influenced Classification performance more than Immediate Cancelling demands is also consistent with the direction and magnitude of the regression weights in that task combination.

Delayed Cancelling paired with home-task Classification. Only the performance of the paired task, Delayed Cancelling, was affected by changing demand, and this was over the three 1.0 combined-demand conditions. This change approached reliability (RI, $p = .09$; proportions, $p = .08$). The only other comparisons showing trends in performance change were in the three conditions in which the Delayed Cancelling demand was .75 and Classification demand was varied (Classification proportion scores, $p = .07$; Delayed Cancelling proportion scores, $p = .08$). The regression analysis did not show reliability of individual regression weights or overall regression. The results above are inconsistent with results of the analogous task combinations in which these two tasks were paired, which showed strong domination by the Classification task demand levels on the performance of both tasks.

Classification paired with home-task Classification. The comparison between means for home and paired Classification tasks did not show reliable performance changes in accordance with increasing or decreasing demands, although the CRI means for home-task performances show changes in the expected direction over the three 1.00 combined-demand conditions and across increasing demands in the three conditions in which the paired task demand was a constant .75. Consistent with the direction of these means, the regression weight related to the impact of home-task demand on home-task performance was reliable (high negative weight). None of the other terms in the regression equations was reliable for either task.

CONCLUSIONS

The equal-demand trials in Phase Two provide the basis for several generalizations relating the functional components presented in the descriptive model to dual-task interference:

1. A major factor in determining the extent of interference between tasks is the similarity of their functional components; qualitatively different tasks will be performed better in combination than tasks with similar functional requirements.

2. The functions of STORING and TRANSFORMING, present in Delayed Cancelling and Classification respectively, have the following interference characteristics:

   a) The requirement to store, retrieve, and make manual keyboard responses based on retrieved items is highly disruptive of similarly arranged discrete response tasks with or without the additional requirement to store; such tasks cannot be interwoven with themselves or with other discrete response tasks.

   b) The type of TRANSFORMING required in Classification does not prohibit interweaving with other Keyboard response tasks and is not so generally disruptive as storing.

   c) Neither TRANSFORMING in Classification nor STORING in Delayed Cancelling appears more disruptive of a functionally dissimilar task, Tracking, than the simple Immediate Cancelling task without these intervening functions; none of the three Keyboard tasks seriously interferes with Tracking.

d) The first generalization above, that functionally similar tasks should interfere more than dissimilar ones, is not inconsistent with the finding that two TRANSFORMING tasks, Tracking and Classification, were performed with little mutual interference, because the TRANSFORMING activities in these tasks are distinctly different.

Table 12, a composite of the combined scores from Phase Two second trials, substantiates the above generalizations. In this table the paired tasks are represented by rows and the home tasks by the columns. When Tracking was the home task, a second Tracking task caused greater interference with home-task performance than did any of the three Keyboard tasks when paired with Tracking. Similarly, for each home Keyboard task, Tracking interfered least. The nine Keyboard/Keyboard combinations had the lowest combined scores, and all were near or below 1.00.

Furthermore, Delayed Cancelling, when paired with each Keyboard task, consistently produced the lowest combined scores (0.83, 0.88, and 0.81 when paired with Immediate Cancelling, Classification, and Delayed Cancelling, respectively.) Thus, the ordinal scaling of interference in this study indicates Tracking paired with Keyboard tasks to be the least interfering, Tracking paired with Tracking to be moderately interfering, and the combination of two Keyboard tasks to be the most interfering, with the additional contingency that if STORING is included in the Keyboard/Keyboard pair, there will be further interference.

The initial generalization, that functionally similar tasks are more prone to interference than dissimilar ones, appears somewhat

TABLE 12

Phase Two Second Trial Combined Scores for All Experimental Conditions

	HOME TASK				
PAIRED TASK	Tracking	Immediate Cancelling	Classification	Delayed Cancelling	$\overline{X}$
Tracking	1.37	1.52	1.60	1.33	
Immediate Cancelling	1.69	0.98	1.04	0.97	1.00
Classification	1.76	1.01	0.97	1.01	1.00
Delayed Cancelling	1.70	0.83	0.88	0.81	0.84
$\overline{X}$		0.94	0.96	0.93	

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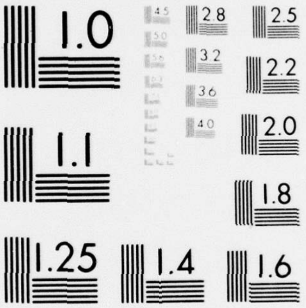

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contradictory to the evidence cited that Tracking and Classification, both requiring TRANSFORMING, are performed well together. It is appropriate, therefore, to re-examine the initial descriptive model and make a more formal distinction between the various kinds of activities that could be included in TRANSFORMING. Clearly, Tracking and Classification, as stated in the introductory section, involve transformations of stimuli prior to MANIPULATING; however, the transformations in these two tasks are mathematically different.

Tracking requires the application of differentiation and integration to convert continuous, dynamic error indications into corrective movements. Classification, on the other hand, requires transformation of a simpler sort, namely, an iterative,discrete, bi-dimensional categorization based on similarities and differences in the digit pair. Figure 8 presents a revised version of the descriptive task model showing the TRANSFORMING function as one that can include different possible TRANSFORMING rules.

The manipulation of task demands had reliable effects on performances in many of the experimental conditions, and changes were generally in expected directions in remaining cases. The absence of consistent agreement in the strength of effects across identical conditions makes it difficult to draw solid conclusions relating functional components to ability to adjust performance. Several cases are of special interest, however.

Combining two Tracking tasks showed a symmetric effect of demands on performance of both tasks. Both tasks suffered when demands were unreasonably high on each, namely calling for the 75th percentile of

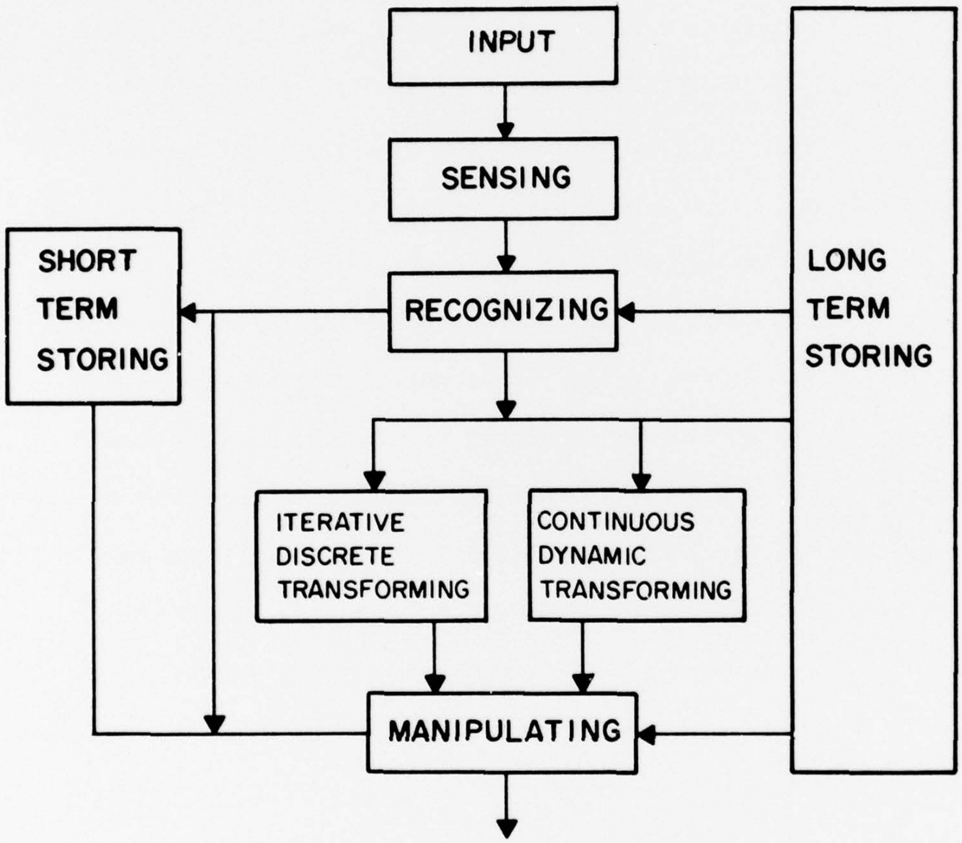

Figure 8. Revised model of functional task components.

previous performance. Both tasks also showed increases in efficiency when demands were decreased on the opposing task.

There were two Tracking/Keyboard task combinations producing consistent results between identical conditions: Tracking/Immediate Cancelling and Tracking/Delayed Cancelling. In both cases, the Keyboard task showed strong resistence to influence by Tracking task demands, and was generally controlled by demands of its own task. This result is in agreement with the findings of Gopher and North (1974) with the same tracking task and a similar digit processing task, and using the same technique to manipulate demands.

Adherence to demands in Keyboard/Keyboard combinations proved to be strongly related to response strategy. The task combinations that showed the best overall adjustment of performance with changing demands were those in which subjects generally responded segmentally rather than alternately. If the task demands called for more responses per time unit to one task than the other, segmented strategy choosers had only to vary the number of responses per segment to approximate the requirements for each task. Because the number of segmented responders in task combinations that included Delayed Cancelling, these conditions showed strong adherence to differential demands.

Thus, although a task with a STORING component is difficult to interweave with itself or with another self-paced discrete reaction task, it is amenable to adjustment to different performance levels because of the prevailing response strategy. In the four task combinations in which subjects tended to make alternating responses (Immediate

Cancelling and Classification paired with themselves and with each other), the manipulation of demands was less effective. The alternating strategy is not conducive to adjusting performance because it tends to produce equal numbers of responses to each task.

The implication of this study for those concerned with design of systems that engage the human operator in multiple tasks is that qualitatively different tasks will be performed together more efficiently than qualitatively similar tasks. Furthermore, the task of continually storing and retrieving items from short-term memory is extremely demanding and highly disruptive of similar tasks, and consequently the operator should not be expected to interweave such tasks efficiently.

The substantial individual differences in retention of single-task performance levels in dual-task situations, in choice of response strategy for concurrent keyboard tasks, and in compliance with changing task demands may constitute a valid basis for operator selection for multi-task situations, such as flight operations.

There was also substantial dual-task improvement from Trial 1 to Trial 2 in Phase Two and continued improvement in Phase Three. Although the goals of the present study did not include an identification of the sources of this improvement, it is acknowledged that isolation of improvement factors is an important direction for future research.

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APPENDIX A

DESCRIPTION OF TRACKING TASK FORCING FUNCTION

Figure A-1 presents a distribution of frequency of occurrence for a sample of 5000 forcing function values. The points in the figure were grouped in intervals of .01 of the maximum amplitude of the control stick input. As indicated by this distribution, the majority of the forcing function values are in the range of 10% maximum control input with extreme values as high as 30% of the control input. This amplitude distribution together with the relatively low cutoff point for forcing function frequency (.3 Hz) presents the subject with a tracking task of moderate difficulty.

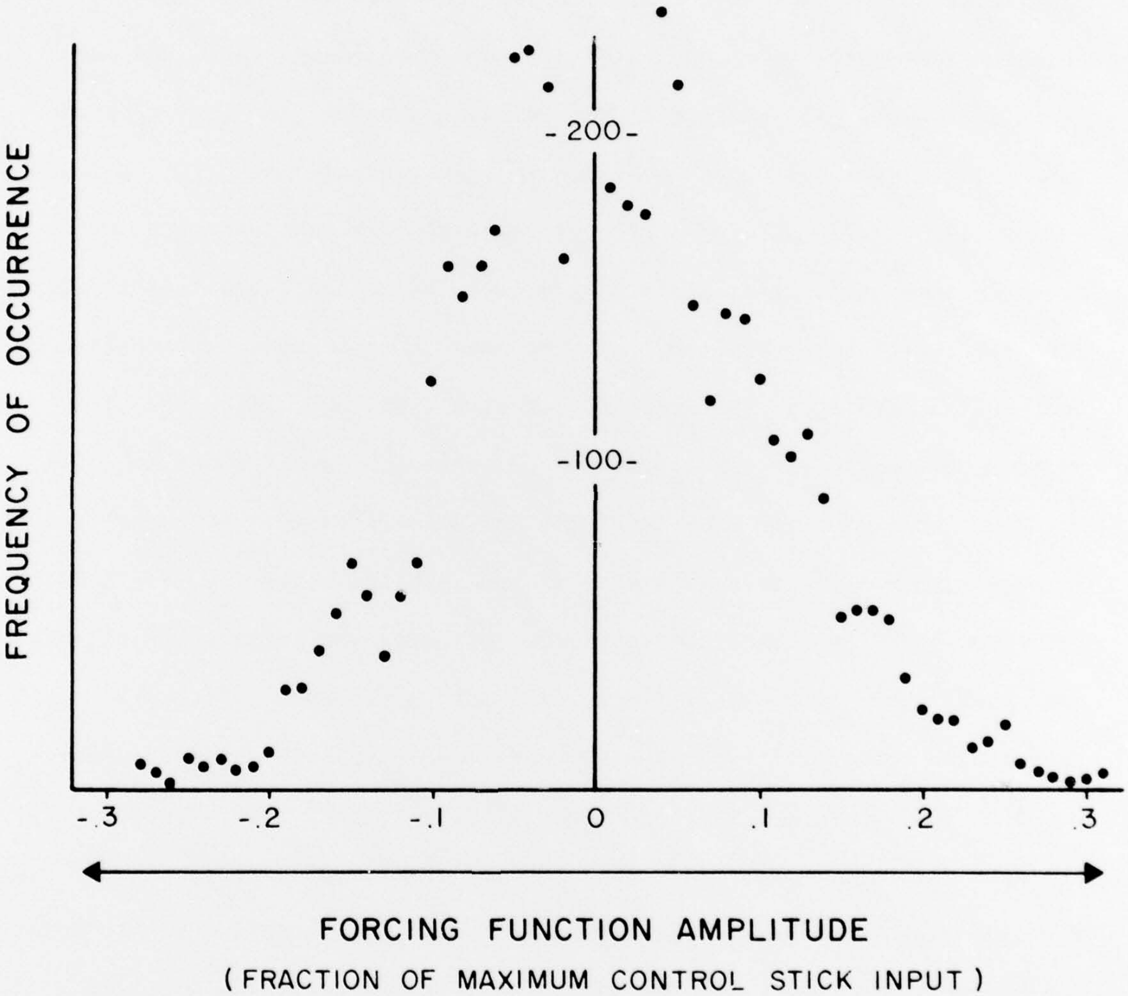

Figure A-1. Frequency of occurrence of forcing function amplitude values. (A sample of 5000 values.)

APPENDIX B

ADAPTIVE ADJUSTMENT OF CONTROL STICK DYNAMICS

The adaptive variable selected for the adjustment of tracking difficulty in single-task performance was the ratio of acceleration to velocity components in the dynamics of the manual controller. The basic equation for the manipulation of this variable was originally suggested by Ince and Williges (1974) and utilized in adaptive training by Crooks and Roscoe (1973). Increase of acceleration percentage in the control stick dynamics imposes increasing tracking difficulty on the subject in an adaptive manipulation of this variable, the percentage acceleration is increased or decreased according to the error output of the subject. The present experiment used an error tolerance of 10 percent of scale absolute error which was sampled in 60 msec intervals and integrated over a one sec. period. Acceleration was increased one step if the absolute error was less than or equal to the 10 percent error tolerance, or decreased one step if the error was greater than this value. (Step size was .1 percent). Figure B-1 presents an example of typical subject data showing both the error output and the corresponding curve for the adaptive variable. The figure presents the data for both the adaptive training and the fixed-level periods of Phase 1 single-task performance. As Figure B-1 shows, the adaptive variable increased rapidly for this subject during the first two minutes of the adaptive period and stabilized at the level of 77.5 percent acceleration with slight deviation above and below this value during the rest of the period. The value of 77.5 percent acceleration represented the fixed level of this subject during the last two minutes of tracking in this phase and determined the control dynamics for Phase 2 and 3.

In preliminary testing the four-minute period of adaptive manipulation was sufficient to adjusting subjects to a stabilized level of performance on the tracking task. The average time for a subject to reach his final acceleration level was 2.7 minutes or about two-thirds of the total adaptive period.

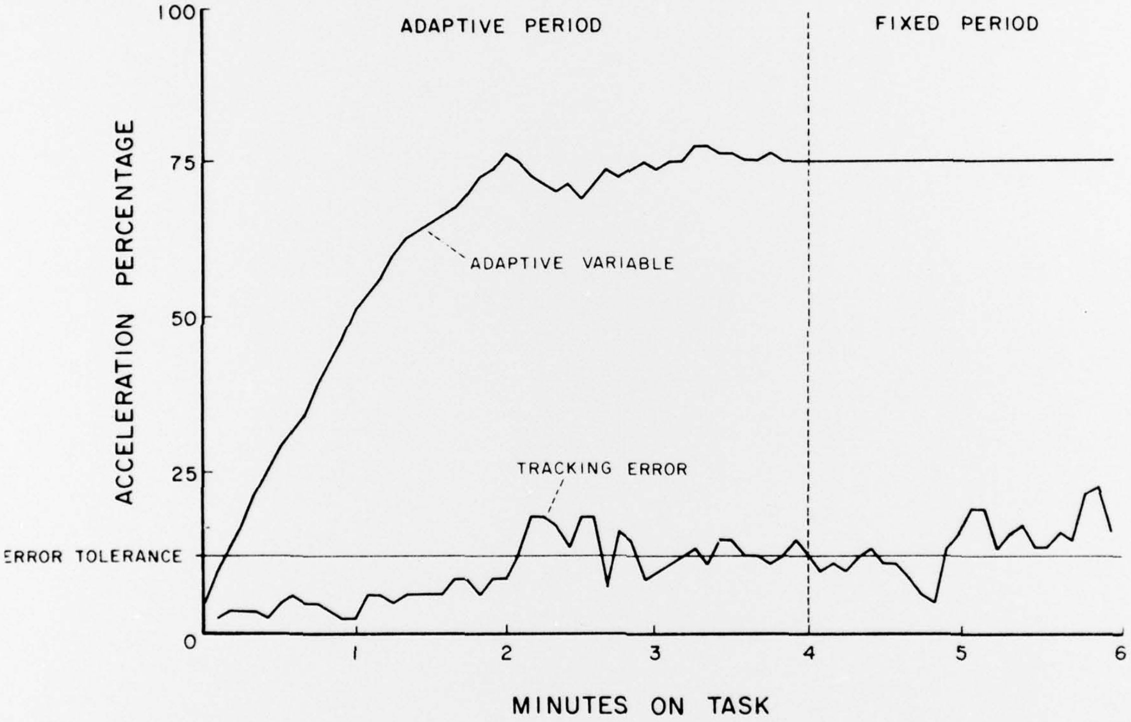

Figure B-1. An example of subject's tracking performance with adaptive adjustment of control stick acceleration in Phase 1, single-task performance.

APPENDIX C

TIME SCORE CONVERSION OF TRACKING ERROR SCORES

Figure C-1 presents two mathematical functions for acceleration control and rate control dynamics which describe the relation between instantaneous scale error and the time required to null this error. The figure presents the function for a pure rate control (0 percent) vs. pure acceleration (100 percent) control with a full deflection of the stick left or right. For example, a correction of 15 mm. error (about 50 percent of the display) in the pure rate controller will require 600 msec. with a full deflection of the stick, while the correction of the same error will require 950 msec. with the acceleration controller. The time to correct a similar error with any intermediate percentage of acceleration will be between these two values.

With an acceleration controller, therefore, the time-distance relation is non-linear with the maximum deviation from linearity in the medium values. Because the effectivity and control dynamics of the stick are not the same for different values of acceleration, a comparison of tracking performance between subjects requires an appropriate correction. It is suggested that an adequate correction for this purpose is the time score equivalent of the subject's raw average RMS error, which represents the average minimum time required in this specific configuration to null errors.

The equation used for this time score conversion RMS error was:

$$t = 1.2\varepsilon(1-\alpha) + \sqrt{1.3\ \varepsilon . \alpha}$$

where ε is the average error score, α is the percentage of acceleration attained in Phase 1, and t is the resulting time score in seconds. This equation was derived from the specific control gain values that were employed in the present experiment, the size of the display, and the adaptive equation which determined the relative contribution of first- and second-order terms for each level of the adaptive variable. Note that because the level of acceleration was fixed, for the last two minutes of Phase 1, and maintained at that value in Phases 2 and 3, different time scores obtained for a certain subject are effected only by his tracking error. Time scores for each subject in the dual-task situation were compared to his time score in the single-task condition, and tracking performance was evaluated as a percentage difference between these scores.

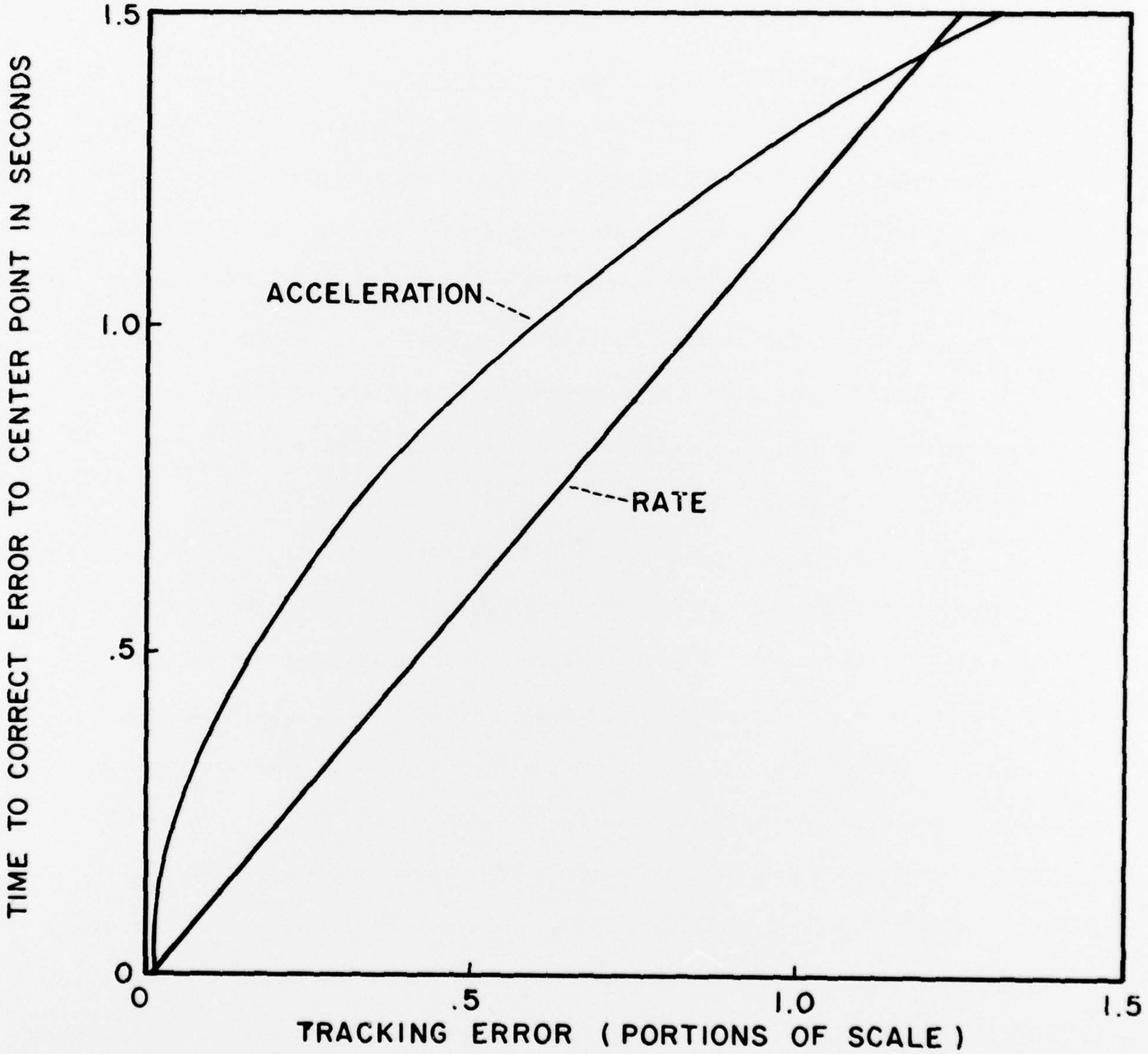

Figure C-1. Distance-time relation between rate and acceleration maximum control output as a function of momentary error magnitude.

APPENDIX D

INSTRUCTIONS TO SUBJECTS

Single-Task Performance: Phase One

Tracking. This task requires you to keep the circle centered within the horizontal track by making appropriate left-right movements of the hand control. Moving the control to the left moves the circle left while moving the control right moves the circle right. There will be random deviations of the circle continuously throughout the performance trial, and you should respond to these deviations as quickly as possible by appropriate movement of the hand control to center the circle on the vertical line. Are there any questions?

Immediate Digit Cancelling. This task requires you to cancel visually presented digits by making the appropriate keyboard response corresponding to the digit shown. The digits will be randomly chosen from the set 1, 2, 3, and 4 (5, 6, 7, and 8). The keys are numbered from left to right 1, 2, 3, and 4 (5, 6, 7, and 8). As soon as you respond to the digit with the correct key, a new digit will be presented. You should work as quickly and accurately as you can on the task. Are there any questions?

Delayed Digit Cancelling. This task requires you to cancel visually presented digits by making the appropriate keyboard response corresponding to the digit previously shown in the sequence. The digits will be randomly chosen from the set 1, 3, 4, and 4 (5, 6, 7, and 8). The keys are numbered 1, 3, 4, and 4 (5, 6, 7, and 8) from left to right. As soon as you respond to the previously shown digit with the correct key, a new digit will be presented. The first digit in the sequence can be cancelled by pressing the leftmost key which will get you started on the task. Succeeding correct responses will correspond to the digit one-back in the sequence. You should work as quickly and accurately as you can on the task. Are there any questions?

Classification. This task requires you to classify digit pairs into one of three categories each of which corresponds to one of the keys on the keyboard. Categorization will be based on two dimensions: the size of the digits and their numerical names. The pair may be different in both these dimensions, different in one dimension, or the same in both. There are two sizes of digits and four possible numerical names chosen from the set 1, 2, 3, and 4 (5, 6, 7, and 8). If the digit pair is the same in both size and name, press the left key. If the pair is either different in size and same in name, or different in name and same in size, press the middle key. If the pair is different in both size and name, press the right key. (Examples of each type shown to subject.) When you correctly classify each digit pair, a new pair will be shown. You should work as quickly and accurately as you can on the task. Are there any questions?

Dual-Task Performance with Equal Demands: Phase Two

In the next portion of the experiment you will perform the tasks together. The display will include both tasks as shown in the diagram. (Appropriate diagram shown to subject, similar to Figure 4 examples.) In addition, the display will give you information on how well you are performing each task represented by the height of the two bar graphs, one for the left task's performance and one for the right. The momentary height represents your average performance over the last few seconds. There will also be a short horizontal line for each task corresponding to a desired performance level which you should attempt to reach and maintain with the two bar graphs. Note that the height of the desired line is the same for both tasks, indicating that the tasks are of equal importance.

(Following given to subjects in Keyboard conditions.)

In performance of the keyboard task there will be three instances causing a new item to be presented: (1) pressing the correct key, (2) pressing an incorrect key, and (3) exceeding the allotted time for that item. Are there any questions?

Dual-Task Performance with Equal and Unequal Demands: Phase Three

During the next portion of dual-task performance you will recieve trials with both equal and unequal desired performance levels on the two tasks, and these changes in demand will be conveyed to you by different heights of the desired performance lines. In general there are three demand levels: high, medium, and low. You will see various combinations of these three demand levels. Each new trial will represent a new combination of task demands, and these demands will remain constant throughout that trial. There will be one minute of rest between trials.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) (6) TASK COMPONENTS AND DEMANDS AS FACTORS IN DUAL-TASK PERFORMANCE		5. TYPE OF REPORT & PERIOD COVERED (9) Technical Report
		6. PERFORMING ORG. REPORT NUMBER (14) ARL-77-2/AFOSR-77-2
7. AUTHOR(s) (10) Robert Arthur/North		8. CONTRACT OR GRANT NUMBER(s) (15) F44620-76-C-0009
9. PERFORMING ORGANIZATION NAME AND ADDRESS Aviation Research Laboratory Institute of Aviation University of Illinois, Savoy, IL 61874		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F (16) 2313A4
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research (NL) Building 410 Bolling AFB, DC 20332		12. REPORT DATE (11) Jan~~uary 19~~77 (17) A4
		13. NUMBER OF PAGES 108
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*) (12) 117p.		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (*of this Report*) Approved for public release: distribution unlimited.		
17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*) Dual-task Performance Human Factors Digit Processing Compensatory Tracking Time Sharing Task Priority Response Strategies Task Interference Task Demand		
20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*) This study explored the effects of interference between tasks as related to their specific functional requirements and under changing priorities. Four tasks were performed singly and in all pairwise combinations to compare their mutual interference levels. The tasks were one-dimensional compensatory tracking, and three self-paced Keyboard response tasks, one requiring a transformation by categorizing, one requiring storing and responding with the previous stimulus, and one → Cont. on 1473B		

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requiring no intervening activity between stimulus recognition and response. Tracking paired with any of the three Keyboard tasks was least interfering, Tracking and Tracking was moderately interfering, and Keyboard/Keyboard combinations the most interfering, suggesting that qualitatively dissimilar tasks are performed better than functionally similar tasks. The Keyboard task requiring continuous storing and response to the previous stimulus was highly disruptive when paired with other Keyboard tasks, and showed little evidence of interweaving with them, while the transformation Keyboard task was not as disruptive and could be interweaved with itself or the simple Keyboard task. The manipulation of dual-task demands produced expected changes in performance in nearly all task combinations, but was strongest in Tracking/Tracking and certain Keyboard/Keyboard combinations. Sequential Response strategies aided subjects in Keyboard/Keyboard performances, because different demands could be approximated by grouping different numbers of responses to each task before switching tasks.