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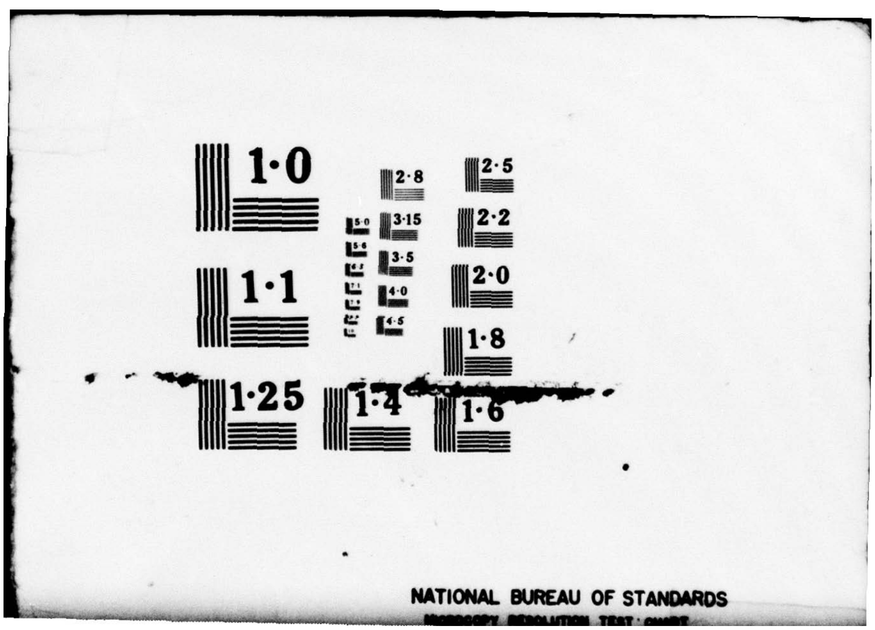
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MEASUREMENT OF ATTENTIONAL CAPACITY LOAD USING DUAL–TASK PERFORMANCE OPERATING CURVES

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This technical report has been reviewed and is approved for publication.

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A fixed attentional capacity theory of human attentional limitations was tested to determine its ability to predict the combination of tasks pilots could perform together without noticeable decrements. Three cognitive tasks and a simulated formation flying task were performed singly and in pairs.

Performance operating curves generated by dual-task performance on pairs of the cognitive tasks were estimated successfully. Their equivalent attentional demands were found. The flying task had a very small, but measurable attentional demand, as determined from dual-task performance. Performance on the cognitive tasks that were performed together with the flying task was consistent with the capacity theory. However, the small attentional demand needed to perform the flying task prevented a strong test of the theory.

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PREFACE

This report represents a portion of the research program of Project 2313, Perceptual Motor and Cognitive Components of the Flying Tasks; Task 2313T505, Acquisition of Flying Skills. Mr. Gary B. Reid, of the Flying Training Research Branch, was the task scientist.

The authors are indebted to Captain Ed Chun of Air Training Command for his assistance in rating the Formation Flight portions of the study.

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MEASUREMENT OF ATTENTIONAL CAPACITY LOAD USING DUAL–TASK PERFORMANCE OPERATING CURVES

I. INTRODUCTION

The limitations imposed on human performance by attentional capabilities have engendered several attempts to describe the nature of this attentional system (Broadbent, 1958; Deutsch & Deutsch, 1963; Kahneman, 1973; Moray, 1967; Norman, 1968). In complex human activities, such as piloting an aircraft, these limitations may become severe, leading to substantial performance decrements. It would be useful to be able to measure the attentional demands made by a task or set of tasks so that the compatibility of combinations of them could be predicted and used to aid in the design of instrument systems and flight procedures to optimize performance while minimizing the likelihood of producing a critical overload. It would also be desirable to have a good measure of attentional demand in order to determine when student pilots had sufficient attentional resources to advance to a more demanding part of the syllabus.

Recently, Norman and Bobrow (1975, 1976) described a fixed-capacity theory of attentional limitation which, if proven reasonably accurate, could be used to provide measures of attentional demand. The theory predicts that every person has a maximum attentional capacity, r_m, and that each task an individual is required to perform draws on this attentional reservoir. Provided that there is no structural interference between them, two tasks will be compatible with one another if the sum of the attentional resources required by each one is less than or equal to r_m, i.e., $r_1 + r_2 \leq r_m$. Two tasks satisfying this condition will be called capacity-compatible. Thus, a task has a single number, r_i, that characterizes its demand, regardless of the component subprocesses utilized to perform the task.

At present, there is no direct measure of the demand, r_i, required by a task at a given level of performance. For each task, there is assumed to be a weakly monotonic relationship between r and the level of task performance. If r and task performance increase together, task performance is said to be resource-limited in that range. The existence of resource-limited performance provides a usable method for testing the assumptions of the fixed capacity theory and if the test is successful, a method for constructing a metric to measure attentional demand.

If two tasks are resource-limited, then increasing the attentional resources devoted to task 1, r_1 should increase its performance without affecting task 2 until $r_1 + r_2 = r_m$. Thereafter, task 2 performance should decrease as r_1 increases. This performance trade off is called a performance operating curve (POC). Figure 1 shows two hypothetical performance operating curves. They show an important property of the fixed capacity theory. Assume that the top curve was generated by pairing a digit shadowing task, DTO, with a tone classification task, TC, and that the bottom curve was generated by pairing a "plus-three" digit transformation task with the TC task. Figure 1 indicates that a rate of performance P_a on the DTO task should require the same attentional resources as the rate of performance P_b does for the DT+3 task because both of them allow the same rate of performance on the TC task. Likewise, P_b of DTO should be equal in resource demand to P_c of DT+3. A *Performance-equivalency curve* between DTO and DT+3 performance can be generated in this way.

The fixed capacity theory predicts that performance equivalency points are equal in resource demand and, therefore, should act similarly when they are paired with another task. The present study examined this prediction. The digit shadowing task DTO and the plus-three digit task (DT+3) were each paired with the same tone classification task and their POCs were estimated. Next, a formation flying task was paired with the tone classification task to find the TC performance ratio that could be combined with the flying task. Finally, each digit task was tested at two presentation rates (DTO at P_a and P_b, DT+3 at P_b and P_c) to determine if the digit tasks behaved similarly. An attempt was made to set the presentation rates so that one was capacity-compatible and the other was capacity-incompatible.

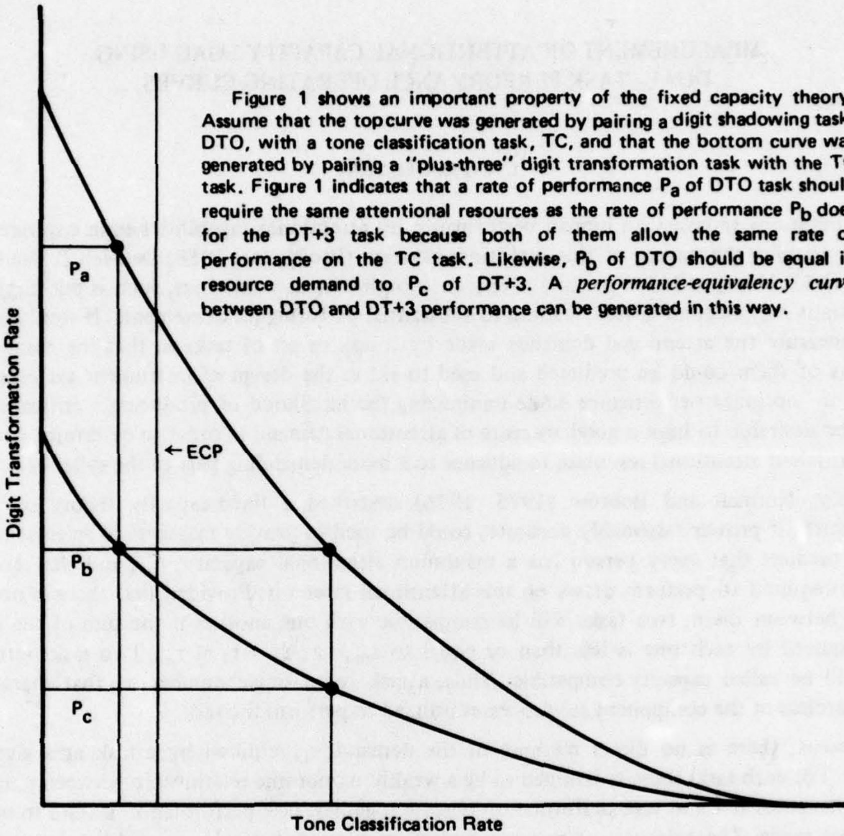

Figure 1. **Performance operating curves and performance equivalence points.**

The TC task was paired with the formation flying task in order to estimate the attentional resources that could be devoted to the TC task without producing a decrement in flying performance. The point at which performance begins to degrade will be called the excess capacity point, (ECP).

According to the fixed capacity theory, since pilots are called upon routinely to perform other tasks while they fly, they must either have some excess attentional capacity (i.e., $r < rm$) or the additional demand of these tasks will produce a decrement in either the flying or other task performance. If the pilots have excess capacity $r_m - r > 0$, this value constrains the TC performance that would be expected. If g is the performance-resource function for the tone classification task, P_{TC} would equal $g(r_m - r)$. This same excess capacity would allow a digit-shadowing performance of $P_{DTO} = f(r_m - r)$ if f is the performance-resource function for digit shadowing. If digit shadowing is resource-limited in this range, then the parametric equation $P_{DTO} = f(r_m - r)$, $P_{TC} = g(r)$ will hold and, therefore, the corresponding excess capacity performance on the TC task would be $P_{TC} = g(r)$. The value g(r) cannot be evaluated exactly without knowing the function g, but a bound can be put on its value. Two tasks such as DTO and flying are capacity-compatible if the *excess capacity* used on TC for each satisfies the condition that $r_1 + r_2 \leq r_m$. If g is monotonic, then $g(r_1 + r_2) \leq g(r_m)$. If g is not a positively accelerated function in the estimation range then $g(r_1) + g(r_2) \leq g(r_1 + r_2)$. Therefore, $g(r_1) + g(r_2) \leq g(r_m)$. Letting $r_2 = r_m - r_1$ yields $g(r_1) + g(r_m - r_1) \leq g(r_m)$ and $g(r_1) \leq g(r_m) - g(r_m - r_1)$. That is, the excess capacity point of the digit-shadowing task in terms of its corresponding TC task performance, $g(r_1)$, is greater than or equal to the maximum rate of performance on the TC task performed singly minus the rate of performance possible on TC while flying. The excess capacity point ECP = $g(rm) - g(rm - r)$ is marked with a vertical line in Figure 1. According to

the fixed capacity theory, performance levels of DTO and DT+3 to the right of this line will be compatible with the flying task; whereas, levels substantially to the left of it probably will be incompatible.

II. OBJECTIVES

The present project is a preliminary attempt to evaluate the feasibility of using a fixed capacity attentional theory to measure attentional demand. A valid measure of attentional demand with properties such as those described herein would be useful as a cognitive parameter that could be used to help design human performance systems. It also could be used to monitor the course of training. A prediction of the fixed capacity theory was to be experimentally evaluated.

III. METHOD

Subjects

Four instructor pilots from the 97th FTW, Williams Air Force Base, Arizona, volunteered to participate in the experiment.

Apparatus and Task Descriptions

Formation Flying. The simulator described by Wood, Hagin, O'Conner, and Myers (1972) was used to test the pilot's formation flying performance in the various experimental conditions. The simulator presents a visual display of a lead aircraft, which can be made to perform various standard maneuvers. The pilot controls his motion relative to it from a fixed cockpit. The simulator allows a range of flying activities, but during the test phases of the present experiment, the lead aircraft performed altitude variations with a peak to peak amplitude of 1,000 feet (305m) while flying at an airspeed of 320 knots. The flight dynamics simulated are the characteristics of a T-38 aircraft. The pilot was to maintain fingertip position on the lead aircraft's right wing.

Cognitive Tasks. Two different types of cognitive information processing tasks were used. Both tasks used stimuli which were presented auditorily via tape recordings. In the tone classification task, the output from each recorder was presented monaurally to the earphones in a headset. For the tone classification task, stimuli were present in 2-minute blocks. Blocks of two-tone sequences were recorded at a fixed rate. Blocks at the rates of 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, 1.5 and 1.75 tones per second were recorded. Each of the two tones had an equal probability of being the tone presented. The tones had frequencies of 2135 and 321 Hz and a common duration of 100 msec. They were presented at an easily audible intensity to the subject's left earphone.

In the tone classification task, the pilot's task was to classify the tones as either high or low in pitch by pressing the trigger switch on the control stick for high tones and the intercom switch on the throttles for low tones.[1] Each of the switches activated a small light. Scoring was performed manually by an experimenter who compared the lighted display with the correct response which was listed on a prepared data sheet.

For the digit transformation tasks, blocks of digit sequences were presented at a fixed rate. Blocks at the rates of 0.25, 0.50, 0.75, 1.00, 1.50 and 2.00 digits per second were recorded. Only the digits 1 through 5 and 8 were used, and each had an equal probability of occurring. The digits were recorded by using a pulse code modulation technique to digitize a speech sample, equate the six digits in intensity and shorten

[1] The first two pilots tested used another switch on the stick instead of the interform switch on Day 1.

them until each had a duration of 250 msec. Each digit was clearly intelligible and was presented at an easily audible intensity to the right earphone.

Two different digit transformation tasks were used. The DTO task was a shadowing task in which the pilot had to say aloud the name of the digit presented. The DT+3 task was an addition task in which the pilot had to add 3 to the digit presented and say the sum aloud. An experimenter monitored the pilot's speech and compared it for correctness with the answers on a prepared data sheet.

Procedure

The experiment consisted of five different sessions of testing. Each pilot received all five sessions. During session 1, the pilots practiced each task individually. They received seven 2-minute trials on the tone classification task with rates that ranged from 0.7 to 1.75 tones/sec. They received three 2-minute trials on the DTO task (1.0, 1.5, and 2.0 digits/sec) and three 2-minute trials of the DT+3 tasks (0.5, 1.0, and 1.5 digits/sec). They were allowed to fly in the simulator for at least 15 minutes, executing a variety of maneuvers.

During sessions 2 and 3, the digit tasks were paired with the tone classification task to estimate their performance operating curves. Only one of the digit tasks was performed together with the tone task during each session. The order of testing was counterbalanced across pilots.

At the beginning of each session, the pilot received two blocks of three trials. On one block of trials the pilot performed the tone task and on the other he performed the digit task that he would be tested on later in the session. Following this, he received three blocks of three trials of digit task-tone task combinations. During each block the presentation rate of the digit task was held constant while the tone task rate was varied. The presentation rates were 0.25, 0.75 and 1.0 digits/sec for the shadowing task and were 0.25, 0.50 and 0.75 digits/sec for the plus-three task. The order of testing was randomly determined for each pilot. On the first trial of a block all of the pilots received the same tone task rate. On the next two trials the tone task rates were increased or decreased by one step in an attempt to bracket the 10% error point.

The sequence of events on each trial was as follows. The first ten tones classified were not scored. After five of them were presented, the digit task began. The digit performance during the second five tones was not scored. A 2-minute test session followed. The pilots were told to give priority to the tone task.

During session 4 the pilots performed the tone task together with the formation flying task. The session again began with three 2-minute trials in which the pilot performed each task singly. Following this, each pilot received two blocks of five flying-tone task combinations. On each of the five trials within a block the pilot received a different rate of the tone task. The rates used for both blocks were 1.1, 1.3, 1.5, and 1.75 tones/sec and 0.0 tones/sec (i.e., no tones were presented). The order of testing the presentation rates was randomly determined within each block for each pilot.

The sequence of events on each trial was as follows. The pilot was allowed to achieve a stable fingertip position with the lead aircraft flying straight and level and again while it performed altitude variations. Following his signal the tone task was started. Scoring started after 10 tones were presented and continued for 2 minutes. An instructor pilot (assigned to AFHRL) rated the pilot's performance during the 2-minute trial. He used the 12-point scale described by Reid and Cyrus (1974).

During session 5 both digit tasks were paired with formation flying in two separate blocks of trials. For practice each pilot had three trials of formation flying singly and two trials with each digit task singly immediately before the trial block on which it was used. The test trials consisted of two blocks of four trials. On two of them the pilot performed formation flying together with the digit task. On the other two they performed the digit task alone. The presentation rates that were used were selected individually for each pilot as described in the introduction. The same rates were used on the dual-task and single-task trials. Testing order was counterbalanced. The sequence of trial events was similar to that used during session 4.

IV. RESULTS AND DISCUSSION

Tone-Digit Performance Operating Curves

The performance operating curves relating DTO and DT+3 performance to tone classification performance were estimated by finding the maximum rate at which each task could be performed singly and the maximum rate at which the tones could be classified for each of the three digit transformation rates that were used. The rate at which a pilot made errors on 10% of his responses was taken to be the maximum rate. The 10 percent error rate was estimated separately for each pilot. Figures 2 and 3 show the means of the individual estimates. The numbers arbitrarily identify the pilots. Missing pilot numbers occurred because the three-rate interpolation procedure did not always yield a clear-cut estimate of the 10% error rate. Because the pilots usually made errors on both tasks in the dual-task conditions and because the function relating their error tradeoffs is unknown, the 10% error criterion was taken as the sum of the percentage of errors made on each task. Weighting each percentage by the number of stimuli presented during a 2-minute trial did not appear to change the estimates appreciably and, therefore, was not used.

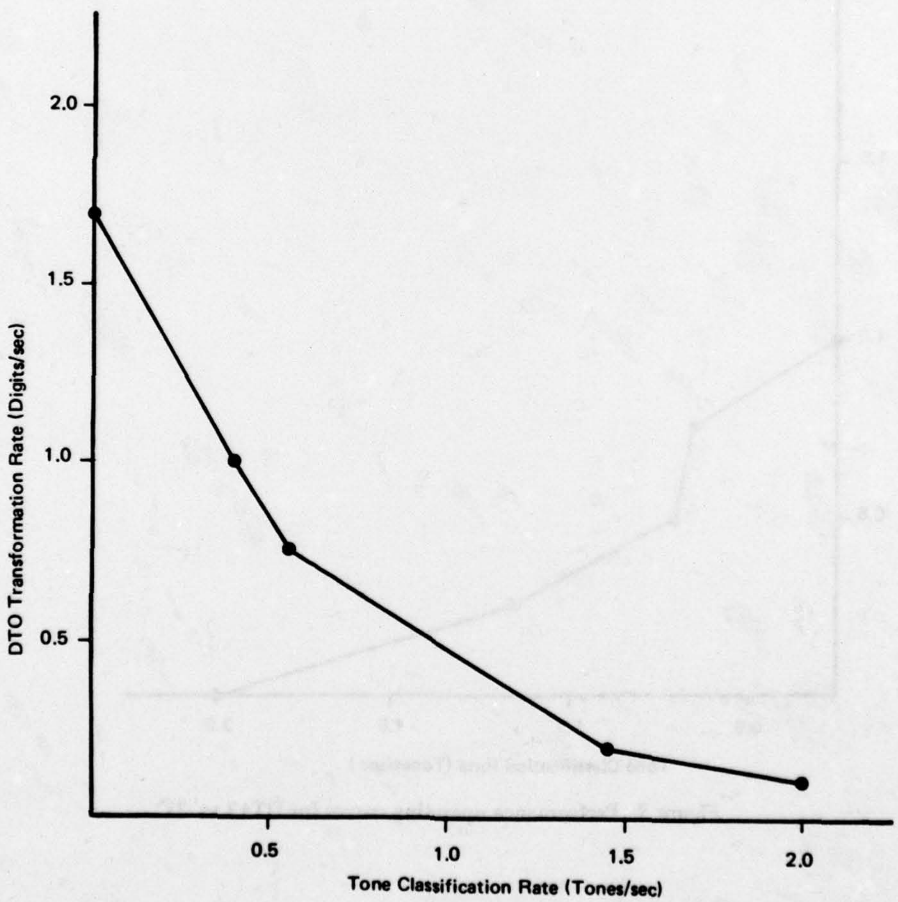

Figure 2. **Performance operating curves for DTO vs. TC.**

Figure 2 shows how performance on the shadowing task DTO covaried with performance on the tone classification task. The rate at which shadowing could be successfully performed decreased substantially as the rate at which tone classification could be successfully performed increased. The curve drawn through the points is the exponential function, P_{DTO} = 1.74 exponent (-1.45 P_{TC}) that provided the best fit to the mean performances. The best fitting exponential function was found by a linear regression on the log-transformed scores. The fit appears to be reasonably good ($r = -0.997$) and was somewhat better than the best-fitting linear function. The mismatch between the rightmost point and the curve is due to the estimation procedure. The zero rate of DTO performance (i.e., tone classification alone) was set at 0.1 to allow it to be logarithmically transformed. Setting the value of zero DTO performance closer to zero appeared to have little influence on how well the estimated curve fit the data. More sensitive estimation procedures were not attempted because the maximum rate that tone classification could be performed singly was inadequately estimated; the value shown may be an underestimate.

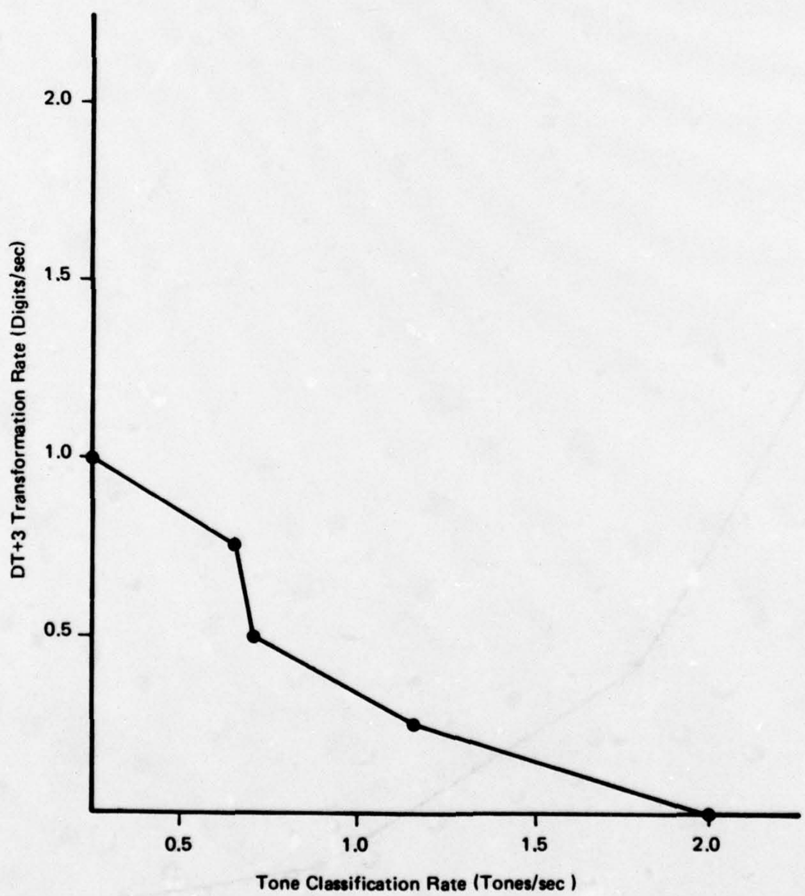

Figure 3. **Performance operating curves for DT+3 vs. TC.**

The maximum rate of classifying tones singly was inadequately estimated because the testing procedure did not permit the testing of rates greater than 1.75/sec and the pilots made errors on fewer than 10% of the tones at this rate. The mean percentage of errors for Days 1–4 on the 1.3, 1.5, and 1.75 tone/sec rates were 2.5, 4.6 and 6.6 percent, respectively. The corresponding means for Days 3 and 4 only were 2.4, 3.5 and 4.1 percent. The 1.9 tones/sec value shown in Figure 2 is a rough extrapolation.

Figure 3 shows the performance operating curve for the plus-three versus tone classification tasks. They were treated in the same way as the data in Figure 2. The best-fitting exponential function (r = –0.992) had the equation P_{DT+3} = 1.03 exponent ($-1.23\ P_{TC}$). The rate at which the plus-three transformation had a demand equal to that produced by a given rate of shadowing can be found by treating the two best-fitting exponentials as parametric equations and solving. The resulting power function: $P_{DT+3} = 0.644\ P_{DTO}^{\ 0.848}$, describes this equivalency, and it will be called their performance-equivalence function. The rate of DT+3 performance is denoted as P_{DT+3} and the rate of DTO performance is denoted as P_{DTO}.

Flying versus Tone Classification

To estimate the attentional demand made by the formation flying task, an attempt was made to determine the rate of tone classification at which each pilot made errors on 10% of the tones presented. The mean percentages from the two blocks are presented separately for each pilot in the middle section of Table 1. Using the estimation procedures as before, only pilots 2 and 3 had estimable maximum demand rates (1.5 and 1.0 tones/sec, respectively). Pilots 1 and 4 had successful classification rates while flying that exceeded the scoring capabilities of the present experiment.

Table 1. **Tone Classification Error Percentages and IP Ratings of Flying from Single and Dual Task Combinations**

	Tone Presentation Rates				
Pilot	0	1.0	1.3	.15	1.75
Tone Classification Singly					
1	–	–	0.0	0.0	5.2
2	–	–	7.1	3.3	5.7
3	–	–	3.2	3.9	5.2
4	–	–	0.0	0.0	0.0
Tone Classification While Flying					
1	–	3.8	3.5	9.7	7.8
2	–	5.6	7.1	9.7	12.6
3	–	12.1	28.8	17.5	22.6
4	–	3.4	4.5	,4.2	3.6
Rating of Flying					
1	10.0	9.5	9.5	9.5	10.0
2	8.0	8.0	8.5	8.0	7.5
3	8.5	7.0	7.5	7.5	7.0
4	9.0	8.5	8.5	8.5	8.5

Note. — Ratings of the pilots' flying performance did not appear to be affected by the classification rates used. The mean ratings for the two blocks are presented in the bottom section of Table 1. The five treatment conditions were not significantly different from each other, $F(4, 12) = 2.26$.

Because of the slight effect of flying on classification performance, a test was conducted to determine if flying produced a significant decrease in tone classification performance. The tone classification performance from the single task trials that were presented at the beginning of day 4, shown in the top section of Table 1, were compared to the performance under dual-task conditions at the same rates. A repeated measures analysis of variance with dual versus single task and rate of presentation as main effects was conducted. The pilots made significantly more classification errors when they flew and classified, than when they classified without flying, $F(1,15) = 17.48$, $p < .01$. Neither rate of presentation nor the interaction of rate with the dual-single condition produced significant performance differences for the rates that were tested, $F(2,15) < 1.0$ for both. It is unlikely that this performance difference was produced by experimental fatigue over the course of the session. If anything, Block 2 dual-task performance was better than Block 1 dual-task performance (10.9% versus 11.9%, respectively).

Flying versus Digit Transformations

The inability to estimate the maximum rate at which the tone classification could be performed singly, together with the problem created by the small attentional demand produced by the flying task made it impossible to use the procedure described in the introduction to select compatible and incompatible presentation rates for each task. It was impossible to find rates that definitely exceeded the compatibility point but that did not exceed the maximum single task rate whose use would have made the prediction trivial.

Despite the inability to predict the compatibility point reliably, Day 5 testing was conducted to check the prediction that the performance equivalency rates for the two different digit tasks should act similarly regardless of how they affect flying. There should be no task type by rate interaction for equivalent rates. This test rests on weaker assumptions, but it becomes convincing only if there are some rate-dependent performance decrements. The rates were estimated separately for each pilot, and are presented in Table 2.

Table 2. **Compatible and Incompatible Presentation Rates Used with each Task**

Condition	Pilot 1	Pilot 2	Pilot 3	Pilot 4
Incompatible				
DTO	1.50	1.50	1.50	1.50
DT+3	0.75	1.00	1.00	0.75
Compatible				
DTO	0.75	1.00	1.00	0.75
DT+3	0.50	0.75	0.50	0.50

A repeated measures analysis of variance was performed on the difference scores obtained by subtracting the percentage of errors made under the single task conditions from the percentage of errors made under the corresponding dual-task conditions. Neither the main effects of task type and of compatible versus incompatible presentation rate nor their interaction were statistically significant, $F(1,9) = 1.57, 0.79, 1.41$, respectively. A similar analysis of the dual-task ratings of flying performance also revealed no significant differences, $F(1,9)$ all <1.

V. CONCLUSIONS

The successful determination of POC curves for the cognitive tasks shows that even different kinds of cognitive processing appear to have trading relationships. Kalsbeek and Sykes (1967) did determine a POC but both tasks used were classification tasks. By generating two different POCs for the transformation tasks against a common classification task, it was easy to rule out single response competition due to the response execution as the major contribution producing the POCs. The rates of performing DT+3 was much slower than the rate of performing DTO for a common TC rate. Also, this allowed the two transformation tasks to be equated. Kalsbeek (1968) made a similar equation, but he used a physiological measure, sinus arrhythmia, to equate them. In both cases some test for the validity of the equation is needed.

Unfortunately, the attempt to test the validity of the performance equivalence function was not successful. The flying task produced too little attentional demand. The test did show the advantage of this approach. Typically, dual-task studies, whether with cognitive tasks (Kerr, 1973) or with tracking tasks which are similar to the flying tasks used in the present study (Poulton, 1974), have constructed task difficulty so that at least one experimental condition produced performance differences. These measures provide ordinal information of difficulty over this narrow range, but they do not allow a comparative evaluation of attentional demand in terms of the total resources available. In the present experiment, flying was shown to demand attentional resources, but by being able to compare it to other tasks using the same metric (i.e., the two cognitive tasks), the demand was seen to be rather small.

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