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16. Abstract

Thirty-nine men were tested on a total of six tasks; performance was measured on each task presented individually and on two complex tasks made up of three-task subsets. The tasks measured monitoring, arithmetic, pattern-discrimination, tracking, and problem-solving performance. Two separate test sessions were conducted for each of the individual tasks and for each of the two complex tasks.

Factor analyses were performed on the resultant data to determine if there would merge a time-sharing ability, defined as a reliable source of variance associated with complex performance but independent of simple-task performance of the constituent tasks. A factor was found that showed high loadings for two different monitoring tasks for complex performance but negligible loadings for these tasks for simple performance; separate independent factors were found for the two monitoring tasks when they were performed under simple-task conditions. The monitoring measures appear to possess properties that would be expected of measures of a time-sharing ability. The findings suggest that a suitable measure of time-sharing ability would be of value in the selection and screening of candidates for complex jobs.

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AN INVESTIGATION OF TIME-SHARING ABILITY AS A FACTOR IN COMPLEX PERFORMANCE

I. Introduction.

People concerned with training personnel for complex jobs have long recognized that individuals differ with respect to the ease with which they are able to master multiple-element jobs and there are some complex jobs that some people cannot master. As stated by Chiles, Jennings, and West[7] on the basis of discussions with instructors at the Federal Aviation Administration (FAA) Academy, a number of trainees are eliminated from the air traffic controller training program, not because they lack specific academic or other skills, but because they are deficient in the concurrent performance of the variety of tasks of which the controller's job is composed. An analogous belief has been expressed by flight instructors about flying trainees.

Underlying these notions is the implicit hypothesis that the acquisition of skill on a complex task, considered in its entirety, somehow rests on the learning of task features that "emerge" when the component tasks are combined to produce the complex task. These notions also assume that the emergent features of a complex task are not only quantitatively but also qualitatively different from the sum of the requirements of the individual tasks. Thus, although the supporting evidence comes largely from anecdotal observation, the wide acceptance of the position that there are abilities (or, perhaps, *an* ability) specific to complex performance provides one reason for seeking to determine if, in fact, such a phenomenon exists and can be quantified.

Another line of reasoning also suggests the possible existence of such an ability. Knowles,[20] in considering the problem of workload measurement, describes a technique in which the performance levels maintained on auxiliary or secondary tasks are used to indicate the level of workload imposed by the performance of a primary task. In discussing this technique, Senders[26] lists several assumptions on which this methodological approach to workload measurement rests. Two of those assumptions are directly relevant to the purposes of this study: (1) the operator is a single-channel system, and (2) the channel has a fixed capacity. We interpret the concept of a single-channel system in this context to mean that an individual can do only one thing at a time. (For present purposes we will disregard the fact that some tasks can be learned to the extent that performance of such tasks can proceed more or less autonomously.) With this interpretation, it follows that if the operator is given two or more tasks to do "simultaneously," attention is shifted back and forth between tasks at a rate intended to insure adequate levels of performance on the individual tasks. The idea of a fixed-channel capacity simply means that there is a limit to the number of things the operator may be asked to do within a given set of time constraints without some degradation of performance on one or more individual tasks.

The secondary task approach was used by North and Gopher[22] in a study of performance in a divided attention task as a predictor of success in flight training. This study required subjects to perform a one-dimensional compensatory tracking task and a digit-processing reaction time task both individually and in combination. They found that measures of both tasks taken during complex performance discriminated reliably between "high-potential" and "low-potential" trainees, whereas measures taken during performance of the tasks singly did not. North and Gopher interpret their results as reflecting differences in the ability of the subjects to distribute their attention between the two tasks.

reason to believe that task elements involving disparate behavioral functions would also exhibit such properties.

The applicability to our problem of the work typified by Conrad on dial monitoring suffers in that the skill level on one task element has a very direct effect on the apparent difficulty of performing the second task. Thus, the Conrad findings are compatible with the time-sharing-ability hypothesis, and Bartlett's concept of timing in skill is closely allied, but the results of those studies cannot be held to substantiate the hypothesis.

Thus, we see that although the existence of a time-sharing ability is widely assumed in discussions of job requirements, definitive quantitative evidence of such ability is lacking. The methodology of factor analysis offers one approach to the development of the desired evidence. Within that context, the hypothesized time-sharing ability would be defined as *a reliable source of variance that contributes to performance of complex tasks but is independent of simple-task performance of the constituent tasks.* This is the definition of the concept *time-sharing ability* that we propose to use in this paper. The specific way in which this would be revealed in a factor analysis would be by the finding of an orthogonal factor with large loadings for some tasks (measures) when performed as a part of a complex task but small loadings on these same tasks (measures) when performed individually. This factor should also show large loadings on other tasks performed as a part of a different complex task.

The purpose of this study is to examine two different complex tasks by using the factor analytic method to determine whether any of the performance measures exhibit the above described statistical properties that could be construed as evidence of a time-sharing ability.

II. Method.

A. *Apparatus.* In this study, the testing was carried out by using the Civil Aeromedical Institute (CAMI) Multiple Task Performance Battery (MTPB). This test battery was designed to test and measure a variety of skills judged to be important to aircrew performance but it was not intended to be a simulator of any particular system.[4] The MTPB consists of five subject testing panels and associated programming and scoring circuitry. The panels contain the displays and response controls for six different tasks, each of which may be presented in isolation or in any combination of tasks. The six tasks are very briefly described in the following sections; see Chiles, Alluisi, and Adams[4] for a more complete description.

1. Warning lights. This is a choice reaction-time task involving monitoring of five green lights and five red lights. Under each light is a pushbutton switch. The green lights are normally on and the red lights are normally off; the subject is instructed to push the button under the light whenever a light changes state. Signals were introduced at randomly selected intervals with a mean intersignal interval of 30 seconds.

2. Meter monitoring. This task involves monitoring four meters mounted across the top of the subject panel. Normally, the meter pointers are moving at random around a mean vertical position. The subject responds to a shift in the mean position of the pointer by throwing the associated lever switch in the direction of the deflection. The signals are introduced at randomly selected intervals, with a mean intersignal interval of 1 minute.

3. Mental arithmetic. In the arithmetic task, the subject is required to add two numbers and substract a third number from the sum of the first two without using paper and pencil. The problem elements were numbers from 10 to 99, selected with the restriction that neither digit of the third number should be identical to the corresponding digit of either of the first two numbers. The arithmetic task is machine paced, and a new problem is presented every 20 seconds. Both response time and accuracy are measured on this task. Accuracy is determined as a percentage of all problems presented.

4. Pattern identification. The display for the pattern identification task is a screen on the lower left of the subject's panel. This screen consists of a six-by-six matrix of close-butted lights covered by a translucent panel. A standard pattern is presented for 5 seconds followed by 2-second presentations of two comparison

dition. A significant practice effect was found for 7 of the 11 measures; the exceptions were response time and response accuracy on problem-solving-confirmation performance, meter response time, and pattern-identification response time. There was a significant interaction between task complexity and practice on both the red and green lights measures. Inspection of the simple effects on these two measures showed that there was a significant practice effect between the two complex-performance sessions but not between the simple-task sessions.

TABLE 2. Mean Performance by Task Complexity and Practice

	Task Complexity		Practice Session	
	Simple	Complex	First	Second
Light Monitoring				
Green response time*	**1.39	6.47	4.38	3.51
Red response time	1.01	2.85	2.26	1.60
Arithmetic				
Percent correct	.70	.58	.59	.68
Time/problem	10.14	10.89	10.79	10.29
Problem Solving				
Solution, time/response	1.88	2.28	2.21	1.95
Confirmation, percent correct responses	.93	.88	.91	.90
Confirmation, time/response	1.57	2.01	1.81	1.78
Meter Monitoring				
Response time	12.53	23.19	18.28	17.41
Pattern Identification				
Percent correct	.90	.80	.83	.87
Time/problem	9.72	10.14	9.98	9.89
Tracking				
Vector RMS error (arbitrary units)	4.64	7.11	6.33	5.42

*All time measures are in seconds; recorded as 1/100 of a second.
**Underlined pairs differ at $p < .05$.

The relative contributions of the effects of practice and task complexity were evaluated for each measure exhibiting a significant effect by use of the omega-squared statistic, which provides an estimate of the proportion of total variance that is attributable to each effect.[18] The omega-squared statistics, which are presented in Table 3, show that although the practice effect is significant for seven measures, that effect is relatively small in magnitude; it accounts for no more than 5 percent of the total variance for any measure. The task-complexity effect, which is significant on 10 of the 11 measures, is in every case larger than the practice effect. The magnitude of the effect of complexity varies widely between measures, ranging from 6 to 71 percent of the total variance for a given task measure. The proportions of variance for those tasks that are most affected by task complexity are: green lights, 71 percent; red lights, 40 percent; tracking, 24 percent; and meters, 20 percent.

TABLE 3. Omega^2 Estimate of Magnitude of Effect of Significant Complexity and Practice Effects

	Complexity	Practice	Interaction
Light Monitoring			
Green response time	.71	.02	.02
Red response time	.40	.05	.05
Arithmetic			
Percent correct	.06	.04	
Time/problem	.07	.04	
Problem Solving			
Solution, time/response	.09	.04	
Confirmation, percent correct responses	n.s.	n.s.	
Confirmation, time/response	.06	n.s.	
Meter Monitoring	.20	n.s.	
Pattern Identification			
Percent correct	.14	.02	
Time/problem	.06	n.s.	
Tracking			
Vector RMS error (arbitrary units)	.24	.03	

C. *Factor Analytic Findings.* The data used in the factor analyses were based on the averages across the two trials for each measure at a given level of complexity. In all of the analyses, the principal components method was used with unity in the major diagonal. Following the rule suggested by Guttman[17] and Kaiser,[19] factors were extracted in a step-wise procedure until a factor with a eigenvalue of less than one was obtained. All factors with an eigenvalue greater than one were then rotated to simple structure by the normal varimax method. The measure identification key used in each of the remaining tables is shown in Table 4.

TABLE 4. Number Key for Measures

	Measure Number	
	Simple	Complex
Green Lights, Response Time	1	12
Red Lights, Response Time	2	13
Arithmetic % Correct	3	14
Arithmetic, Time/Problem	4	15
Problem Solving		
Solution Phase, Time/Response	5	16
Confirmation Phase, % Correct Response	6	17
Confirmation Phase, Time/Response	7	18
Meters, Response Time	8	19
Pattern Identification, % Correct	9	20
Pattern Identification, Time/Problem	10	21
Tracking, Vector RMS Error	11	22

The first analysis was applied to the measures from all tasks; there was a total of 11 measures for each of the two conditions of complexity. The results of this analysis are presented in Table 5; in this and the subsequent factor loadings tables, those loadings that exceeded .60 are marked with an asterisk for ease of reference. The correlation matrix on which the analyses are based is shown in Table 6. A total of seven factors were extracted.

The first factor extracted showed the largest loadings for the red and green lights under the simple condition, one of the problem-solving measures for the simple condition, and the pattern-discrimination time measure under both the simple and complex conditions. The second factor showed the largest loadings for the arithmetic task for both complexity conditions and for both speed and accuracy. The third factor showed the largest loading for the meters task under the simple condition and a slightly smaller loading for the problem-solving task, percent measure, during the confirmation phase under the simple condition. The fourth factor showed large loadings for only the tracking task under both the simple and complex conditions. The fifth factor showed loadings for the problem-solving time measures for both complexity conditions and for both solution and confirmation phases. The sixth factor showed the largest

TABLE 5. Factor Matrix for All Measures After Varimax Rotation

Measure Number*	Factor Number 1	2	3	4	5	6	7
1	* .88	-.08	.15	-.03	.02	.01	-.14
12	.36	-.07	.00	.03	-.01	*-.75	-.18
2	* .82	-.08	.21	-.07	-.25	-.11	-.12
13	.20	-.24	.22	.32	-.02	*-.70	.08
3	.20	*-.82	-.07	.08	-.01	-.02	.14
14	.05	*-.85	.12	.05	.08	.00	.02
4	.04	*-.69	-.06	.06	.02	-.27	-.43
15	-.12	*-.61	-.05	-.11	.02	-.32	-.48
5	.31	-.15	-.07	-.10	*-.80	.01	.08
16	-.11	.19	.02	-.04	*-.83	-.07	-.16
6	* .82	.06	-.14	.00	-.05	-.28	.21
17	-.35	-.22	*-.78	.06	-.10	.02	-.03
7	.50	.01	.05	.00	*-.65	.20	.26
18	-.17	.19	-.36	.35	*-.67	-.01	-.13
8	.02	.15	*-.87	-.04	.01	-.03	-.01
19	.04	-.03	-.17	-.23	.08	*-.79	.10
9	.34	-.09	-.49	.49	-.14	-.06	-.41
20	.33	-.01	-.06	.36	-.06	.13	*-.71
10	* .62	-.17	-.16	-.04	-.27	-.47	-.21
21	* .70	-.09	.13	-.14	.14	-.43	-.24
11	-.11	-.27	.04	* .85	.14	.01	.04
22	-.10	.15	-.02	* .87	-.10	.00	-.20
Eigenvalue	3.97	2.63	1.98	2.18	2.44	2.42	1.50
% of variance	.18	.12	.09	.10	.11	.11	.06

*See Table 4 for code.

TABLE 6. Correlation Matrix for All Measures

Measure Number*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
2	.80																				
3	.12	.13																			
4	.22	.24	.52																		
5	.28	.42	.18	.08																	
6	.57	.46	.14	.00	.20																
7	.32	.41	.10	-.21	.54	.35															
8	-.06	-.04	-.07	.05	.11	.01	-.10														
9	.18	.09	.22	.27	.15	.29	.16	.19													
10	.50	.58	.21	.36	.40	.55	.25	.13	.36												
11	.03	-.05	.18	.30	-.11	-.16	-.16	.00	.20	-.13											
12	.33	.36	.18	.35	.08	.43	.02	.05	.26	.65	-.06										
13	.17	.35	.25	.39	.04	.25	.02	-.17	.19	.47	.22	.62									
14	.10	.07	.77	.60	.06	.03	-.07	-.21	.01	.17	.24	.10	.18								
15	.07	.02	.36	.83	-.02	-.07	-.17	-.07	.21	.31	.13	.39	.26	.52							
16	-.05	.16	-.15	-.04	.52	.05	.25	.09	.07	.18	-.12	.02	-.09	-.19	-.07						
17	-.32	-.27	.09	.16	.02	-.14	-.12	.32	.28	.05	.12	-.14	-.11	.02	.24	.06					
18	-.26	-.06	-.18	-.07	.38	-.07	.39	.28	.39	.10	.11	-.03	-.08	-.25	-.03	.47	.34				
19	.05	.08	.10	.21	.05	.28	-.21	.17	.03	.30	-.12	.61	.39	.04	.27	.00	.00	-.06			
20	.34	.30	.09	.32	.08	.05	.04	.05	.68	.28	.16	.21	.06	.03	.22	.08	-.06	.25	-.22		
21	.56	.48	.20	.21	.04	.48	.07	-.14	.16	.63	-.09	.53	.23	.16	.24	-.07	-.23	-.21	.41	.23	
22	-.11	-.12	-.11	.01	-.05	-.07	-.10	-.04	.37	-.01	.61	.02	.04	-.04	-.09	.17	.07	.41	-.21	.41	-.09

*See Table 4 for code.

monitoring and tracking measures would appear to be the most likely to exhibit evidence of a time-sharing ability.

It should be noted that, although the problem-solving task was presented both by itself and as a part of complex Task A, it is a group-performance task in the literal sense. Therefore, since it would quite likely be subject to group influences, it should be regarded primarily as a source of increased workload for the purposes of this study.

The results of the factor analysis for the entire set of measures can be readily interpreted as providing direct support for the hypothesis that there is a time-sharing ability that is involved in complex performance. Specifically, three orthogonal factors involving the monitoring tasks emerged: red and green lights performance loaded under the simple condition on one factor; meters performance loaded under the simple condition on another factor; and meters and lights performances both loaded on a third factor under the complex condition. The specific performance requirements of the meter monitoring task under the simple condition were identical to those of the complex condition, and the same was true of the red and green lights monitoring task. Thus, it seems reasonable to interpret the fact that these tasks are orthogonal under simple conditions but related under complex conditions as evidence of a higher-order process. It also seems quite reasonable to interpret that high-order process to be a reflection of differences in the ability of subjects to shift attention quickly and efficiently from the active tasks to the monitoring.

The factor analyses that were applied separately to the Task A and Task B data did not appreciably alter the general nature of the findings of the overall analysis. In each of these analyses, the factors on which the monitoring tasks were found to load under the simple condition were orthogonal to the factor on which they loaded under the complex condition. The findings of the fourth analysis, which involved only the monitoring data, were directly analogous to those of the overall analysis; there emerged two simple condition factors, one for lights and one for meters, and one complex condition factor on which meters and lights loaded. Whether one chooses to call the factor for the complex condition *complex monitoring ability* or *time-sharing ability* is perhaps arbitrary, but the results suggest a factor that clearly fits our proposed definition of a time-sharing ability—a source of variance for complex performance that is orthogonal to the implicated measures for simple performance.

An important aspect of this study was what was *not* found; namely, no complex performance factor emerged that could be called a Task A factor or a Task B factor, nor was there a factor that crossed over the two tasks as a general complex performance factor. Only the monitoring tasks appeared to have properties that warrant an inference about time sharing.

The best explanation for this general pattern devolves from a consideration of the notion of task priorities. Subjects appear to develop a hierarchical response strategy in which performance of a given (higher priority) task is protected at the expense of lower priority tasks. We have been generally aware of this for some time in an observational sense, and we have data from previous studies that seem to be best interpreted in this manner. For example, Chiles and Jennings[6] conducted a study on the effects of alcohol on complex performance. It was found that, with average blood alcohol levels on the order of 100 mg%, tracking and monitoring performance showed significant degradation but mental arithmetic performance was not affected. The nature of the arithmetic task was that the most reasonable explanation of those findings was that the subjects had "protected" their performance of the arithmetic task, presumably by devoting more of their attention to it. Therefore, our interpretation of these findings was that arithmetic performance was maintained at the expense of the performance of the other tasks.

If the subjects in the present study are assumed to be operating with some sort of response hierarchy, then it is reasonable to argue that the performance of the higher priority tasks under both the simple and the complex conditions would be primarily a function of the skill levels of the subjects on those tasks. From this it would follow, then, that performance of the lower priority tasks (presumably the monitoring tasks) under the complex conditions would be primarily a function of the ability of the subject to shift attention from a higher priority task to scanning and detecting signals on the lower priority tasks. The results of the factor analyses clearly suggest that the skills that are important in the simple situation are also those that are of primary importance in the complex situation in the case of the arithmetic, pattern-discrimination, and (at least during the initial solution phase) problem-solving tasks. The results relating to these active tasks also clearly suggest that the findings for the monitoring tasks were not simply some sort of complementary process in which subjects who were better, for example, on the arithmetic task simply had more time to scan the monitoring displays. The orthogonality of the active task and monitoring task factors suggest that the skills underlying the performance of these two types of tasks are independent.

The extent to which the tasks used in this study may or may not yield "factorially pure" measures of fundamental abilities is only an academic concern. These tasks were selected originally because, and the rationale for their continued use is, they were judged to measure behavioral functions of relevance to complex performance as it is found in operational aviation systems. The content validity of these tasks has been confirmed by a large number of operational personnel. For this reason, it is of no particular concern that, for example, the pattern-discrimination-response time measure loads on the same factor as the red and green lights measure under the simple condition in the overall analysis and on the factor on which the meters task loads under the complex condition in the analysis of the Task B measures. It will be noted that there was ambiguity in the loadings of the pattern-discrimination time measure in the overall analysis; it had rather large loadings on the first factor for both complexity levels, but it also had moderate loadings for the complex-monitoring (time-sharing) factor, factor 6. It should also be noted that the measure of accuracy in the problem-solving task, confirmation phase, is rather unstable, presumably because there is very little variance on this measure; most subjects make very few errors in entering the second solution.

Although this type of study requires replication before final acceptance of the validity of the concept of time-sharing is warranted, there are, nonetheless, some important implications of these findings for research methodology. The findings strongly support an argument we have presented elsewhere:[2 3 5 6] if the goal of a research effort is generalization to complex operational tasks, then the tasks used must involve an element of complexity analogous to the time-sharing demands characteristic of the target operational situation.

In this regard, the "time-sharing ability" identified in our study is clearly related to the "divided-attention ability" referred to by North and Gopher[22] in interpreting their results on the prediction of success in flight training. The findings are also quite compatible with the argument that complex tasks are more likely to be sensitive to environmental and procedural variables than are simple tasks. The findings suggest that selection and screening programs for complex jobs, such as air traffic control, might very well be improved by the incorporation of suitable measures that tap time sharing as a basic ability. Furthermore, these findings provide indirect support for the use of secondary tasks to assess the workload properties of primary tasks.

V. Summary and Conclusions.

It has long been held that people differ with respect to their ability to master complex jobs. In the operational context, this ability is often referred to as though it represented variations in the facility with which people can simultaneously perform two or more tasks in a "time shared" manner. However, the existence of such an ability has never been quantitatively verified. This study attempted to determine whether such an ability could be isolated that is specific to proficiency in complex performance. For the purpose of this study, and within the context of the tasks employed, *time-sharing ability* was defined as "a reliable source of variance that contributes to performance of complex tasks but is independent of simple task performance of the constituent tasks."

Thirty-nine subjects were tested on two sets of performance tasks. Each set consisted of three individual tasks that could be presented in isolation for a simple-task-performance condition or in combination for a complex-performance condition. All of the subjects were tested on both sets of tasks in two sessions of simple-task performance and two sessions of complex-task performance.

A factor analysis revealed a single factor associated with performance of two monitoring tasks (lights and meters) under the complex condition, whereas simple performance of these tasks was represented by two separate factors. The factor that had high loadings on the monitoring tasks in the complex-task situations may reasonably be interpreted to be reflective of the existence of a time-sharing ability or skill. At the levels of complexity, difficulty, and training used in this study, the time-sharing factor was apparently not important in the performance of active, more demanding tasks. We suggest that the best explanation of the findings is that subjects tend to develop a response strategy that results in their "protecting" their performance of the active tasks. Thus, the hypothesized ability is revealed in the ease with which the subjects can shift attention from the active tasks to the less demanding monitoring tasks.

An important methodological implication of this study is that if research results are to be generalized to complex jobs such as those found in aviation operations, then the research tasks should exhibit an analogous level of complexity. The findings suggest that selection and screening programs for complex jobs, such as air traffic control, would be improved by the use of suitable measures that tap time sharing as a basic ability.

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