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METHODOLOGY IN THE ASSESSMENT OF COMPLEX PERFORMANCE: THE EFFECTS OF SIGNAL RATE ON MONITORING A STATIC PROCESS

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I. Introduction.

The human operator is frequently required to perform monitoring functions as a part of his job. In a significant number of aviation-related jobs, the signal to which the man must be alert and to which he must respond rapidly is in the nature of a discrete change in any one of the displays he is required to monitor. Any particular such display indicator assumes a given state and may remain in that state for a relatively long period of time, as, for example, an engine fire warning light in an aircraft cockpit. Should the indicator change its state, e.g., the warning light come on, the operator must respond quickly with the action appropriate to the emergency condition signaled by the onset of the light. It is rare that a man's real-world job calls for nothing other than monitoring such displays. Typically, in the field of aviation, the operator will be engaged in a number of other tasks that make varying demands on his performance capacities.

Much of the laboratory research that has been conducted on the ability of man to perform tasks requiring the monitoring of a static process has been of the nature of the classical reaction time experiment. In this kind of experimental situation, the subject is required to execute only one response to one specific stimulus, and, frequently, he is given an alerting signal that tells him that a stimulus will appear shortly. The situation may be somewhat more complex; he may be required to choose one of two or more possible responses to two or more stimuli. The important point to be made as regards the value of such research to the prediction of complex performance in a work context is that in this kind of experiment, the subject can devote essentially his entire attention to the task at hand.

Thus, the properties of monitoring behavior have not been investigated systematically when that behavior is exercised in the context of a complex performance situation that places demands on the operator comparable to those placed on the pilot or air traffic controller. One of the important pieces of information needed relates to the effects on monitoring performance of the rate at which events take place within the monitoring task as a function of the number and nature of other tasks the man is required to perform concurrently. Of equal interest are the effects of monitoring task signal-rate on the performance of the concurrently presented tasks.

An important methodological problem that relates closely to the above question concerns the achievement of satisfactory statistical reliability of measures of monitoring performance with relatively short periods of measurement. It is widely accepted that the reliability of a measure will increase as the number of observations (responses) on which that measure is based increases. However, when the rate of presentation of stimuli exceeds some value, the task will change in nature so that it can no longer be thought of as requiring monitoring behavior. When this occurs, the performance of the monitoring task will change, and, if the subject assigns a high enough priority to monitoring, something else that he is required to do concurrently must certainly suffer.

Thus, the study to be reported here is concerned with three questions:

1. What is the effect of signal rate on the performance of a task involving the monitoring of a static process when that task is performed concurrently with other tasks?

2. What are the effects on concurrently performed tasks when the rate at which signals are introduced on the monitoring tasks is varied?

3. What is the effect of signal rate on the reliability of response times in the performance of the monitoring task?

II. Method.

Subjects. The 10 subjects who served in this experiment were college students who had received extensive preliminary training and experience on the battery of tasks used. For purposes of efficiency, they were trained and tested as two five-man groups. They were paid for their services at a rate of approximately $9.00 per 4-hour session. They were also offered a bonus of $2.00 for a given session if their performance "equalled or exceeded the level" they had previously demonstrated themselves to be capable of achieving. However, knowledge of having earned the bonus on any given session was withheld until the end of the experiment.

Apparatus. The apparatus used in this experiment has been described in detail elsewhere[1] and, therefore, will be described only briefly here. The subjects performed a total of five tasks presented in six different combinations as indicated in Table 1.

TABLE 1.—Basic 2-Hour Task Performance Schedule

Task	Minutes 00–15	15–30	30–45	45–60	60–75	75–90	90–105	105–120
Warning-lights monitoring	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
Probability monitoring	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
Arithmetic computation		xxx	xxx					
Code-lock solving			xxx	xxx	xxx	xxx		
Target identification						xxx	xxx	
Level of demand on performance	low	med	hi	med	med	hi	med	low

The primary task of interest in the present study was called "warning lights." One aspect of this task was represented by five red lights—one at each corner and one in the middle of the panel. A button was located below each light, and the subject was instructed to push the button associated with a given light should that light be illuminated; pushing the button extinguished the light. The second aspect of the task consisted of five green lights paired with the red lights. In this case, the subject was instructed to push the button below a given green light should that light go out. For each aspect of the warning lights task, response times were measured in tenths of a second from the onset (or offset) of a light until the subject returned the light to its normal condition by pushing the appropriate button.

The second task, called "probability monitoring," required the subject to scan four randomly fluctuating meters to determine if the average of the pointer positions of any meter had deviated from zero (12 o'clock position). The signal to which the subject was to respond was a shift of the distribution of pointer positions of a given meter from a mean of zero to a mean that was 25 units to the right or the left of zero. If the subject suspected a bias to be present on a particular meter, he tested the hypothesis by throwing a three-position, spring centered, lever-type switch in the direction of the suspected bias. The pointer would automatically come to rest on its correct mean, thus, giving him immediate feedback as to the accuracy of his hypothesis. Time was recorded to the nearest second from the introduction of a bias until the appropriate response removed the bias or until that bias was replaced by a new bias on the same or some other meter. Signals were introduced on this task at an average rate of 15.5 signals per hour, and only one meter was biased at any given time. Two measures were computed: Mean detection times for those signals that were detected and percent of signals detected.

The third task was called "mental arithmetic." It required the subject to sum two three-digit numbers and subtract a third three-digit number from the obtained sum. The subject entered his answer by appropriate manipulation of a set of three decade pushbuttons for the first three digits and a three-position, center-off switch to indicate whether the fourth digit was a "0" or a "1." Problems were presented at a rate of three per minute; performance was scored in terms of the percentage of problems answered correctly.

The fourth task, called "target identification," required the subject to view a standard "target image" and then decide whether the first, second, or neither of two comparison images was the same as the standard image. The task was made somewhat more difficult by random distortion of the comparison images. The subject indicated his answer by depression of the appropriate one of three buttons marked "1," "2," and "N" (Neither). Problems were presented at a fixed rate of two per minute. Performance was measured in terms of the percentage of problems answered correctly. This task also had a "crew" component. After one of the subjects, who was designated as the crew commander, had made his response as an individual, an auxiliary display was illuminated at his crew position showing the choices of each member of the crew (including his own). Making whatever use he wished of this information about the crew responses, the commander made a selection of an answer "on behalf of the crew." The commander's choice was then displayed at each individual crew position. Only the crew commander received direct feedback as to which answer was correct, and it was his option as to whether or not to pass this information on to the remainder of the crew. Both crew commanders almost always indicated the correct answer to the crew. Performance on the task, both individual and crew, was measured in terms of the percent of correct responses.

The fifth task, called "code-lock," involved group performance in the solution of problems. The subjects were required to find the correct sequence in which each subject should push the code-lock button located on each subject's panel to illuminate a green light indicating that the problem had been solved. The onset of a red light on each subject's panel indicated that a problem was present. When the subject who was number one in a particular sequence pushed his button, the red light would go out and remain out as long as the subsequent responses made were in the correct sequence. A button pushed out of sequence would re-illuminate the red light and the problem would automatically reset to the beginning, thus requiring the subjects already identified to push their buttons again before the search could continue. The subjects were trained to follow a standard search procedure so that redundant responses could be more readily prevented. A 30-second delay followed the solution of a given new problem after which the same problem was presented again and the subjects were to enter the solution as rapidly as possible without error. After another 30-second delay, a new problem was presented. The subjects used an earphone intercom system to coordinate performance of the task, and the crew commander was responsible for maintaining an efficient attack on the problems. Although measures were made of the time required to solve the problems, the number of errors, and the total number of responses made by all subjects, the code-lock data were not subjected to statistical analyses; since the unit of analysis was the crew, the one degree of freedom available for the appropriate error term made any such analysis of questionable value. Thus, the major functions served by this task were to provide a workload factor and to introduce an element of subject interaction.

Procedure. Prior to the beginning of the experiment, subjects were given extended training on the task complex and served in an experiment[2] involving three 4-hour sessions in which different signal rates were used on the probability monitoring task.

The experimental phase of the study consisted of three, 4-hour sessions for each of the two groups of subjects. The first group (Able crew) was tested on the morning of the 11th, 15th, and 22nd of March. The second group (Baker crew) was tested on the afternoons of the 13th, 19th, and 21st of March. (The month is of significance only in that the specific schedule of test sessions resulted from inclement weather.) On the first test session, each group was presented warning light signals at the same rate used during training and during the earlier experiment. The average signal rate was 17 signals per hour; the mean intersignal interval was 212 seconds and the range was 119 seconds. On the second session, the average signal rate was 10.3 signals per hour; the mean intersignal interval was 348 seconds; the range was 195 seconds. On the third session the average signal rate was 22.5 signals per hour with a mean intersignal interval of 160 seconds and a range of 90 seconds.

Performance was measured on the combinations of tasks shown in Table 1, each session consisting of two of these 2-hour programs in succession. Although no formal rest period was provided in the 4-hour session, subjects were granted permission, on request, to leave their duty stations one at a time for the purpose of going to the rest room or getting a drink of water.

III. Results and Discussion.

Warning Lights Monitoring. A separate non-parametric statistical analysis (Friedman's two-way analysis of variance by ranks) was applied to the data for response times to the red lights for each of the six combinations of tasks under which performance was measured. The mean response times for each signal rate and each task combination are shown in Table 2; the means for the data combined over the first 2 hours of a session, the second 2 hours, and the entire 4 hours are also shown. In no case did the resultant statistic (Chi-square r) even approach significance.

TABLE 2. Mean Response Time in Seconds to Red Lights

Task Combination	Signals/hour			X^2r	P
	17.0	10.3	22.5		
Monitoring only	.9	.9	1.0	------	------
Arithmetic	1.0	1.3	.9	------	------
Arith & code-lock	1.2	1.0	1.0	------	------
Code-lock	1.0	1.0	1.0	------	------
Target ident & code-lock	1.0	1.2	1.4	3.65	.20
Target ident	1.0	1.0	1.0	------	------
1st 2 Hours	1.0	.9	1.0	------	------
2nd 2 Hours	1.0	1.2	1.1	------	------
4 Hours	1.0	1.0	1.0	------	------

The attention value of the illumination of a red light was reported by all subjects to be relatively high, and it was unusual for a signal to go undetected for even as long as 5 seconds. Presumably, the scanning habits developed by the subjects during the course of training at a rate of 17 signals per hour were adequate to prevent performance changes at the higher as well as the lower rates of signal presentation.

The data for mean response times to the offset of green lights are shown in Table 3. Again, none of the statistical tests approached significance. The attention value of the offset of a green light is not as high as that of the onset of a red light. This is seen clearly in the fact that the grand mean response time for red lights was 1 second whereas the grand mean for green lights was 3.8 seconds. However, as with the red lights, the most likely explanation of the lack of an effect of signal rate is that the levels of training of the subjects had resulted in the development of efficient scanning habits with respect to the detection of extinguished green lights.

TABLE 3. Mean Response Time in Seconds to Green Lights

Task Combination	Signals/hour			X^2r	P
	17.0	10.3	22.5		
Monitoring only	4.1	2.0	1.7	------	------
Arithmetic	4.2	5.0	3.7	------	------
Arith & code-lock	5.5	4.0	3.7	------	------
Code-lock	3.0	2.6	3.5	------	------
Target ident & code-lock	4.3	3.7	7.9	------	------
Target ident	3.1	6.7	4.4	------	------
1st 2 Hours	2.9	4.1	3.4	------	------
2nd 2 Hours	5.0	4.1	3.8	------	------
4 Hours	3.7	4.1	3.6	------	------

Thus, changes in signal rate within the range of values used in the present experiment do not affect the speed with which subjects detect signals. This finding holds for both responses to the onset of a red light and the offset of a green light.

Probability Monitoring. Data for the percentage of detections of meter biases are not presented since essentially all signals were detected, and those few signals that were missed were scattered across the three rates at which warning lights signals were presented. The finding that nearly all biases were detected is consistent with previous research with this task with test sessions of 4 hours or less.[1,2]

The mean detection times for the three experimental conditions are shown in Table 4. Of the nine statistical tests applied to these data, significant differences were found in four cases. The first significant statistic was for the "monitoring only" condition; the slow rate of presentation of warning lights signals resulted in the longest detection times for meter biases, and the fast rate of presentation was the best. However, the difference between the two extreme values was only 3 seconds or approximately 12% of the mean detection time at the fast rate of signal presentation. It is of some interest to note that a test of the two extreme values resulted in a Wilcoxon T that was not significant ($N=10$; $T_{.05}=8$; obtained $T=9$).

TABLE 4. Probability Monitoring Mean Detection Times in Seconds

Task combination	Signals/hour on warning lights task			X^2r	P
	(Training) 17.0	10.3	22.5		
Monitoring only	25	27	24	6.2	<.05
Arithmetic	35	34	30	------	------
Arith. & code-lock	41	41	36	------	------
Code-lock	41	31	31	7.8	<.05
Target ident. & code-lock	32	45	37	------	------
Target ident	39	39	34	------	------
1st 2 Hours	33	36	29	------	------
2nd 2 Hours	36	34	33	6.2	<.05
4 Hours	35	35	31	9.8	<.01

The differences in bias detection times across warning lights signal rates were also significant for the condition in which the probability monitoring task was performed concurrently with warning lights and code-lock. Here, the differences between the mean detection times at the medium signal rates on warning lights and both the fast and slow rates were substantial (10 seconds in each case). Individual Wilcoxon T's showed the middle and slow rates to differ significantly ($P<.05$) but not the middle and fast signal rates ($P>.05$).

The differences across signal rates were also significant in the case of the combined data for the second 2 hours of the sessions and for the entire 4 hours of testing. However, it should be noted that these latter two tests are not independent of the other tests (or of each other) in that the data used in the tests of the individual task combinations are contained in the 2–hour and 4–hour data. In the case of the data for the second 2 hours, the rank orders of the mean detection times at the medium and slow rates are reversed as compared to the ordering during the first 2 hours; performance was better under the medium signal rate during the first 2 hours (though not significantly) but was better under the slow signal rate during the second 2 hours. The detection times were the same for these signal rates for the 4–hour data. From these facts it can be inferred that increasing the rate at which warning lights signals are introduced from 10.3 to 17.0 signals per hour probably does not have a real effect on the detection times for probability biases. Increasing the rate from 17 signals to 22.5 signals per hour probably does have an effect. Clearly, more data are required to determine whether or not the effect is real and, if it is, to determine the warning lights signal rate at which the effect is produced.

Inspection of Table 4 suggests that the obtained significance for the performance condition in which code-lock and the monitoring tasks were active concurrently may have been the result of unusuallly poor performance for the session involving the medium rate of signal presentation on the warning lights task. Fortunately, another set of data were collected in an earlier study under the same experimental conditions that obtained in the present study. These data were from an experiment (in which these subjects served) on the performance effects of the rate at which signals were presented on the probability monitoring task.[2] The signal rates on all tasks were identical in the two experiments for the "training" (medium rate) conditions. Therefore, a second set of statistical tests was carried out in which these data from the earlier experiment were substituted for the data collected at the 17–signals/hour rate in the present experiment. The tests for the monitoring only, the second 2 hours, and the entire 4 hours still showed signal rate on the warning lights task to have a significant effect on detection times on the probability monitoring task. However, in the case of the code-lock task, the effect was not significant.

Responses to warning lights were elicited a little over twice as often at the fast signal rate than at the slow signal rate. The result of this could very well be that the general level of alertness of the subject was higher at the fast signal rate than at the slow rate. This effect would be most pronounced during the parts of the session in which only the monitoring tasks were being performed. There is another possible effect of the increased rate of responding at the fast rate of presentation of warning lights signals. Although substantive data are not available, observation of and discussion with subjects in previous experiments have led to the tentative conclusion that responding to a warning light serves as a stimulus to scan the four probability meters. Thus, since subjects respond to virtually every signal, then the more frequently signals are introduced on the warning lights task, the more frequently will the subjects scan the probability meters. This scanning would be for the most part in addition to the scanning the subjects do as a result of habits developed through practice. Clearly, these two possible modes of operation of signal rate on the warning lights task are not mutually exclusive and probably both were operating.

Mental Arithmetic and Target Identification. The "percentage correct" data for both of these tasks are summarized in Table 5 for each signal rate condition and each task combination. None of the statistical tests revealed the rather small differences across warning lights signal rates to be significant.

TABLE 5. Mean Percent Correct on Arithmetic and Target Identification Tasks

Task combination	Signals/hour on warning lights			X^2r	P
	17.0	10.3	22.5		
Arith. only					
1st 2 Hours	91.1	92.2	92.7	------	------
2nd 2 Hours	91.8	90.7	93.0	------	------
4 Hours	91.5	91.5	92.9	------	------
Arith. & code-lock					
1st 2 Hours	87.0	84.9	87.8	------	------
2nd 2 Hours	87.4	86.4	91.0	------	------
4 Hours	87.2	85.7	89.4	------	------
Target ident. only					
1st 2 Hours	86.3	88.0	86.3	------	------
2nd 2 Hours	90.3	86.3	86.0	------	------
4 Hours	88.3	87.2	86.2	------	------
Target ident. & code-lock					
1st 2 Hours	72.7	75.3	81.0	------	------
2nd 2 Hours	79.7	80.3	78.6	------	------
4 Hours	76.2	77.8	79.8	------	------

All of the previous work with these tasks supports the appropriateness of the assumption that subjects tend to assign relatively high priorities to the performance of the arithmetic and the target identification tasks. Perhaps the major reason is that the subject gets immediate feedback as to how well he is doing on arithmetic and usually gets feedback (from the commander) that permits him to determine how well he is doing on the target identification task. Another, social incentive for doing well on the target identification task derives from the fact that the commander sees what response a given subject has made on each problem, and the commander of the Baker crew in particular urged a subject to do better if that subject was wrong on very many responses. Thus, there is no reason to expect the signal rate of the warning lights task to have a facilitative effect on the performance of either arithmetic or target identification. On the other hand, the workload-producing characteristics of the warning lights task are not such that there would be any reason to expect the high signal rate condition to interfere with either task.

Stability of Warning Lights Data. The relative stabilities of the response times to the red and green light signals across the three rates of signal presentation were evaluated by comparing the reliability coefficient for each rate. Specifically, the correlation between the mean response times for the first 2 hours of performance and the second 2 hours of peformance for each signal rate was computed. Both Spearman rank correlation coefficients and product-moment coefficients were computed.

The Spearman rank coefficients are shown in Table 6. For both the red and the green lights, the coefficients at the two faster rates of presentation were significant at better than the .05 level of confidence using one-tailed tests. One coefficient, green lights at the rate of 17 signals/hour, was significant at the .01 level. As regards this latter coefficient, the obtained value of .94 is the highest reliability coefficient ever obtained for this specific task; typical values previously obtained with larger subject samples have ranged from .50 to .70 for data based on a greater total number of responses per subject.

The product-moment coefficients for the two faster rates were also significant at better than the .05 level of confidence (one-tailed tests), and one coefficient, red lights at the 17 signals/hour rate, was significant at the .025 level of confidence. For both the product-moment and the Spearman rank coefficients, the reliabilities at the slow signal rate (10.3 signals/hour) were low and not significant.

TABLE 6. Half-Session Reliability Coefficients: Spearman's Rank Correlations

Lights	Signals/hour		
	17.0	10.3	22.5
Red	.69*	.18	.62*
Green	.94**	-.07	.59*

One-tailed test:
*.05 level of confidence
**.01 level of confidence

TABLE 7. Half-Session Reliability Coefficients: Product-Moment Correlations

Lights	Signals/hour		
	17.0	10.3	22.5
Red	.772**	.200	.689*
Green	.626*	.027	.705*

One-tailed test:
*.05 level of confidence
**.025 level of confidence

The Spearman-Brown prophesy formula was used to predict the reliabilities to be expected for the full 4 hours of testing. In the case of the red lights, the predicted reliabilities were .871, .280, and .815 for the medium, slow ,and fast rates of signal presentation, respectively. The prepicted reliabilities for the two faster rates are significant at the .025 level of confidence. For the green lights, the predicted 4-hour reliabilities were .69, .053, and .826. Again, the reliabilities at the two faster rates are significant at the .025 level of confidence.

Most of the previous research with this battery of tasks used the slow rate of presentation of signals on the warning lights task.[1] However, in that research, subjects were typically tested for a total of 12 hours (or more) per day, and the unit of analysis for the more important variables was the mean of a full day's performance. Thus, the number of responses on which the data entering into the calculations were based was large enough that the apparently low reliability of a 2–hour session was not a problem.

The present data clearly suggest that an important gain in the stability of the response data for the warning lights task can be realized by using a signal rate on the order of 17 signals/hour. Although in theory a rate of 22.5 signals/hour should yield even more stable data, this was not demonstrated by the present study.

IV. Summary and Conclusions.

This study was concerned with the effects of the rate of presentation of stimuli on a task involving the monitoring of a static process when that task is performed concurrently with a variety of tasks designed to assess aviation-related performance. The task (called warning lights monitoring) consisted of two aspects; the subject responded to the onset of normally-off red lights and to the offset of normally-on green lights by depressing a button to return the light to its normal state. Five red lights and five green lights were located in pairs on the subject's performance panel—one red light and one green light at each corner and one pair in the middle. Three signal rates were used: 10.3 signals/hour, 17.0 signals/hour, and 22.5 signals/hour. Each signal rate was presented during a different 4-hour session of testing. The subjects performed on a standard schedule involving four other tasks presented in different combinations to vary both the level and the nature of the workload imposed. The other tasks involved monitoring (of a dynamic process), mental arithmetic, visual discrimination, and group problem solving. Subjects were given extensive preliminary training on the task complex prior to the beginning of testing.

The only task for which performance varied significantly across the three rates of signal presentation was the task requiring the monitoring of a dynamic process(probability monitoring). This task required the subject to determine whether or not the mean position of the continuously fluctuating pointer of any of four meters had deviated from zero. Significant differences were found when the probability monitoring task was performed with only the warning lights task, and when performed with the warning lights task plus the group problem solving task. The effect of signal rate was also significant for the data combined across all task combinations for the second 2 hours of the test session and for the combined data for the entire 4-hour session. The explanation offered for the effect of the signal rate of the warning lights task on the performance of the probability monitoring task is; (1) the increased rate of response to warning lights at the higher signal rates served to increase the level of alertness of the subjects particularly during the periods when only the two monitoring tasks were performed, and (2) based on previous observations, the warnlights signals tended to serve as stimuli for the subjects to scan the meters on the probability monitoring task; thus, the more frequently signals were introduced, the more frequently the subjects scanned the four probability meters.

It was also found that the reliability coefficients for the warning lights task (first 2 hours of a session versus the second 2 hours) were substantial and significant for the two faster signal rates; the coefficient was low and nonsignificant for the slower rate.

The following conclusions are drawn:

1. The rate at which signals are presented on a task involving the monitoring of a static process does not significantly affect the speed with which signals are detected. The major assumptions underlying this conclusion (as well as the remaining conclusions) are: (a) the attention value of the signals is relatively high, (b) the signal rate is within the aproximate range of from 10 to 23 signals per hour, and (c) the task is performed as a part of a task complex.

2. The concurrent perfomance of other tasks on which subjects would be expected to place high priorities is not affected by variations in signal rate on a static monitoring task. Clearly, above some signal rate (presumably much higher than that used in the present study), direct interference would result. Either the concurrently performed task would suffer or the monitoring task would be largely ignored.

3. Concurrent performance of a task involving the monitoring of a dynamic process may be facilitated by increasing the signal rate of the static monitoring task. This assumes that the signals on the dynamic monitoring task are of relatively low attention value and require close attention to determine their presence.

4. Increased rate of presentation of signals on a static monitoring task will result in increased reliability of the response measures for test periods on the order of 2 to 4 hours. Thus, more reliable assessment of this aspect of complex performance, as it is related to the demands placed on the human operator in aviation operations, is now possible.

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