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CHANNEL CAPACITY AND THE LOCUS OF INTERFERENCE UNDER DUAL TASK CONDITIONS

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Wayne L. Waag

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August 1977

NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
PENSACOLA FLORIDA

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(9) Interim rept.

(16) F51524

Naval Medical Research and Development Command
(17) MF51 524 004-5002-BX5G

(14) NAMRL-1037

Approved by

Ashton Graybiel, M.D.
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Captain R. E. Mitchel, MC, USN
Commanding Officer

(12) 16p.

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NTIS	White Section	☒
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SUMMARY PAGE

THE PROBLEM

In current mission systems, naval aviators and flight officers are required to perform complex tasks under excessive pressure of environmental and task induced stress. The effectiveness of these systems may be dependent upon the operator's capacity to process and respond to a large variety of information. There are currently no adequate measurement techniques for quantifying either human workload capacities or system's demands made upon these capacities. The use of faulty techniques and misinterpretation of available data lead to the development and deployment of systems in which the operator is severely overloaded and required to perform nearly impossible sequences of perceptual, cognitive, and manual tasks. The purpose of this study was to investigate an individual's maximum information processing capacity under complex task conditions in order to provide data necessary in the development of techniques to quantify operator workload capacities and system demands.

FINDINGS

A sample of 120 male naval officer candidates participated in two multitask experiments. The results suggest that performance on the primary task deteriorates as a joint function of both primary and secondary task processing loads. These data provide support for the maximum interference of information processing to occur within the memory dependent and response selection stages of processing.

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Dr. Waag held an NRC-Bureau of Medicine and Surgery Postdoctoral Research Associateship while this research was conducted.

INTRODUCTION

In a summary of the literature on divided attention, Welford (6) concludes that increasing the load of either the primary or the secondary task beyond a critical point can greatly impair performance of one or both of the tasks. The addition of the secondary task can produce differences in the effects of the loads imposed by different primary tasks, effects that are normally undetectable when the tasks are performed alone. This suggests that a subject has a limited information processing capacity and that this capacity must be shared among total processing demands. Whenever demand exceeds capacity, performance will deteriorate.

In an attempt to conceptualize human information processing, E. E. Smith (4) has proposed the following four-stage model: Stage 1, the encoding processes, wherein stimulus information is initially registered, sampled, and subject to gross analysis; Stage 2, central processing, wherein detailed analysis of the stimulus information is carried out for purposes of stimulus definition or identification; Stage 3, response decoding where a selected response is processed for execution; and Stage 4, response execution, which is primarily a motor response.

Major questions to which researchers have addressed themselves concern subjects maximum processing capacity under dual task conditions and the stage of processing at which interference takes place. Moray (3) suggests that discrepancies in the literature may be due to differences in the particular processing demands of the secondary tasks used in different experiments. Secondary tasks requiring primarily detection (e.g., (1)), and those requiring primarily discrimination (e.g., (5)), tend to produce conflicting views regarding processing capacity and the locus of interference. Briggs et al. consider the locus of interference to be in the input stage, or Stage 1 of E. E. Smith's (4) four-stage paradigm. However, M. C. Smith favors the central processing stage; i.e., E. E. Smith's Stage 2. Welford (6) suggests that it might be the result of a translation process; that is, E. E. Smith's Stage 3. Most researchers do not consider response execution, Stage 4, to be a primary source of interference.

The purpose of this study was to probe the maximum capacity of the human information processing system through manipulation of load on both the primary and secondary tasks. The use of a serially presented four-choice discrimination task seemed especially suited to the aims of the study since load (presentation rate) could systematically be increased beyond subject's capacity. The use of a secondary task requiring combinations of detection, short-term memory, and long-term memory provided a means whereby further evidence could be generated concerning the laws of the divided attention effect. Most important, the variation of both primary and secondary load provided a methodology whereby possible interactive effects could be studied.

EXPERIMENT I

PROCEDURE

Sixty male naval officer candidates, all college graduates between the ages of 21 and 29 year, undergoing training at Naval Air Station, Pensacola, Florida, participated in the experiment.

The apparatus consisted of a General Dynamics Response Analysis Tester (RATER).* RATER presents a four-choice discrimination task that requires the subject to match a response key to each of four geometric shapes (circle, cross, triangle, and diamond) appearing in a display window. The presentation of stimuli is in random series. The device is operated in an automatic-paced mode with experimenter control over the rate of stimulus presentation, which can vary from 1 to 2 sec. per symbol. Three digital counters record the number of presentations, the total number of responses, and the number of correct responses.

The effects of primary task load and secondary task load were investigated using a 3 x 4 factorial design. Performance on the RATER served as the primary task. Three levels of primary task load were studied by presenting the symbol-stimuli on the RATER at a 1, 1.5, and 2 sec. per symbol rate. Concurrently, with this primary RATER task, four secondary task conditions were investigated. Specifically, one task condition required subject to monitor a tape recording (as explained below), two tasks required subject to make verbal responses in the event a signal was detected from the recording, and the fourth condition requiring no verbal or monitoring response thus served as a control function.

These three levels of primary task load and four levels of secondary task load were tested using 12 independent groups of five subjects each. Three of these groups served as control group (C) and performed no secondary task while receiving one of the three possible primary task loads. Three other groups (M) performed one of the three primary task loads each while monitoring a tape recording on which were present 22 three-digit three-letter combinations (e.g., 457-GRS). Upon detecting the three-digit combination "214", subjects were instructed to respond verbally with the three letters of the alphabet that would follow the letters given. For example, if subject heard "214DEF", he was instructed to respond "GHI". Without subject's prior knowledge the 214s under this condition were purposely omitted. This constituted a detection task with no target-stimuli and hence no overt response.

Three other groups were designated as stimulus repetition (SR) groups which were similar to the M groups described above except that the subjects were instructed to repeat in order the same letters that followed the "214" combination. Nine "214" sequences were randomly presented among the 22 combinations

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*RATER Model 3 (GDC-DBD69-003).

employed. Conceptually, the task required detection, the use of short-term memory, and the execution of an overt verbal response.

The last three groups, which were designated stimulus transform (ST) groups, received instructions identical to the M groups. However, in contrast to the M groups, subjects were presented with nine "214" sequences that required a response. Conceptually, the task required detection. the use of short-term and long-term memory, and the execution of an overt verbal response.

Five subjects were randomly assigned to each of the 12 groups (3 Control, 3 Monitor, 3 Stimulus Repeat, and 3 Stimulus Transform). Instructions for primary and secondary tasks were both written and oral. Subjects were told that their final score would depend upon how well they performed on both tasks, and, therefore, they were not to concentrate on one task at the expense of the other. For preparation, subjects practiced until they achieved 15 correct responses to the geometric stimuli on the RATER at the 2-sec. presentation rate. Subsequently, the card displaying the correct symbol-button relationship was removed. Simultaneous practice of primary and secondary tasks was then conducted for 1 min. With a primary task presentation rate of 2 items per sec., the secondary task consisted of 6 stimuli of which two "214" sequences were included. If subjects had no further questions, the appropriate 4-min. experimental session was begun.

RESULTS

The data for percent correct responses on the primary task for all experimental conditions are presented in Figure 1.

Significant main effects were obtained for primary task load (presentation rate) ($F = 58.51$, df = 2/48, $p < .01$); secondary task load (type of processing) ($F = 8.76$, df = 3/48, $p < .01$), and their interaction ($F = 2.81$, df = 6/48, $p < .01$). Tests of simple main effects produced significant differences across the primary task conditions at each secondary task load condition. Tukey's HSD tests for pair-wise comparisons revealed that the 1-sec. presentation rate produced significantly lower performance means than did either the 1.5-or 2-sec. presentation rates.

At the 1.5-and 2-sec. presentation rates, group ST produced significantly fewer correct responses than did Groups SR, M, and C. No differences were obtained among Groups SR, M, and C except between M and C at 1.5-secs. At the 1-sec. presentation rate, Groups SR and ST differed significantly from Groups M and C, but not from each other.

To investigate the effects of the secondary task (verbal) in relation to the primary task response measure, the secondary task responses were analyzed in a 3 x 3 factorial design. The data for percent correct responses on the secondary task revealed significant main effects for the primary task load (presentation

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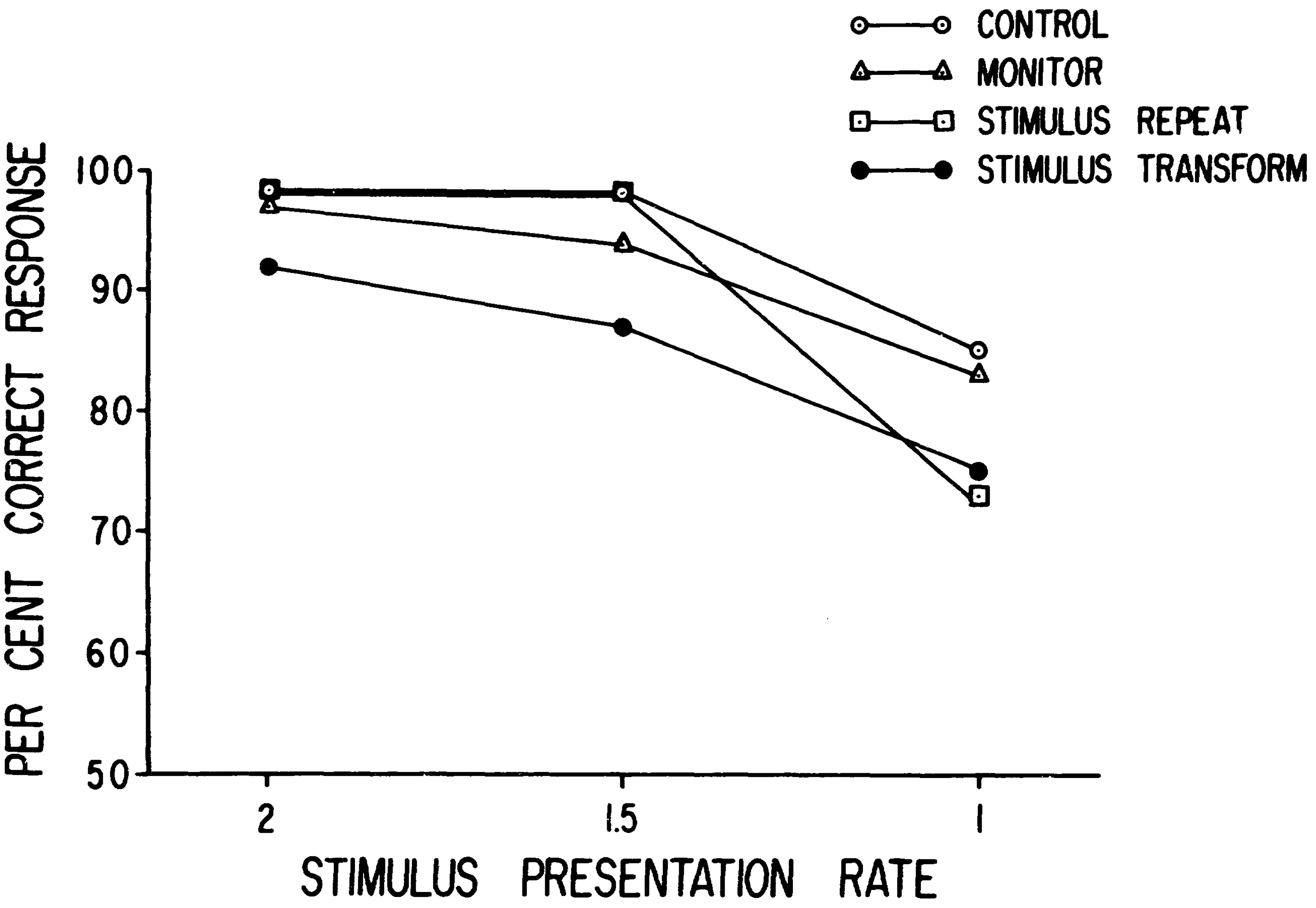

Figure 1: Mean percent correct responses in 2-, 1.5-, and 1-sec. presentation rates for each secondary task condition.

rate) (F = 42.0, df 2/36, $p < .01$); secondary task load (type of processing) (F = 7.21, df 2/36, $p < .05$), and their interaction (F = 2.92, df 4/36, $p < .05$). Tests of simple main effects produced significant differences across the primary task conditions at each secondary task load condition. Tukey's HSD test revealed similar patterns of comparisons as reported with the primary task response measure.

COMMENT

The results of this study are consistent with previous findings, indicating that performance is degraded as a function of increasing loads of both primary and secondary tasks. To explain the resultant interactive effects it is convenient to consider the primary tasks (RATER) in bits of information processed. The primary tasks required subject to process, at an upper limit, 1 bit per sec. at 2-sec. intervals, 1.33 bits per sec. at 1.5-sec. intervals, and 2 bits per sec. at 1-sec. intervals (2). The important relationship between processing capacity and secondary task is revealed most clearly in the comparison of Groups ST and SR. While processing 1 and 1.33 bits per sec., Group SR performed as if no secondary task existed (Group SR = Group C). However, Group ST is significantly different from Group SR while processing 1.33 bits per sec. This indicates that Group ST is experiencing interference from the secondary task due to increased processing load, while Group SR is able to handle the primary task with no apparent interference from the secondary task. However, upon increasing the primary task load from 1.33 bits per sec. to 2 bits per sec., Group SR seems to have exhausted the capacity needed to accommodate the secondary task. Between 1.33 and 2 bits per sec. the significant interaction occurs; within this interval lies the critical point at which spare capacity becomes exhausted. It is at this processing capacity that the individual is unable to accommodate additional task loads that require an overt response. It is important to note that if no response is required, as in Group M, performance is minimally affected. To determine if subject had truly monitored the secondary task, the subjects in Group M were asked if they had detected any "214" sequences. All subjects with correct scores responded in the negative, which was correct. The performance of Group M, thus, suggests that minimal channel capacity is required in a simple detection task requiring no overt response.

Since the ST group experienced performance decrement in both the primary and secondary tasks as the processing load increased on the primary task from 1 to 1.33 bits per sec., and while the SR group did not begin to experience performance decrement until the transition from 1.33 to 2 bits per sec., differentially placed loci of interference are suggested. For the two groups, the essential difference is one of long-term memory processing on the secondary task. It can be concluded that for both the SR and ST groups, the initial sampling (Stage 1) and response execution (Stage 4) are identical. However, comparing the ST and SR group at the 2- and 1.5-sec. intervals suggests the locus of interference for the ST group to be within the central processing stage; the essential difference in the secondary task was one requiring central processing for the long-term memory response. But comparing the data at the 1-sec. interval indicates parity for both the ST and SR groups. This rapid and substantial performance decrement by the SR group seems to be the result of requiring a verbal response by subject. This decreased dependence on central processing for the SR group compared to be within the response decoding stage (Stage 3). Nevertheless, it seemed possible that such results may have been due to the actual number of verbal responses required by subject. In other words, the verbal response load may have had an interactive effect with the primary and secondary task conditions.

In order to investigate this possibility, a second experiment was performed in which the number of verbal responses required by subject in the secondary task was manipulated.

EXPERIMENT II

PROCEDURE

The apparatus and instructions for Experiment II were identical to those of Experiment I. The difference involved the number of verbal responses required by subject in the secondary task. An additional 60 male naval officer candidates were assigned, five each, to one of 12 conditions. For each primary condition of 2, 1.5-, and 1-sec., there were four secondary task conditions. Group SR-6 had six "214" sequences in a total of 22 stimuli, thus requiring six verbal repetitions. Group ST-6 had six "214" sequences from a total of 22 stimuli, thus requiring six verbal transforms, while Groups SR-12 and ST-12 had 12 "214" sequences requiring 12 verbal repetitions and 12 transforms. With this method both Groups SR and ST had a 50 percent increase and decrease (9 ± 3) in verbal responses in relation to requirements of Experiment I.

RESULTS

The data for percent correct responses on the primary task are presented in Figure 2. The data were analyzed by a factorial design having three between-subject factors (primary task presentation rates of 1, 1.5-, 2-sec.); two secondary task processing conditions (SR vs ST); and two verbal response rate conditions (6 vs 12). Significant main effects were obtained for presentation rate ($F = 57.03$, $df = 2/48$, $p < .01$); and secondary task condition ($F = 6.56$, $df = 1.46$, $p < .01$); but not for verbal response rate ($F = .43$, $df = 1/58$). None of the interactions was significant.

These results suggest response load to have little effect upon primary task response function. Although not statistically significant, a trend was noted toward differences between the ST and SR groups at the 1.5-sec. presentation rate. Since no effects due to response load were obtained, the data for the ST and SR groups were combined from Experiments I and II. These combined data are presented in Figure 3. Individual orthogonal comparisons revealed a significant difference ($p < .01$) between the ST and SR groups at the 1.5-sec. rate only.

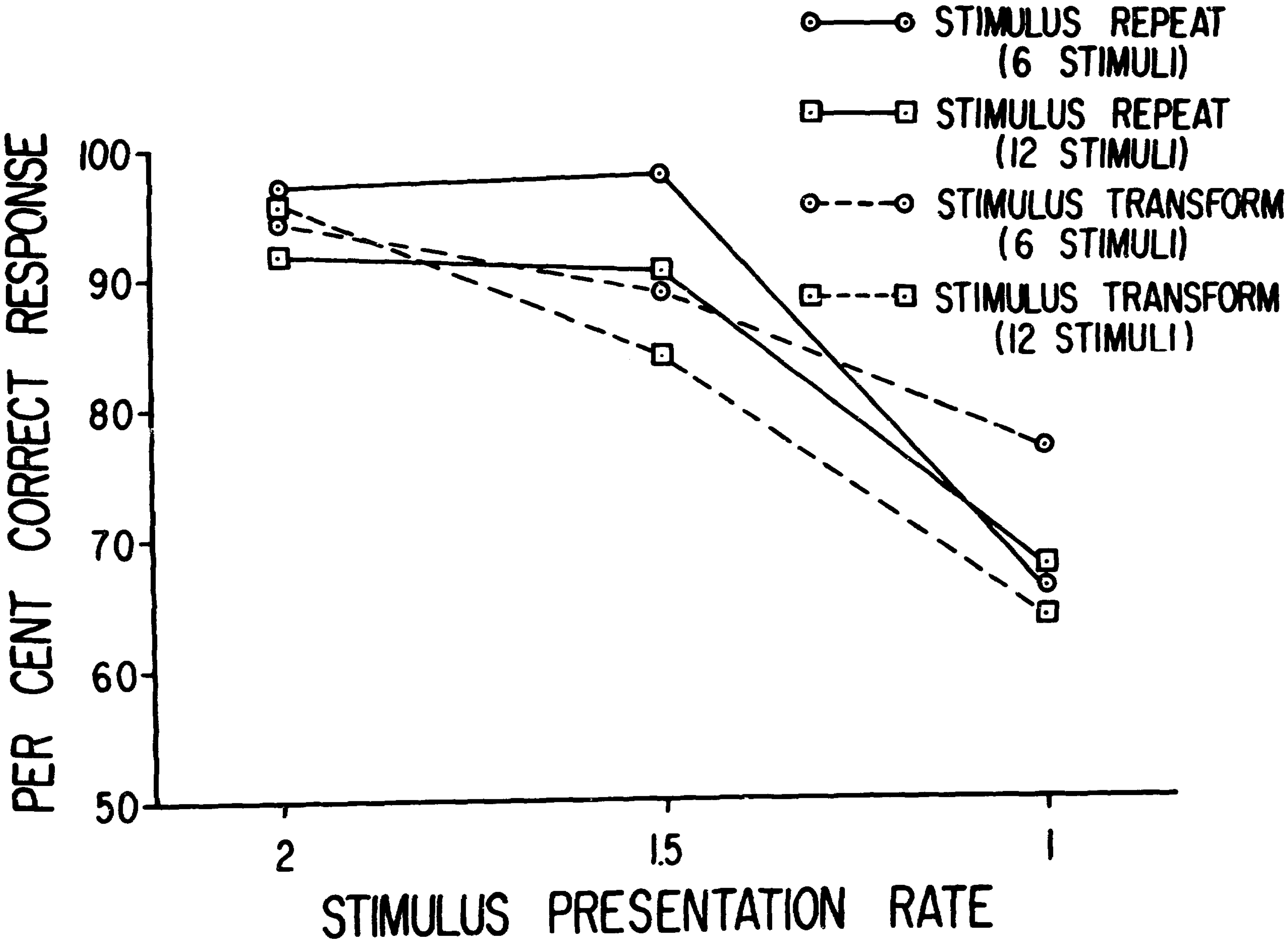

Figure 2: Mean percent correct responses in 2-, 1.5-, and 1-sec. presentation rates for stimulus repeat and *stimulus transform* 6 and 12 target conditions.

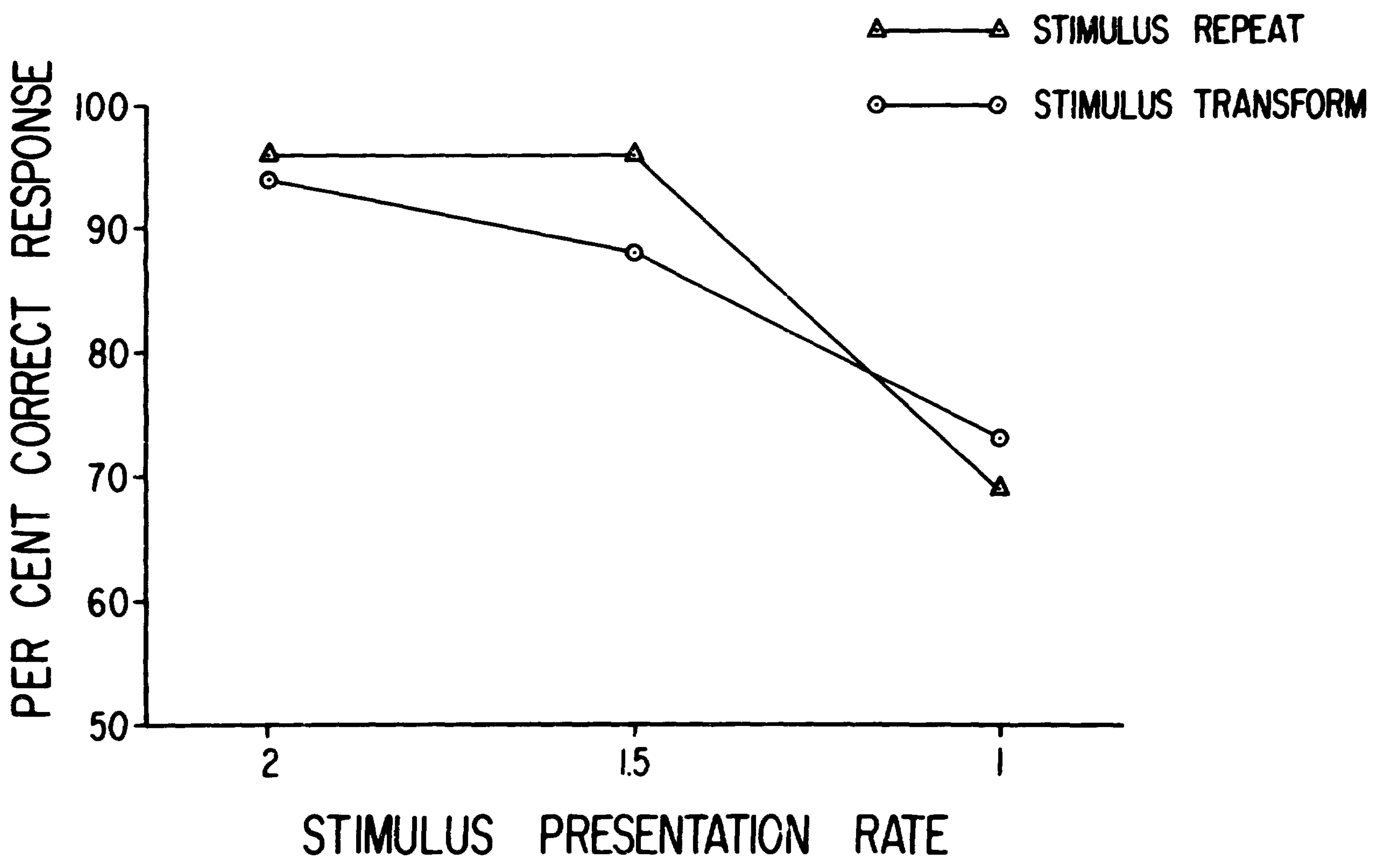

Figure 3: Mean percent correct responses in 2-, 1.5- and 1-sec. presentation rate for combined data from Experiments I and II. Stimulus repeat and stimulus transform groups only.

COMMENT

The results of Experiment II indicate that an increase or decrease in verbal responses for Groups ST-6 and ST-12 had no discernible effects on primary task performance. The only detectable difference between Experiment I and Experiment II occurred at 2 and 1.5 sec. for Group SR-12, which had a significant decrease in performance compared to Experiment I. The combined data for the 6, 9, and 12 verbal response conditions for Groups SR and ST reveal no difference in performance for Groups SR and ST at the 2- and 1-sec. intervals but a significant difference at 1.5 sec.

CONCLUSIONS

The results of Experiments I and II provide little support for the locus of interference being located at either: (a) the stimulus sampling process within an initial encoding stage (Stage 1) as reported by Briggs, Peters, and Fisher (1); or (b) the area of response execution and control (Stage 4). Because in both the ST and SR groups the stimuli were identical,and responses were equivalent in nature, there should have been no difference, or a constant difference between the two groups across primary conditions. Group SR's secondary task can be assumed to require detection and use of short-term memory, while Group ST's task required detection, short-term memory, and long-term memory. For example, Group SR detected the stimulus and then repeated it verbatim, while Group ST detected the stimulus, held it in short-term memory, retrieved the correct response from long-term memory, and then gave the correct response. The additional retrieval time from long-term memory was not significant at the 2-sec. interval (1 bit per sec.), but as the primary task load increased to 1.5-sec. (1.33 bits per sec.), the additional time required for retrieval became significant enough to degrade Group ST's performance.

This performance decrement that seems to be the result of the long-term requirement suggests that for the ST group, the locus of interference is in the central processing stage (Stage 2). However, group SR equivalency at the 1-sec. interval with Group ST seems best explained by considering the locus of interference for group SR to be within the response decoding stage (Stage 3). It seems at this high processing rate of 2 bits per sec. on the primary task that subject has insufficient space capacity to accommodate any additional secondary task load that requires an overt verbal response. The primary task seems to be approaching subject's maximum processing capacity, and any additional response decreases performance for the SR group.

Further evidence for this position is provided by the analysis of the secondary task (verbal) data. With the secondary task data paralleling the pattern of the primary task data, it can be concluded that the subjects were following instructions and attending to both tasks equally. The parallel patterns in the data preclude the possibility that subjects were concentrating on one task at the expense of the other.

The findings of this investigation indicate that in a dual task situation, the critical point at which performance begins to deteriorate is a function of secondary task load. If a secondary task requires detection with no overt response (Group M), then performance does not begin to diminish until somewhere near the processing rate of 2 bits per sec. However, if the task requires detection, the use of short-term memory, and the execution of an overt verbal response (Group SR), then performance begins to drop rapidly just past 1.33 bits per sec. If the task requires detection, the use of short term and long term memory, and the execution of an overt response (Group ST), performance has a gradual and definite decline beginning at 1 bit per sec.

In summary, the results of this study provide evidence suggesting the locus of interference to be differentially located within the control processing and response decoding stages, depending upon the requirements of the secondary task. Tasks involving detection and short-term memory result in interference effects within the response decoding stage. The addition of a long-term memory requirement appears to shift this effect to the central processing stage. It appears that there is no single locus of interference within the processing system; rather, the locus may shift as a function of the requirements of the secondary task.

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1. REPORT NUMBER NAMRL- 1239	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Channel Capacity and the Locus of Interference Under Dual Task Conditions.		5. TYPE OF REPORT & PERIOD COVERED Interim 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Wade R. Helm Robert P. Fishburn, Jr. Wayne L. Waag		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Aerospace Medical Research Laboratory Naval Air Station Pensacola, Florida 32508		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS MF 51.524.004-5002-BX5G
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE August 1977 13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		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)

Information Processing
Workload Capacity
Task induced stress

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In current mission systems, naval aviators and flight officers are required to perform complex tasks under excessive pressure of environmental and task-induced stress. The effectiveness of these systems may be dependent upon the operator's capacity to process and respond to a large variety of information. There are currently no adequate measurement techniques for quantifying either human workload capacities or system's demands made upon these capacities. The use of faulty techniques and misinterpretation of available data lead to the development and deployment of systems in which the operator is severely overloaded and required to perform nearly impossible sequences of perceptual, cognitive, and manual tasks. The purpose of this study was to investigate individual's maximum information processing capacity under complex task conditions in order to provide data necessary in the development of techniques to quantify operator workload capacities and system demands.

A sample of 120 male naval officer candidates participated in two multi-task experiments. The results suggest that performance on the primary task deteriorates as a joint function of both primary and secondary task processing loads. These data provide support for the maximum interference of information processing to occur within the memory dependent and response selection stages of processing.