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SOME SOURCES OF LOAD AND CONSTRAINTS ON OPERATOR PERFORMANCE IN A SIMULATED RADAR AIR TRAFFIC CONTROL TASK

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FOREWORD

This report covers part of the research on man-machine systems being conducted in the Laboratory of Aviation Psychology and the Department of Electrical Engineering of The Ohio State University, with Dr. George E. Briggs as Principal Investigator. The objectives of this research are (1) the development of new human factors methodology for studying man-machine systems, (2) the application of new methodology to several different types of systems in order to modify and improve the validity and generality of concepts, (3) the development of human factors principles for the analysis and synthesis of systems, and (4) the formulation of human factors principles and information in terms compatible with standard engineering practice.

The present report was prepared for the Engineering Psychology Branch, Behavioral Sciences Laboratory, Aerospace Medical Laboratory of the Wright Air Development Division, under Contract No. AF 33(616)-6166, Project 7184, Task 71583, with Dr. George O. Wright acting as Task Scientist. This work was initiated under Contract No. AF 33(616)-43 and continued under Contract No. AF 33(616)-3612 with Dr. James C. McGuire acting as Project Scientist and Dr. Paul M. Fitts as Principal Investigator.

ABSTRACT

Two general factors relevant to human performance in a man-machine system were subjected to experimental analysis: (a) the influence of task load on operator capacity and (b) the effects of situational constraints on operator adaptability. Four variables, traffic input rate, control zone area, control team organization, and arrival sequencing procedures, were manipulated. Results from the observation of six 2-man teams indicated that physically defined constraints were more detrimental than those imposed by rules or organization structure. Procedures intended to enhance performance which depend on operator predictions or anticipations were observed to have a limited utility. Under high load stress, operator's actions seemed entirely determined by the immediate circumstances.

PUBLICATION REVIEW

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INTRODUCTION

The present experiment is the eighteenth in a series of investigations of human performance in a radar air traffic control system in which system simulation has been employed as a research technique. The purpose of the program is to develop simulation methods in conjunction with the comparative evaluation of system design and system management alternatives. A by-product of this process has been the tentative specification of some of the underlying general characteristics of man-machine interactions (ref. 4). Two factors, the influence of task load on operator capacity and the effects of situational and procedural constraints on operator adaptability, have appeared with sufficient consistency to warrant an attempt at specific identification and analysis.

The nature of the first factor is largely self-explanatory. The problem involves identifying the sources of load on the system and balancing the momentary demands (engendered by the input load) against the capacity characteristics of the operator population.

The second factor requires further specification. A basic ingredient in effective performance of many systems is the ability of the human operator to modify his activities in adjusting to a wide variety of circumstances. Many apparently desirable or innocuous features of the task situation can operate such that the freedom of choice available to the operator is severely compromised (ref. 2, 5, 8). Thus, the problem is similar to the one generated by the load-capacity interaction. Experimental analysis is required to determine the sources of constraint and to assess their true effect on system performance. An example of the latter facet of the problem is provided in a recent report in this series (ref. 2) which indicated a positive benefit from certain procedural constraints under emergency operating conditions and a negative effect on performance from the same constraints under normal operating conditions.

The purpose of the present experiment was to assess further both man-system interactions specified above. In addition, we wanted to explore the hypothesis that system operators tend to concentrate on short-range outcomes and discount long-range effects under conditions of high input load in a reiterative decision-making task, such as is provided by the air traffic control problem. If such were the case, any procedure which required the operator to respond counter to this tendency would function as a severe constraint and thus become a potential source of reduction in system performance.

The approach adopted was a multivariate experimental design which included the following: (a) traffic input rate (as a direct source of load), (b) size of the control zone (as a possible constraining factor and a practical issue), (c) in-line versus sector allocation of responsibility within the two-man control team (as an attempt to directly compare the load and constraint factors), and (d) a long-range scheduling procedure (to evaluate the hypothesis concerning short-term versus long-term outcomes).

METHOD

Apparatus

In this experiment, as in those preceding it in the series, we used the 30-target OSU Electronic ATC Simulator (ref. 1) as the basic task-generating device. The equipment consists of 30 radar target generators and appropriate analog facilities to provide realistic plan-position readouts via cathode ray tube displays. The basic unit was augmented by a variety of communication and data recording equipment.

Traffic Control Task and Simulated Control Center

The approach control segment of the total air traffic control system was simulated for test purposes. Using radar-type inputs, the operator was required to guide the approach of inbound aircraft from points 50 miles from their destination into position for "final" (GCA) let-down which covered the last 10 miles of the landing sequence. GCA capacity was arbitrarily fixed at one aircraft every 30 seconds, assuming a single active runway.

In the present study, two operators were assigned to the approach control segment. They were responsible for the safety of the incoming aircraft (avoidance of mid-air collisions) and the efficiency of the process as measured by the extent of delay enroute. The precise allocation of functions between the two controllers constituted one of the experimental variables and is described in a subsequent section.

The control task was presented as a preprogrammed "problem." Each problem consisted of the arrival of 20 aircraft during a fixed period of time, contingent on the traffic input rate established. Four different aircraft were used: a high performance jet bomber, a jet cargo, a piston engine cargo, and a piston engine utility or training aircraft. The performance characteristics of these aircraft

Table 1

Aircraft Performance Characteristics

Aircraft	Parameters				
	Cruise Speed (knots)	Cruise Altitude (thous. ft.)	Descent Rate (K-ft./min.)	Descent Speed (knots)	Pattern Speed (knots)
Jet Bomber	400	40	12	300	200
Jet Cargo	300	30	6	250	150
Conventional Cargo	250	20	2	200	100
Conventional Utility	200	15	2	200	100

are presented in table 1. Of necessity, these characteristics represent a composite extrapolation from existing operational aircraft and represent hypothetical prototypes of aircraft which can be expected as future users of air traffic control facilities.

The control center environment was a miniature replica of an actual operational setting. In addition to the two approach controllers' stations, two other positions in the center were manned to enhance realism of the simulation. The GCA function was simulated by an assistant experimenter who also acted as an umpire by initiating and recording go-arounds for those aircraft which did not meet established requirements for position, speed, heading, altitude, or separation when released to GCA. A second man functioned as a pickup operator—passing flight progress slips to the approach control operators as the designated aircraft arrived at the boundary of the approach zone. This second operator also acted as a monitor; he was responsible for the maintenance of simulation fidelity and also recorded violations of air safety (near misses) when they occurred.

In several ways the simulated control center was an idealized version of operational settings. For example, voice communications were relatively free of channel interference and background noise. The visual display was free of clutter, and targets were omnipresent and carried identification symbols (ref. 10, 12). Furthermore, ambient illumination was of the Broad Band Blue type designed to enhance the signal-to-noise characteristics of cathode ray tube presentation (ref. 9). The idealization of information flow facilities was done to achieve maximum test sensitivity.

Experimental Variables

Four factors were manipulated to provide the independent variables for the present experiment: traffic input rate, control zone size, arrangement of the 2-man approach control team, and the procedure for establishing landing sequence. In operational terms the variables are defined as follows:

1. Traffic input rate: Two levels of this factor were employed: an average arrival interval of 90 seconds and an average arrival interval of 120 seconds between aircraft. Within the limits imposed by a fixed average for the 20 aircraft constituting a problem, arrival time was random.

2. Control zone area: Two levels of this variable were compared: a control area with 50-mile radius and an arc of 157 miles at the greatest range (in other words, the area bounded by 0° and 180° of a circle of 50-mile radius and origin at the touchdown point of the runway) and an area just half as large with the same radius but with an arc of 78.5 miles. Figure 1 shows the arrangement in diagramatic form.

3. Control team organization: Two configurations were compared. In the sequential, or in-line version, one operator was responsible for guiding the incoming aircraft from entry into the 25-mile radius. Initial speed reduction and descent instructions would normally be required during this phase of the approach. The second operator took responsibility for each aircraft at the 25-mile radius when he received the appropriate progress strip from the first operator. The second operator would normally be required to monitor the descent of each aircraft, instruct the pilot regarding final speed reduction, and establish position and heading for GCA acceptance.

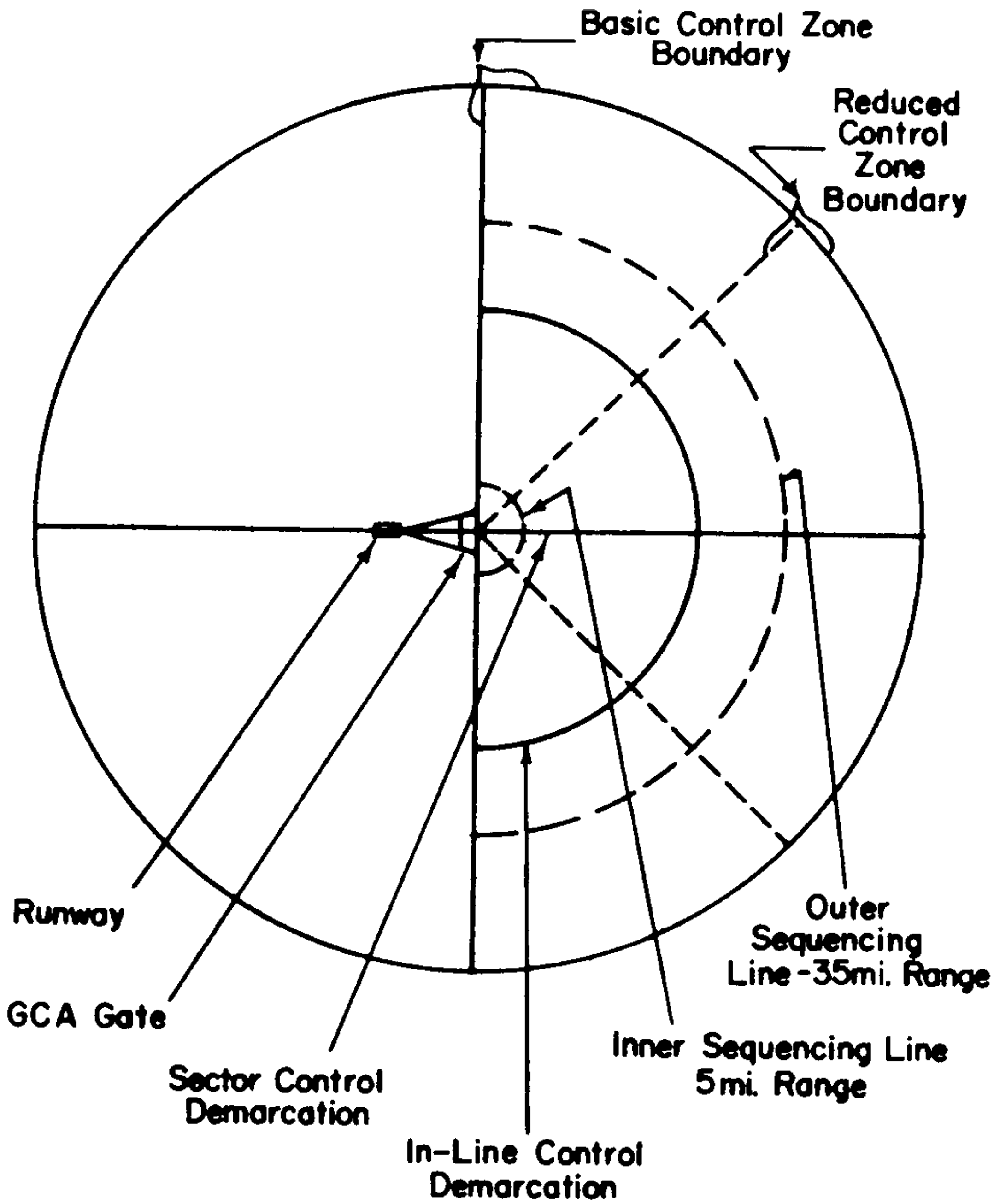

Figure 1. Diagram of Control Zone Boundaries and Arrival Sequencing Structure.

In the parallel, or sector set-up, each controller was responsible for the complete approach sequence for all aircraft entering through his area. Coordination between the operators was required for interlacing the inbound aircraft as they were being fed into the final common GCA approach path.

Both configurations are illustrated in figure 1.

4. Procedure for arrival sequencing: Three alternate procedures were compared. In the basic condition, fixed limits on arrival interval were imposed only at the GCA gate. In the second condition, specific intervals were required at a range of 5 miles from GCA turnover to insure proper spacing when the turnover point was reached. In the third condition, sequencing (in terms of separation interval) was required at a 35-mile range to insure that GCA standards would be met when the inbound aircraft came to the GCA transition point.

Each of the variables compared were considered useful in terms of the goals of the experiment. Traffic input rate was employed as a primary and reliable source of load which could be expected to interact with and accentuate the effect of the other factors. Control zone area was seen as one means of directly influencing the number of response alternatives available to the operator. Thus, while some increase in separation errors could be expected solely as a consequence of increased crowding in the smaller area, a finding of an increase in delay enroute could be interpreted as an effect of the reduction in the number of available flight routes open to the controller's choice.

The arrangement of the controller team as a variable follows a pattern established in earlier studies in this series (ref. 5, 11). Under the in-line arrangement, response constraint effects could be expected to predominate since the close-in controller's actions are limited by the output of his partner. In the sector arrangement, the load factor would predominate, since the communications interchange required for coordination is a demonstrated source of load (ref. 3, 5, 7).

Finally, the sequencing procedure was included to force the operators to respond to long-range considerations. We considered that such a requirement could well enhance system performance by allowing the operator the means of solving the sequencing problem in advance. However, on the basis of previous evidence (ref. 6) we expected performance degradation would be the more likely outcome.

Subjects and Statistical Design

Six teams of 2 controllers per team participated as experimental subjects. These subject-operators had received intensive training over periods ranging up to 18 months prior to their participation in the present experiment. All had had at least 20 hours practice under comparable loads and procedures.

The 4 experimental variables were arranged in a factorial design resulting in 24 unique conditions. Each subject-team was exposed to each condition once. Table 2 illustrates the factorial design and table 3 presents the sequence of conditions as experienced by each team.

Procedure

An experimental session consisted of 6 problems, each lasting 35 to 40 minutes. Four sessions were required for each team to complete the cycle of 24 conditions. Twenty-four hours elapsed between the start of each session. Four traffic programs were used to create the control problem. These programs were reused in a counterbalanced format. Table 4 presents a typical program.

Table 2

Factorial Experimental Design

Variable	Conditions																							
Arrival Sequencing Procedure	Sequencing at GCA Gate								Sequencing at 5-Mile Range								Sequencing at 35-Mile Range							
Traffic Input Rate	90-Second Interval				120-Second Interval				90-Second Interval				120-Second Interval				90-Second Interval				120-Second Interval			
Control Team Organization	In-Line		Sector		In-Line		Sector		In-Line		Sector		In-Line		Sector		In-Line		Sector		In-Line		Sector	
Control Zone Area	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small	Large	Small
Condition Code	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X

Table 3

Schedule of Experimental Conditions*

Team	Session 1						Session 2						Session 3						Session 4					
	Trial						Trial						Trial						Trial					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	N	L	P	J	R	V	T	X	S	U	W	Q	H	D	F	B	C	A	E	G	I	K	O	M
2	B	H	D	F	A	E	C	G	I	M	O	K	J	P	L	N	W	Q	U	S	X	T	V	R
3	E	G	A	C	W	U	S	Q	P	J	L	N	M	O	K	I	V	X	R	T	F	H	B	D
4	U	S	Q	W	O	M	I	K	D	B	H	F	T	R	X	V	L	J	N	P	C	A	G	E
5	T	V	X	R	B	F	D	H	E	G	C	A	Q	W	U	S	M	K	I	O	P	N	L	J
6	K	I	M	O	N	L	J	P	X	R	V	T	A	C	E	G	F	D	B	H	S	Q	W	U

* See table 2 for condition code.

Table 4

Typical Entry Program
(Conditions: 120-second entry interval, large control zone)

Entry No.	Entry Time	Entry Quad.	Desti-nation	A/C Code	Set-Up NS	Set-Up EW	Heading	Type	Altitude	In-Line All Channel 1 Channel
1	000	S	17	B7	31	39	308	KC	30A	2
2	078	S	13	C8	5	50	276	T	15	2
3	126	N	2	C5	50	7	188	T	15	1
4	210	N	6	A1	38	32	220	B	40	1
5	222	S	20	B4	44	23	332	KC	30	2
6	306	N	10	D2	15	48	252	C	20	1
7	346	S	15	B1	19	46	292	KC	30	2
8	412	N	8	A4	28	41	236	B	40	1
9	424	N	12	C2	2	50	268	T	15	1
10	448	S	23	D5	50	3	356	C	20	2
11	510	S	18	C7	36	35	316	T	15	2
12	614	N	9	C4	22	45	244	T	15	1
13	736	S	16	D8	25	43	300	C	20	2
14	770	S	24	B8	50	2	358	KC	30	2
15	818	N	1	D1	50	2	182	C	20	1
16	852	S	19	B5	40	29	324	KC	30	2
17	986	N	5	A7	42	26	212	B	40	1
18	1022	S	22	D4	49	10	348	C	20	2
19	1072	N	3	A2	48	14	196	B	40	1
20	1140	N	11	A5	9	49	260	B	40	1

Criteria

Two major performance measures were employed: safety, which consisted of a tally of the frequency of separation errors (potential mid-air collisions or near-misses), and flight delay which was the excess flight time proportional to a base figure provided by the theoretical minimum flight time for a given aircraft type. In addition, errors such as missed approaches (GCA go-arounds) were recorded and communications between controller and pilot were analyzed.

RESULTS

The results based on the delay enroute criterion were subjected to both analysis of variance and nonparametric tests. The observed mean percent delay and the results of the nonparametric evaluation are presented in table 5. Table 6 presents the summary of the analysis of variance.

The effect of traffic input rate was as predicted: a 12.1 percent increase in delay occurred under the high-input rate condition which was statistically significant at $P < .05$. The reduction in control zone area increased delay by 9.0 percent, which was also statistically significant at $P < .05$. The slight difference in delay attributable to the different control team organizations was not statistically reliable. The difference favored the sector arrangement, however.

Table 5

Comparison of Conditions Using Mean Percent Delay Criterion

	Conditions								
	Traffic Input Rate		Control Zone Area		Control Team Organization		Arrival Sequencing Procedure		
	120-Sec. Interval	90-Sec. Interval	157-Mi. Arc	48.5-Mi. Arc	In-Line	Sector	GCA Gate	5-Mi. Range	35-Mi. Range
Mean Percent Delay	104	117	105	116	113	108	107	108	117
Statistical Test	$d_2 > 0$*		$d_1 > 0$		$d_1 + d_2 \not> 0$		$\chi_r^2 = 2.3$**		
P	.047		.016		NS		NS		

* Walsh Test

** Friedman Test

Table 6

Summary of Analysis of Variance Using
Mean Delay Criterion

Source	df	MS	F
Trials	23	1241	1.47
Teams	5	4715	5.59**
Input Rate	1	6454	7.65**
Control Zone Size	1	3521	4.17*
Control Team Organization	1	822	0.97
Arrival Sequencing Procedure	2	1413	1.67
Pooled First Order Interactions	9	633	0.75
Residual	93	844	

* Significant at the .05 level of confidence.
** Significant at the .01 level of confidence.

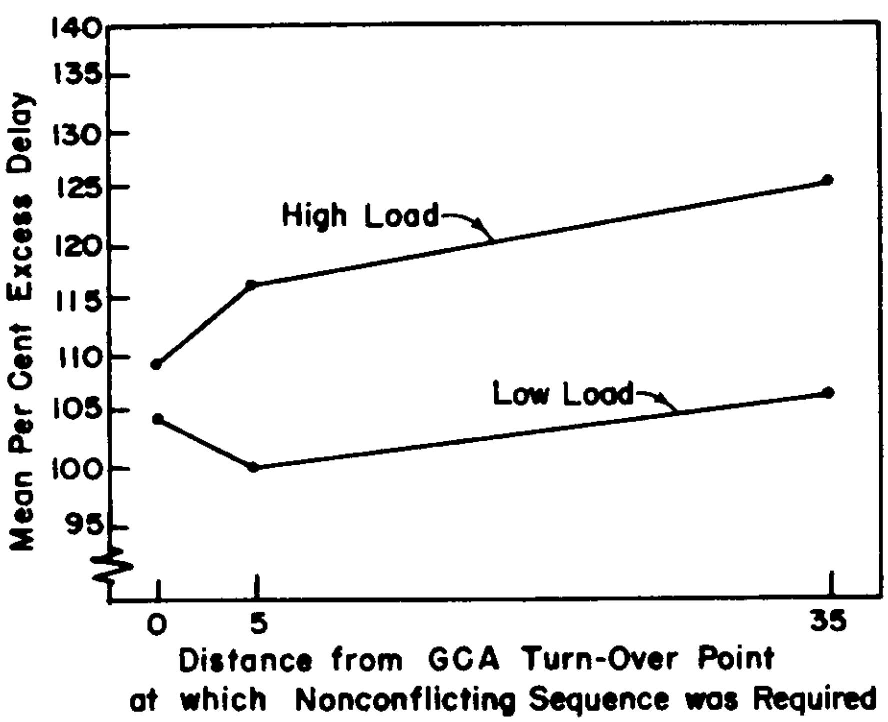

Figure 2. Percent Excess Delay as a Function of Traffic Input Rate and Sequencing Range.

Table 7

Comparison of Conditions Using Gross Error Criteria

	Conditions								
	Traffic Input Rate		Control Zone Area		Control Team Organization		Arrival Sequencing Procedure		
	120-Sec. Interval	90-Sec. Interval	157-Mi. Arc	48.5-Mi. Arc	In-Line	Sector	GCA Gate	5-Mi. Range	35-Mi. Range
Separation Errors*	2.27	2.83	2.39	2.71	2.60	2.50	2.41	2.70	2.54
Statistical Test	$d_1 > 0$		$d_2 \not> 0$		$d_2 \not> 0$		$\chi_r^2 = 1.0$		
P	.016		NS		NS		NS		
GCA Go-Arounds	1.21	1.33	1.01	1.53	1.39	1.15	1.35	1.31	1.15
Statistical Test	$d_2 > 0$		$d_1 > 0$		$d_2 > 0$		$\chi_r^2 = 3.6$		
P	NS		.016		NS		NS		

* Mean number of instances wherein one aircraft approached within 30-sec. flight time of another aircraft per problem.

The overall effect of the prearrival sequencing procedure was somewhat equivocal since the trend observed was not statistically reliable. The interaction effect expected between sequencing and input load was not prominent in the analysis of variance. However, the raw data on this outcome are instructive. Figure 2 presents the case. While statistical significance was not achieved even when the high-load condition was tested in isolation, the observable trend seemed to justify including the input-rate condition.

Experimental effects in terms of frequency of separation errors and GCA go-arounds could not be statistically substantiated. However, insofar as these findings are in agreement with the trends established via the delay criterion, they provide corroborative evidence. These data are presented in table 7. The major discrepancy in trend between criteria occurs for prearrival sequencing factor. The presequencing did effect a slight reduction in the frequency of GCA go-arounds.

DISCUSSION

The conclusions from the practical system design issues touched upon in the present investigation appear straightforward, particularly in terms of their agreement with prior findings. Traffic input rate, for example, has had an entirely consistent effect from study to study: performance falls off as traffic load is increased. When this variable is increased at more than two levels, the performance decline is accelerated. The present finding then is merely a reaffirmation.

The control zone size factor, however, raises something of a new issue. The nature of response constraints can be perceived as including the variable of "fixity." That is, if an operator were given sufficient incentive, he could conceivably break an operational rule or procedure. However, constraints having their source in the physical or geographical parameters of the system may be relatively much more fixed and immutable. Thus, whereas procedural constraints are susceptible to management review and modification, physical-geographical constraints are more truly system design features which may require overall redesign to modify. The present finding, then, implies that possible sources of response constraints should be considered early in the system design-development program. A thorough exploration of the problem raised by the present finding with respect to ATC systems would include investigation of such parameters as control zone shape, position of the terminal within the control zone, runway arrangement, and location of restricted areas within or adjacent to the control zone.

As has been indicated, the problem of control team organization has been investigated several times prior to the present study (ref. 3, 5, 12), where the findings were essentially identical in the present experiment: the collateral or sector arrangement was slightly superior to the sequential in-line arrangement. On a practical level there seems to be little to recommend one specific arrangement over the other.

The inclusion of the presequencing procedure also has antecedents within the research program. A previous study revealed a slight and unreliable negative effect on performance in instances wherein arrival of inbound aircraft at the control zone boundary was highly regularized (ref. 6). In a sense, the present experiment extended this notion by providing for such regularization at three different fixed stages in the landing approach proper. The outcome was comparable in that the effect of such regularization was more pronounced, the earlier it was required in the approach operation. Thus, any temporal patterning arbitrarily imposed either by or for the controller has seemed to exert a potentially negative influence on system performance.

The direct psychological implications of the present findings are somewhat less readily specified. In fact, it would have been preferable had the results not so closely conformed to prior findings. With respect to traffic input rate and control zone size, the expectations generated in the preliminary analysis were confirmed: heightened demand and response constraint both degrade system performance.

From the outcome derived from control team organization, the response constraint factor may be the most insidious. On the basis of subjective observation, the teams organized in a sector configuration were able to minimize the task demands effectively since they could observe the traffic configuration and thus adjust to the coordination requirements. In the in-line setup, however, no amount of cooperation could overcome the deficit resulting from differences between the two operators. A highly capable man in the inside position might be forced to waste his time while his less capable partner floundered through the initial processing. A less capable man in the inside position might be swamped by the output of his more capable partner in the outside position. The in-line arrangement, then, seems more susceptible to the "weak link" phenomenon and may show up mildly but consistently inferior to other arrangements.

The direction of the outcome of the prearrival sequencing procedure appears to confirm the proposition that increasing load tends to reduce the operator's inclination to deal effectively with longer-range outcomes. Such a conclusion must be highly qualified, however, in light of the lack of statistical significance and the admittedly tenuous connection between the hypothesized mechanism and the experimental operations. Several additional analytic steps are in order before even tentative validity can be established.

There is one final methodological point that is pertinent. The congruence of present findings with the results obtained in previous studies with somewhat different task and team composition and different sized subject samples tends to enhance the confidence that can be put in the techniques of system simulation.

SUMMARY

The performance of six 2-man control teams was observed in a simulated radar air traffic control center. Their task was guiding incoming aircraft through a 50-mile approach course. Experimental variables were two levels of traffic input rate, two levels of control zone size, two conditions of interoperator organization, and three conditions in which arrival sequencing procedure was modified.

The results revealed significant effects on performance due to traffic input rate and control zone size. Differences between control team arrangements were slight but consistent with prior findings. The outcome with respect to the scheduling procedure was equivocal due to lack of statistical reliability. However, the trend was sufficiently congruent with experimental prediction to encourage further validity testing.

The results indicated the potential importance of sources of immutable response constraints in the geographical-physical environment of the system. It was also suggested that constraints due to interoperator dependencies are difficult to circumvent by means of operator adaptation. Finally, it was suggested that procedures that run counter to the "normal" perceptual or response tendencies of the operator act in a fashion which is analogous to the effect of more explicit procedural constraints.

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