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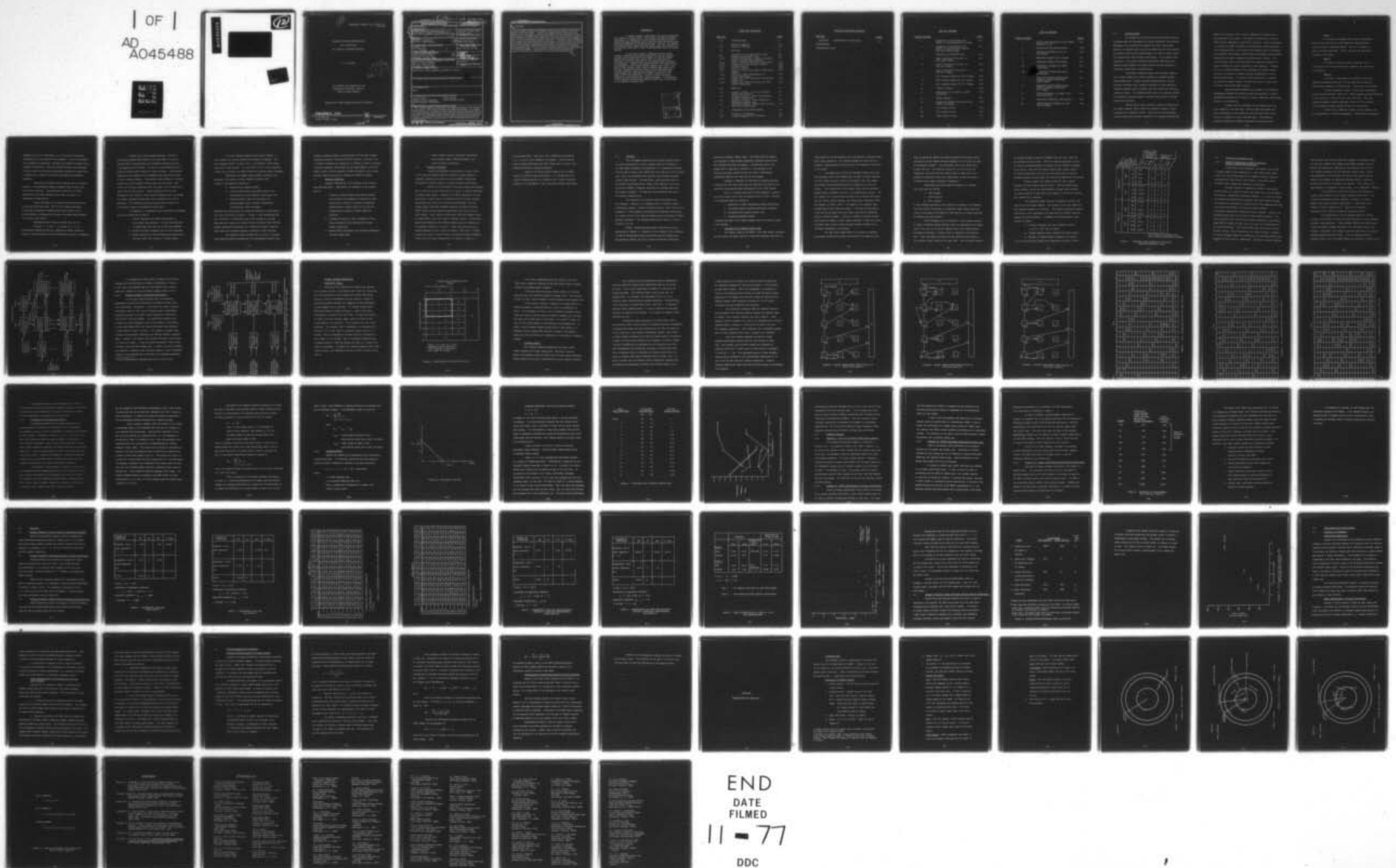

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TECHNICAL REPORT NO. OTR-62-77-1
June 1977

MANNED SYSTEM PERFORMANCE
AS A FUNCTION
OF DISPLAY CHARACTERISTICS

E. M. Connelly

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In manned systems, performance can change significantly with changes in display design. With today's computer and display technology, it is possible to provide virtually any display function desired including automating many of the information processing tasks previously performed by the human operator. However, the relationship between display design and total system (man and machine) performance must be known in order to systematically select the display features.

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ABSTRACT

In manned systems, performance can change significantly with changes in display design. With today's computer and display technology, it is possible to provide virtually any display function desired including automating many of the information processing tasks previously performed by the human operator. However, the relationship between display design and total system (man and machine) performance must be known in order to systematically select the display features.

A new human operator modeling technique termed "operator measures and criteria" (OMAC) was used to represent the ship control performance of the Officer of the Deck (OOD). OMAC's are measures and criteria which are determined by calculation to be those optimized by the observed OOD controlled ship responses. OMAC's were determined from data obtained from an experiment in which three different displays were used. With each of those displays, OOD subjects demonstrating superior performance resulted in identical criteria, but an apparently self-imposed constraint called purview (range from own ship within which contacts are processed by the OOD), was shown to be different for each display type. Purview is shown to explain differences in performance with different displays. The proportion of OOD subjects demonstrating superior performance is also shown to be a function of display type.

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1.0 INTRODUCTION

The designer of a man-machine system typically performs his design task with knowledge of the system objectives, human factors principles, and a concept of the display and control requirements. However, he typically does not know how effectively the human operator will perform given various display designs, nor does he have a model for predicting the human operator performance. If the designer had a model which could predict significant performance differences with different display designs, the display features could be selected in a systematic, performance oriented manner.

Performance prediction models have long been sought to aid in system design and to better understand how display designs affect performance. Present modeling methods (McRuer, Preyss, Sheridan, Kleinman) which typically represent the human operator's moment-to-moment control response, have not provided the necessary predictive models. The modeling method used in the analysis reported here employs a construct based on optimal control theory to provide performance prediction.

Optimal control theory provides a means for determining the system response which, within the constraints imposed, is best according to the specified criteria. Given criteria and constraints, optimal control theory permits evaluation of all possible responses that satisfy the constraints, and in doing so identifies the response that is best according to the criteria. Its property of interest here is that it relates system responses to criteria and vice versa. With this capability, it is possible to model a response by identifying the criteria optimized. This modeling process is the inverse of the process used by the designer of an automatic control system wherein criteria are selected first followed by determination of system responses that optimize that criteria. The inverse process used in this study starts with observed responses and seeks to identify the criteria optimized by these responses. Rationale for such a modeling strategy is that responses are situation specific and thus do not permit a compact, general representation of human operator performance. In contrast, criteria optimized by responses may not be as situation specific and thus may provide a model which is valid in many control task situations.

Several example problems are presented in the following paragraphs to illustrate the modeling concept and especially to provide operational descriptions of the terms: criteria, constraints, performance measure, and performance.

Consider first an automobile control problem starts with a car stopped at a red stop light. When the light turns green, the driver accelerates the car towards the next stop light which is red. The car is brought to a halt at that stop light. Three different automobile responses are defined to illustrate the concepts involved:

Case I

A Corvette is accelerated with maximum acceleration from the first stop light to a point before the second stop light where the break is maximally applied. The car is brought to a halt at the second stop light. Travel time from one stop light to the other is 15 seconds.

Case II

This case is identical to Case I except the car is a VW and due to the reduced acceleration capability, the travel time is 25 seconds.

Case III

A Corvette is accelerated at a constant but less than maximum acceleration away from the first light and is breaked at less than full breaking at the second light. Travel time is 25 seconds.

The auto responses in Cases I and II can be represented by the criteria optimized: travel time. Those responses minimize the amount of time required to travel from one light to the next. Thus, the complex responses involving calculation of when to "hit the breaks" can be modeled by simply stating that they are time optimal.

Transit time is different in Cases I and II, however, due to the differences in acceleration capability. The maximum acceleration capability of a car is constrained, i.e., the driver can choose any acceleration up to the maximum but no greater. Thus the acceleration level available is constrained. Similarly, the amount of breaking force available is constrained. While the criterion (transit time) optimized in Cases I and II is the same, performance (measured by transit time) is different due to different constraints (acceleration and breaking capability).

Note that performance can be measured with any measure selected. The performance measure employed does not have to be the criterion optimized. The performance measure in the above example could have been selected as fuel used, tire wear, or a combination of these factors.

Case III provides a car response that optimizes the sum of fuel and transit time used. Note that the criterion optimized by the Case III response is different from that of Cases I and II, but performance as indicated by the transit time performance measure is the same as for Case II.

Weighting factors on fuel and transit time such as:

$$\text{Criterion} = A \text{ Time} + (1-A) \text{ fuel}, \quad 0 \leq A \leq 1$$

would permit modeling of many car responses by simply finding the value of A that provides the criterion optimized by a given car response.

Consider now a more practical example. Consider a ship control problem whose Officer of the Deck (OOD) is to direct the ship from a starting location to an objective location and arrive at the objective in 90 minutes. The ship is to be controlled so as to avoid all contacts (other ships) by at least two miles. A performance measure for this problem can be developed using measures of transit time and contact avoidance. This measure would penalize for excessive transit time and for passing contacts closer than two miles. Ship control also involves constraints such as an upper limit to speed and a lower limit to turning radius. Using an analysis similar to that described for car control, a ship transiting response which may include any contact avoidance maneuvering, can be modeled by the criteria optimized. This modeling concept and manual control problem are the problems treated in the analysis reported here.

The expectation in identifying criteria optimized by responses is that the criteria can be used to:

1. Predict responses (and thereby performance) in many control task situations - not just those observed in experiments from which the criteria are identified.
2. Reveal the control strategies used by human operators.
3. Reveal variations in control strategy (and performance) that may result from variations in display design.

The term "operator measures and criteria" (OMAC) is used to denote the criteria optimized by an observed response. The term "apparent OMAC" is used to refer to the apparent criteria being used by the human operator. It is not known if he is in fact using that criteria, but it predicts his control actions and resultant system responses.

Returning to the display design problem identified at the beginning of this section, previous research (Connelly 1976) resulted in development of methods of:

a. Determining the apparent OMAC,

b. Predicting performance using OMAC shown to be representative of human operator performance, and

c. Analyzing OMAC's which are associated with different display types to identify representative human operator control strategies.

Results of that work showed that significant differences in performance can result using different displays. Further, it was demonstrated that these differences in performance may not be revealed by summary measures which measure the number of ship collisions or near collisions. Instead, performance differences are revealed by transition measures which detect ship responses leading to collisions or near collisions.

The research further indicated that, in order to accurately model observed subject performances, the representative OMAC's must include a circular boundary, termed purview, for the radar contacts considered relevant to the control of one's own ship. Purview is not a limitation imposed by the display but is included in OMAC to represent a boundary apparently self-imposed by the subject Officer of the Deck (OOD). Finally, a limited analysis of OMAC parameters, which include purview, showed that purview is different for different displays.

1.1 Research Objectives

Research reported here is an extension of the previous work described above. Specifically, the objectives of this program were to:

1. Validate a contact avoidance performance measure which predicts the probability of collisions or near collisions as a function of transition probabilities representing the relative motion of own ship and contacts along a sequence of states leading to collisions.
2. Complete the search of OMAC parameters to find those providing the best representation of each subject performance.
3. Identify OMAC parameters that represent performance with each display type.

4. Analyze display content to determine relationships among display content, OMAC parameters, and contact avoidance performance.

1.2 Summary of Results

Transition probabilities representing the relative motion of own ship, and contacts along the sequence of states leading to collisions, effectively characterize contact avoidance maneuvering and provide a sensitive measure of contact avoidance performance.

OMAC's can be identified to represent subject performances, and to represent average performance of a group of subjects performing with each display design. Analysis of the OMAC parameters (purview and criteria, criteria used is a weighted function of contact avoidance performance and transit time) representing performance with each display design shows that a greater proportion of subjects using the PACS* display provide superior performances than those using the OLD* display. Also, superior performances with both displays exhibit the same OMAC criteria but exhibit a different purview. Furthermore, performance differences with different display types are explained by the respective difference in purview. Since a purview area can be readily translated into the number of contacts in that area, a limited purview also means a limited number of contacts are being considered

*PACS and OLD display configurations are defined in Section 2.1.

by the subject OOD. Since this limit is apparently self-imposed, i.e., it is not a limit imposed by the display, it may be that the factor limiting performance with each display type is a limit to the subjects information processing capability.

Based on the overall results obtained with the OMAC method of modeling human performance, it is concluded that this criteria modeling approach is a practical way to model human performance in an operational or near operational problem environment.

2.0 METHOD

The investigation reported here used data collected during a series of experiments in which a subject acting as an Officer of the Deck (OOD) controlled a simulated ship in a simulated environment. His task was to direct a ship transit from the initial point to the terminal point, within a pre-specified time interval, while avoiding simulated contacts along the way. The experiment, using equipment known as the Surface Ship Bridge Console System (Gawitt/Beary), was run by personnel of NSRDC, Annapolis, Maryland, for purposes other than this research program. The data from that experiment was used in the research reported here.

The objectives of the research were accomplished with four analyses. Analysis I is a validation test of a contact avoidance performance measure, termed "transition measure," which predicts the probability of near collisions using transition probabilities representing the relative motion of own ship and contacts along the sequence of states leading to collisions. The transition performance measure is used in Analyses II and III.

OMAC's representing each subject performance trial are determined by Analysis II. Analysis III is an analysis of the parameters of OMAC's representing subjects performing with each display type. Representative OMAC's are used to explain performance differences obtained with different display types. The PACS and OLD displays were analyzed in detail because statistically significant performances were obtained with these two displays. Performance with a third display "RVV", described in Section 2.1, was analyzed in the research previously reported and did not result in performance significantly different from that with the OLD display.

Analysis IV identifies the information processing required to perform the OOD ship control task and identifies that portion of the information processing provided automatically by the PACS display.

Prior to a detailed description of these analyses, a description of the manual control task and analytical tools is given. Included in the analytical tools are methods of:

1. Identifying an OMAC representing subject performance,
2. Calculating contact avoidance performance measures,
3. Comparing ship response patterns, and
4. Developing candidate OMAC's.

A detailed description of the display designs used for the study is given in the Appendix.

2.1 Description of the Manual Control Task

The subject, acting as an Officer of the Deck (OOD), commands the ship course and speed required to transit the simulated ship from the initial position to the final position while avoiding each simulated contact (other ship) encountered. The distance between the initial and final positions is approximately 30 miles and the time allotted for the transit is 90 minutes.

The subject sits in front of a simulator console which has three computer driven CRT displays and a number of control switches. The CRT display directly in front of the subject is the main display and provides visual information about the location of own ship and contacts. The configuration of that display varies with the particular display function simulated, and thus, is an experimental variable. The CRT display on the subject's left provides a list of contact information such as location, speed, heading, and closest point of approach (CPA). This display is termed "LIST". The display on the subject's right provides data on ship course and speed. It can also provide data on "trial" course and speed which the subject may input for evaluating decision command changes. There are a number of control switches which allow the subject to select display functions, to input trial course and speed, and to direct course and speed change commands to an individual representing the Helmsman.

The task of the subject OOD is to visualize or calculate the possible courses from present ship position to the objective point.

Next, by taking into account the contact positions and velocities and by utilizing the various display functions available, he is to direct the ship to the objective location. The instructions read to the subject prior to each trial are: "the objectives during the run are to be at the rendezvous at the end of the 90 minute period, to pass clear of all contacts (if possible by more than 4,000 yards), to obey the Rules of the Road, and to observe economy of operation."

Performance with three types of displays is of interest. The three types are termed:

1. "OLD system"
2. "PACS system"
3. "RVV system"

A more detailed description of the displays is presented in the Appendix. The OLD system is essentially a conventional radar display where the center of the screen is the position of own ship and the relative positions of contacts are shown as blips.

PACS (Probable Area of Collision) is a new display providing a number of different display functions which are selectable by the subject. PACS is the name of the function <u>and</u> the name of the display system providing that function. In PACS, LIST is available on the left-hand CRT. Also, the subject can select the new display function PACS, or True Velocity Vector modes on the center CRT. With the PACS function, the display provides the locus of collision points for each contact for all possible own ship courses. Since this requires projection of future own ship and contact positions, the display aids the subject in selecting a new course. With the true velocity vector mode, velocity vectors are superimposed both on the own ship and contact blips to show the predicted position of all the ships at a future time selected by the operator.

Finally, another new display termed the "RVV system" includes LIST plus relative velocity vectors. With this display type, relative velocity vectors are superimposed on contact blips indicating the relative position of each contact with respect to own ship at a future time selected by the operator.

The experiment design required 16 subjects to perform with each of the three display designs. This design is a two way experiment with repeated measures on one factor. Two display orientations, Head-up and North-up, were controlled in the experiment by randomly selecting subjects for each orientation. In addition, the following factors were selected at random:

- Problem orientation (the path to objective location is at 0° or 120° from the North)
- Problem difficulty (three variations of contact speeds)
- Sequence of display designs presented to the subject

A chart summarizing the design of the experiment is given in Table 1.

Display Orientation	Control Task Orientation	Subject ID	Order & Type of Displays Presented to Subjects (O - OLD, R - RVV, P - PACS)	Control Task Scenario: OLD	RVV	PACS
NORTH-UP	360°	A4	O,P	C	–	B
		A5	P,R	–	C	B
		A6	P,O	B	–	C
		A7	O,R	B	C	–
	120°	A8	O,R,P	B	A	C
		A10	O,R,P	C	A	B
		A12	P,O,R	C	A	B
		A14	O,R,P	B	C	A
HEAD-UP	360°	B4	R,O,D	C	A	B
		B5	R	–	C	–
		B6	R,P,O	B	A	C
		B7	P,O,R	B	C	A
	120°	B8	O,R	B	A	–
		B10	O,R,P	C	A	B
		B12	O,R	C	A	–
		B14	O,R,P	B	C	A

A,B,C refers to the sequence with which displays are presented to subject.

TABLE 1 CONTROL TASK CONDITIONS FOR EACH SSBCS EXPERIMENT TRIAL

2.2 Concepts and Analytical Tools

2.2.1 Method of Identifying an OMAC to Represent Subject Controlled Ship Responses

As described in the introduction, the analysis of the effect of display design on ship responses (i.e., ship motion under subject control from the starting location to the objective location) employs a constraint which uses optimal control theory. With control theory the OMAC which models ship responses is determined.

The basic problem in identifying an OMAC is that optimal control theory is a synthesis process which starts with criteria selection and results in identification of optimal responses, i.e., first the criteria are selected and constraints are identified, then each possible response that satisfies the constraints is evaluated and the one judged best according to the criteria is identified. The theory provides an efficient computational algorithm for identifying the best response. However, the procedure desired here is the inverse of that synthesis process. The desired process starts with the ship responses generated in experiments using OOD's to control the ship, and is to result in the identification of the criteria optimized. Thus control theory does not provide the exact process required. But an equivalent to the inverse process is obtained if a set of candidate criteria are selected and the associated optimal ship response for each criteria is determined. (Note that the phrase "optimal ship response" does not mean best ship response in an absolute sense, but only best response with respect to associated candidate criteria.) Each of the optimal ship responses can be compared with one of the ship responses obtained from the experiment subject trials. Where close agreement is found between the optimal ship response and the subject trial response, the associated candidate OMAC is identified as being optimized by the subject trial response. This process is an approximation to the desired inverse process. It is illustrated in Figure 1.

The comparison of optimal and subject trial responses is a test of the similarity of their contact avoidance performance. The transition performance measure validated in Analysis I is used to measure that contact avoidance performance. A description of the measure is given in Section 2.2.2. Section 2.2.3 provides a description of the method of comparison using the measure.

As outlined above, a set of candidate OMAC's is formed as part of the process to identify the OMAC optimized by a ship response obtained in the experiment. These candidate OMAC's are formed using a sum of weighted variables identified in the instructions given to the subjects. Specifically, the variables used are transit time and minimum passing distance from each contact. A set of weighting values is selected to form a set of candidate OMAC's as described in Section 2.2.4.

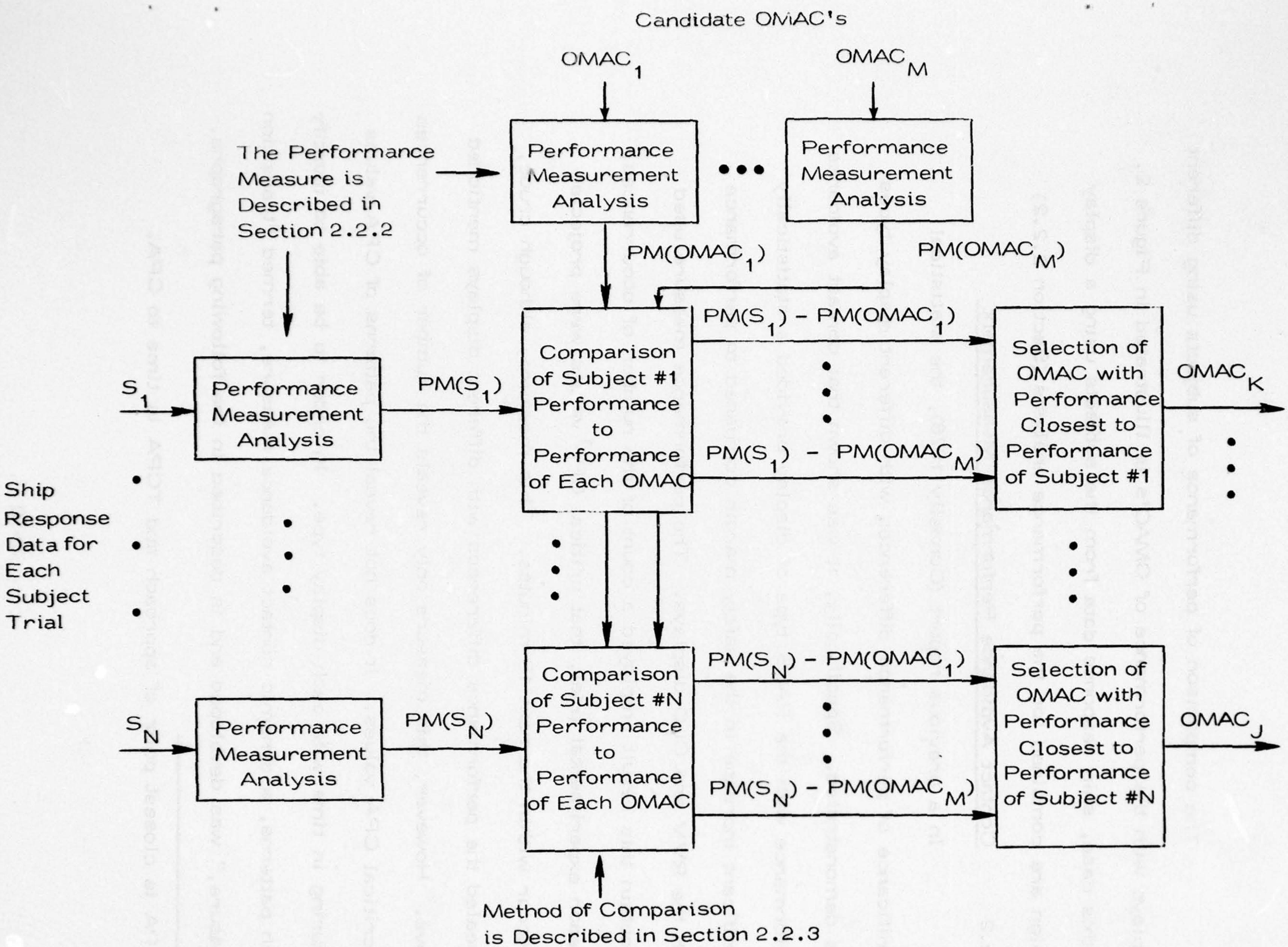

FIGURE 1 COMPARISON OF PERFORMANCE WITH OMAC's TO PERFORMANCE WITH A SUBJECT

The comparison of performance of subjects using different displays with the performance of OMAC's is illustrated in Figure 2. In this case, ship response data from the subjects using a display design are combined for the performance analysis (Section 2.2.2)

2.2.2 Contact Avoidance Performance Measurement

In a previous report (Connelly 1976), the statistical significance of performance differences with different display types was demonstrated. Specifically, it was shown that contact avoidance performance with the PACS type of display provided a statistically significant increase in the safety margin compared to performance with the RVV and OLD displays. The performance measure used to obtain this result employed a count of the number of occurrences, in each experimental trial, that critical CPA[1] values were projected to occur within the next 15 minutes. This measure, although crude, revealed the performance differences with different displays mentioned above. However, this measure only reveals the number of occurrences of critical CPA values. It does not reveal the patterns of CPA values occuring in time with each display type. In order to be able to identify such patterns, a dynamic contact avoidance measure, termed "transition measure," was developed and is described in the following paragraphs.

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[1]CPA is closest point of approach and TCPA is time to CPA.

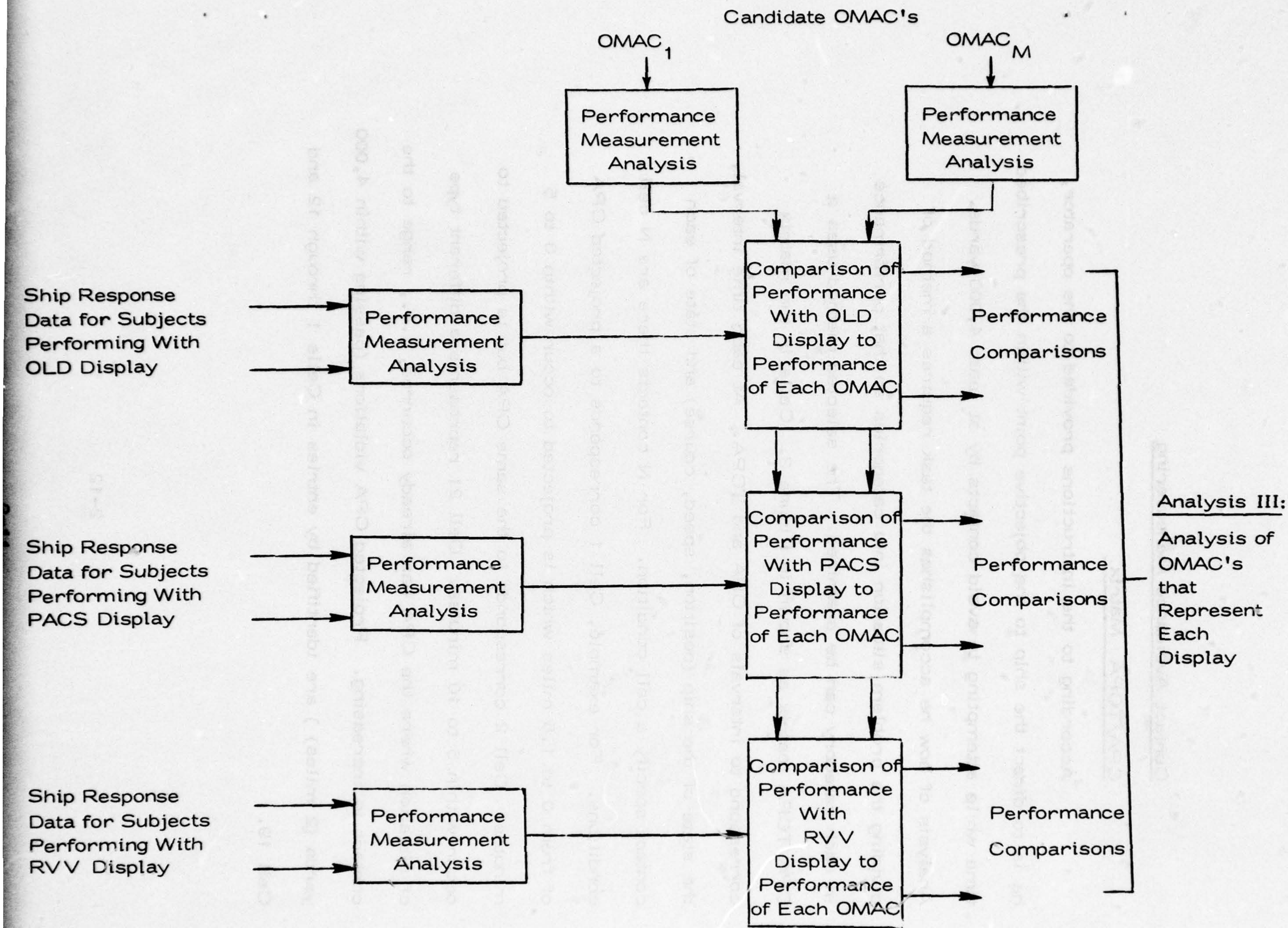
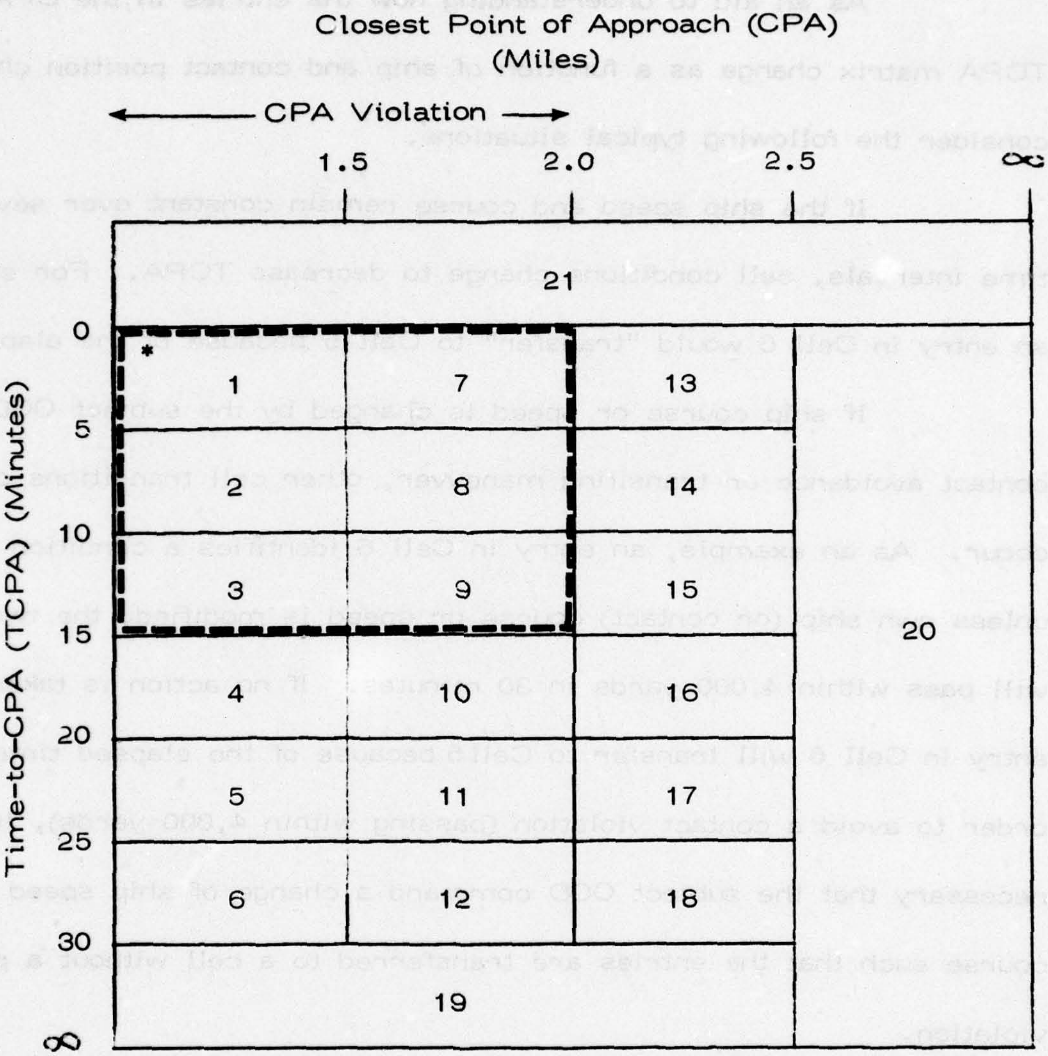


FIGURE 2 COMPARISON OF PERFORMANCE WITH OMAC'S TO PERFORMANCE OF SUBJECTS WITH EACH DISPLAY DESIGN

Contact Avoidance Maneuvering

CPA/TCPA Matrix

According to the instructions provided to the operator, he is to direct the ship to the objective point within the prescribed time while attempting to avoid contacts by at least 4,000 yards. Analysis of how he accomplishes the task requires a method of dividing the problem situation into categories so that performance in each category can be examined. The selected method uses a CPA/TCPA matrix as shown in Figure 3. Cells in the matrix correspond to intervals of CPA and TCPA. At each time interval, the state of the ship (position, speed, course) and state of each contact specify a cell condition. For N contacts there are N cell conditions. For example, Cell 1 corresponds to a projected CPA of from 0 to 1.5 miles which is projected to occur within 0 to 5 minutes. Cell 2 corresponds to the same CPA but is projected to occur within 5 to 10 minutes. Cell 21 represents a different type of situation where the CPA has already occurred, i.e., range to the contact is increasing. Projected CPA violations (passing within 4,000 yards (2 miles)) are identified by entries in Cells 1 through 12 and Cell 19.



*Cells 1, 2, 3 and 7, 8, 9 are designated critical cells where a CPA violation is projected to occur within 15 minutes.

FIGURE 3 DEFINITIONS OF CPA/TCPA CELLS

As an aid to understanding how the entries in the CPA/ TCPA matrix change as a function of ship and contact position changes, consider the following typical situations.

If the ship speed and course remain constant over several time intervals, cell conditions change to decrease TCPA. For example, an entry in Cell 6 would "transfer" to Cell 5 because of the elapsed time.

If ship course or speed is changed by the subject OOD as a contact avoidance or transiting maneuver, other cell transitions can occur. As an example, an entry in Cell 6 identifies a condition where, unless own ship (or contact) course or speed is modified, the two ships will pass within 4,000 yards in 30 minutes. If no action is taken, the entry in Cell 6 will transfer to Cell 5 because of the elapsed time. In order to avoid a contact violation (passing within 4,000 yards), it is necessary that the subject OOD command a change of ship speed or course such that the entries are transferred to a cell without a projected violation.

Transition Matrix

Cell transition patterns characterize the subject OOD's contact avoidance and transit maneuvering. Similarly, transition patterns representing a group of OOD's (such as those using a particular display design) can be used to characterize the group maneuver patterns.

Cell transitions are represented by transition probabilities since cell sequences obtained from experimental data are not always the same. This is due to performance variations in individuals and among individuals. The transition pattern from a given cell, for example Cell i, is recorded in the associated row of a 21 by 21 transition matrix representing all possible transitions. Probability (P_{ij}) is the probability of transferring to Cell j from Cell i. Probabilities along the matrix diagonal (where i = j) do not describe cell sequences and have no meaning in this analysis. As a result, the diagonal matrix elements are zero.

Although the above description of the CPA/TCPA matrix, the transition matrix, and the method of calculating transition probabilities is presented as though cell entry changes occur for only one contact at a time, there are in fact multiple simultaneous changes. Each course or speed change commanded by the OOD can cause multiple simultaneous changes in the cell entries because of the existence of multiple contacts. Transition probabilities are developed from the transitions that occur both simultaneously and sequentially throughout an experimental trial. When a transition matrix is developed to represent performance of a group of subjects, data used are obtained from all subject runs. In spite of the fact that the transition matrix probabilities represent both simultaneous and sequential occurrences and multiple subject runs, it is often convenient to visualize the transition matrix as describing the relationship between own ship and one contact - in the presence of many other contacts. With this visualization, it is possible to trace the cell sequences from the point of contact activation (contact appearance on the display) until the ship reaches the objective point. Different contact initial conditions (conditions at time of contact activation) may lead to different cell sequences.

As a means for illustrating both cell transition matrices and the different cell transition patterns obtained with different types of display, three transition diagrams have been prepared. These diagrams, shown in Figures 4, 5, and 6, are developed from transition matrices shown in Figures 7, 8, and 9 for the PACS, OLD and RVV displays respectively. Only transitions with a probability greater than 0.10 and transitions from Cells 1 through 5 are illustrated.

From the transition diagrams the superior contact avoidance performance obtained with the PACS display is easily seen. For example, with the PACS display the probability of transition from Cell 5 to cells where no CPA violation is projected is 0.35 (.22 + .12). This represents superior contact avoidance maneuvering as compared to the corresponding probabilities of .17 and .16 for the OLD and RVV displays respectively. Superior transition patterns for PACS also exist for Cells 4 through 1 as illustrated in the Figures.

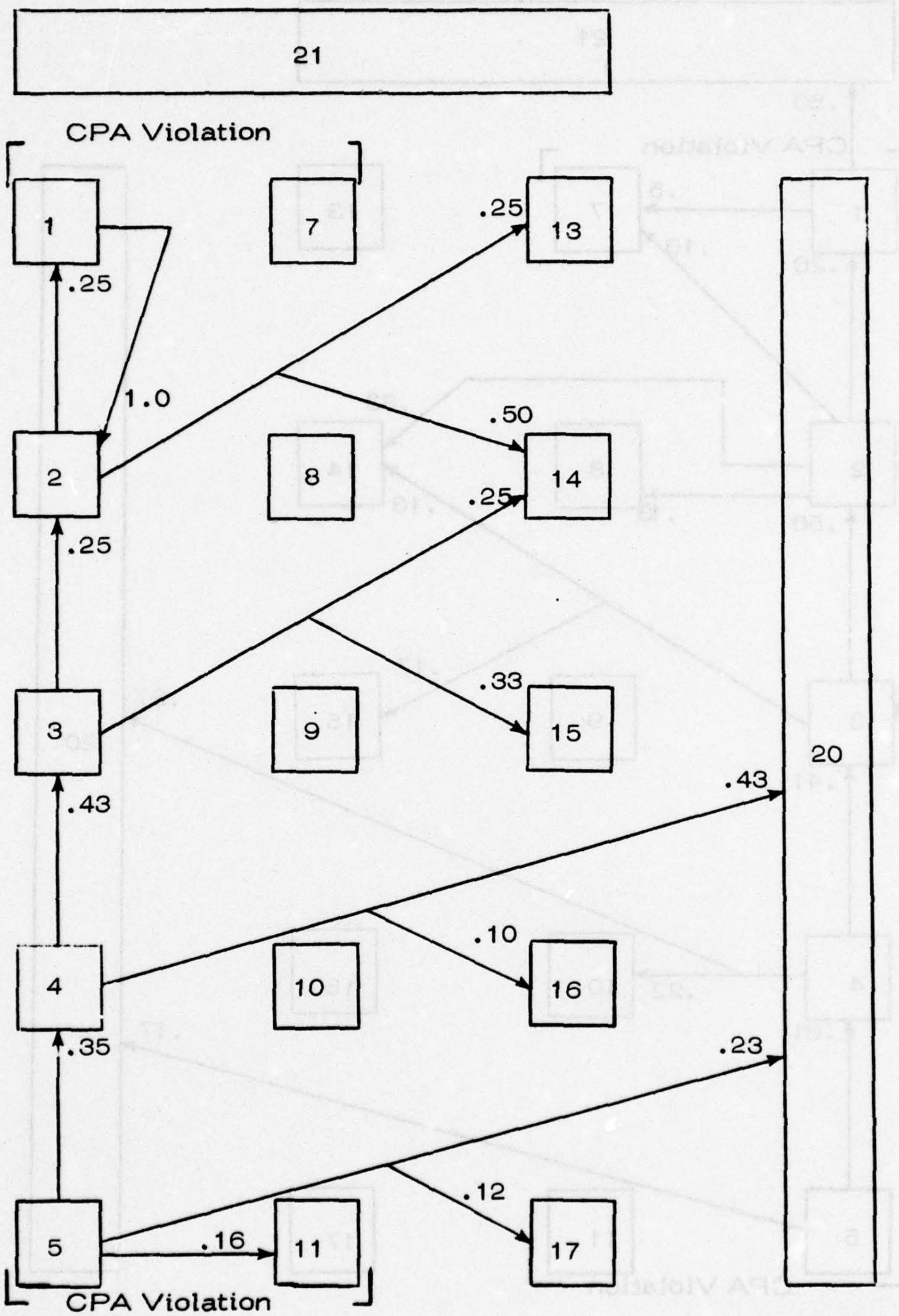


FIGURE 4 MAJOR TRANSITIONS FROM CELLS 1-5
WITH PACS DISPLAY

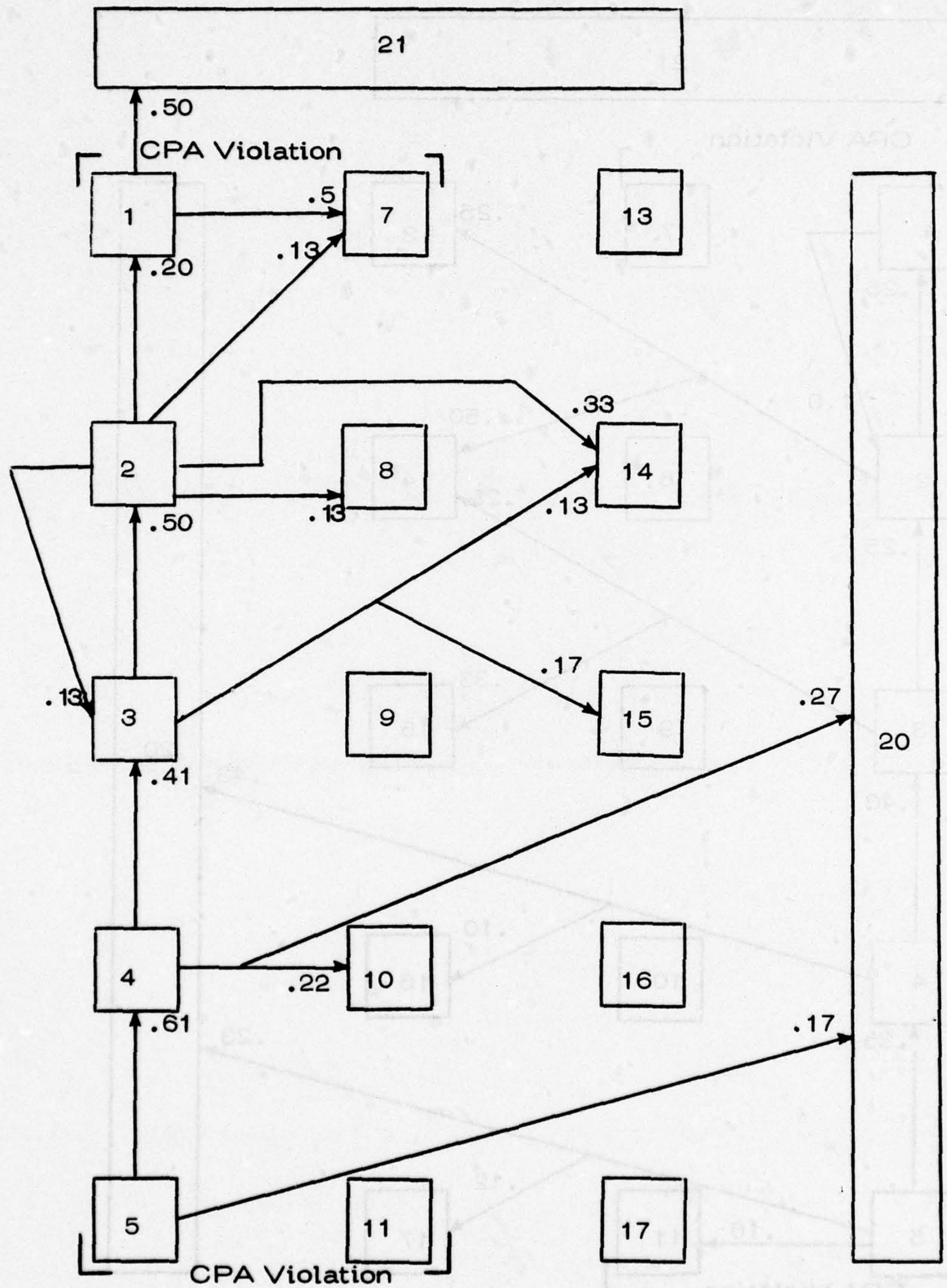


FIGURE 5 MAJOR TRANSITIONS FROM CELLS 1-5 WITH OLD DISPLAY

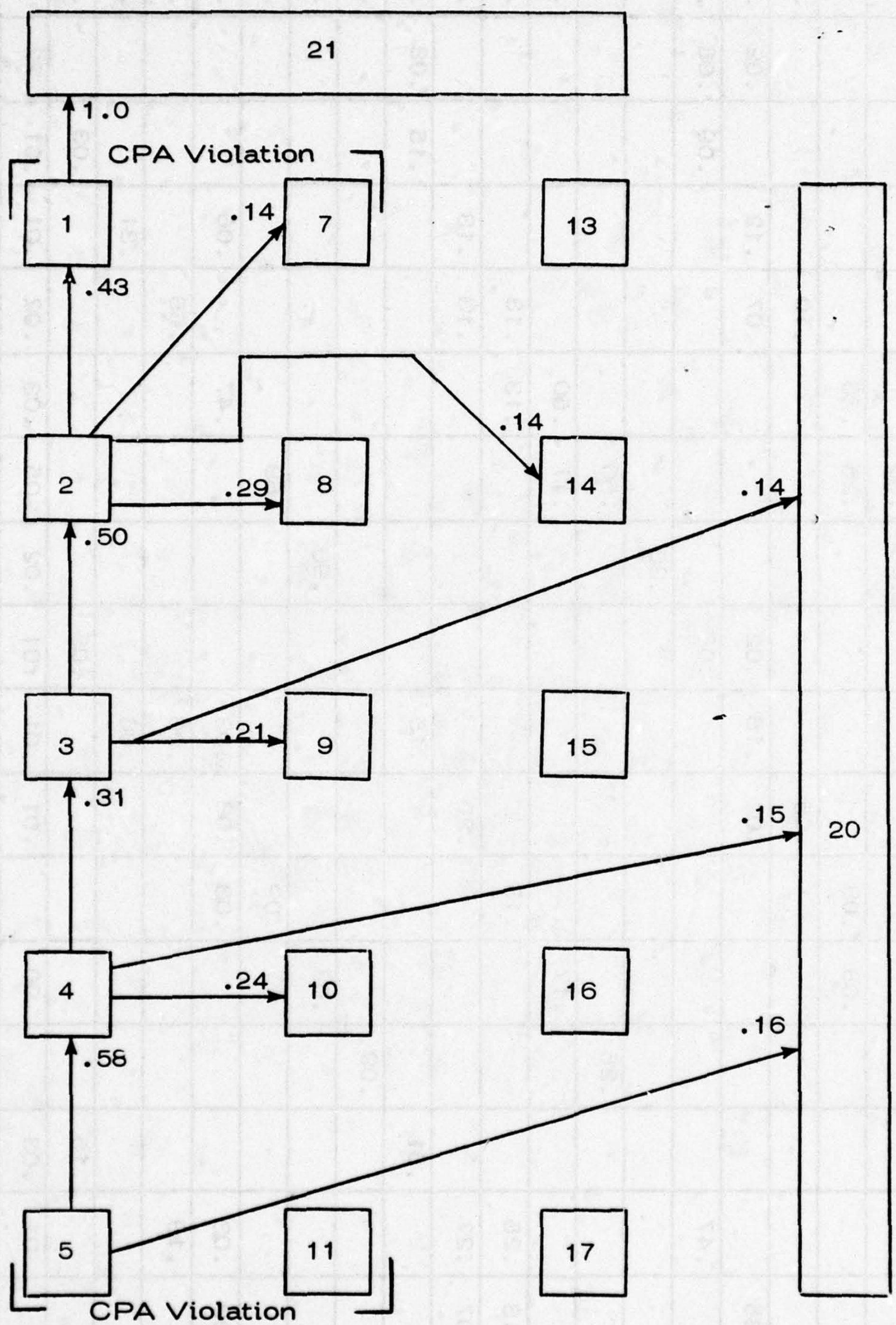


FIGURE 6 MAJOR TRANSITIONS FROM CELLS 1-5 WITH RVV DISPLAY

CELL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1		1.0																			
2	.25												.25	.50							
3		.25						.08	.08					.25	.33						
4			.43							.05						.10				.43	
5				.35						.02	.16	.02				.07	.12		.02	.23	
6					.47							.06						.09	.06	.31	
7													.20								.80
8	.25						.25							.50							
9								.17						.17	.50					.17	
10				.13	.25				.13						.13	.13				.25	
11				.07	.27					.20						.13	.13			.20	
12						.31					.15							.15	.08	.31	
13							.09													.03	.88
14								.02					.90							.08	
15									.09					.69						.23	
16				.03	.03				.03	.06	.03				.47		.06			.31	
17					.13						.06					.66				.16	
18											.06						.31			.63	
19						.15						.05						.03		.75	.03
20			.01		.01	.03		.00		.01	.01	.01	.02	.05	.03	.02	.01	.01	.22		.57
21							.03						.02						.02	.93	

FIGURE 7 CELL TRANSITION MATRIX FOR PACS DISPLAY

CELL

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1							.50														.50
2	.20		.13				.13	.13						.33	.07						
3		.50						.04	.08	.04				.13	.17					.04	
4			.41			.03				.22						.08				.27	
5				.61						.07	.07					.02	.07			.17	
6					.57						.04	.07					.04		.18	.11	
7	.17												.17								.67
8		.14					.36							.50							
9			.23					.39							.15					.23	
10			.07	.17	.04				.38		.04				.07	.10				.14	
11				.06	.17					.56						.06	.06			.11	
12					.19						.31						.06	.06	.13	.25	
13	.02						.06													.04	.89
14		.03						.05					.82							.10	
15			.03					.03	.03					.59						.31	
16				.09						.15					.46					.30	
17					.03					.07	.13					.65		.03		.10	
18						.13						.06					.44			.38	
19					.01	.13						.08						.04		.74	
20		.00		.00	.01	.00		.01		.00	.01	.01	.01	.02	.02	.01	.01	.00	.21		.67
21													.05						.04	.91	

FIGURE 8 CELL TRANSITION MATRIX FOR OLD DISPLAY

CELL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1																					1.0
2	.43						.14	.29						.14							
3		.50						.07	.21						.07					.14	
4			.30		.03					.24	.06				.06	.09	.03			.15	.03
5			.02	.58						.07	.07						.09	.02		.16	
6					.53							.05					.03	.08	.11	.21	
7								.05					.21							.05	.68
8		.05					.55						.27	.10	.05						
9			.05				.05	.45							.35					.10	
10				.04				.04	.30		.04				.11	.19				.30	
11					.12					.36						.16	.12			.24	
12					.11	.06					.33							.22		.28	
13			.02				.08	.02	.02											.05	.83
14								.11					.70							.19	
15								.02	.10					.59						.29	
16				.09	.02				.05	.12	.02				.51		.02			.16	
17				.02						.02	.12					.51				.29	.02
18											.04	.21					.21		.13	.42	
19				.01		.21						.06						.05		.68	.01
20			.01	.01	.02	.02	.01	.01	.01		.00	.00	.03	.02	.02	.03	.02	.03	.18		.60
21		.01					.01				.01		.03						.04	.91	

FIGURE 9 CELL TRANSITION MATRIX FOR RVV DISPLAY

These diagrams provide convincing graphical evidence of the performance differences obtained with different displays. Quantitative measurement of those differences, as a step in identifying the reason for those differences, is described in the next section.

2.2.3 Comparison of Ship Response Patterns

Considerable analysis of ship maneuvering patterns can be accomplished by inspection of the transition matrix probabilities. For example, an entry in Cell 6 corresponds to a projected CPA violation in 25-30 minutes. Transitions to Cells 5, 4, 3, 2, 1 will occur if no OOD control actions are taken to cause a transfer to cells where no CPA violation is projected. Also, as time to CPA decreases in cells where a CPA violation is projected, the situation becomes less desirable. Thus, Cell 1 is less desirable than Cell 2 which is less desirable than Cell 3 and so forth. Therefore, examination of transition probabilities provides a way of evaluating contact avoidance performance and also comparing performance with different experimental treatments.

One difficulty in the quantitative evaluation of performance by comparing transition probabilities directly is that transitions from a given cell are not weighted by the probability that the cell is "used." For example, with one treatment (one display type), transitions from Cell 3 may be better (a higher probability of transfer to cells that do not project a CPA violation) than that of another treatment.

But the probability that conditions corresponding to Cell 3 exist during the experiment may be so small that transitions from Cell 3 may be of little consequence. A method for solving this problem is described in the next paragraph following introduction of a required concept.

Once a contact is passed, where the distance to the contact is increasing, there is little likelihood that own ship will maneuver so as to approach that contact again. Assuming that restriction is true, Cell 21 can be treated as an absorbing cell, i.e., the probability of leaving Cell 21 after it is entered is zero. With that assumption, the transition matrix can be analyzed as an absorbing Markov Process (Kemeny & Snell, 1960). This means that the process is considered as starting in any cell (but especially Cells 19 and 20) and transferring to a series of other cells ending in Cell 21. The process may return to a given cell in that process but once it enters Cell 21, it remains there. The analysis of interest is the calculation of the mean number of times each cell will be entered before entering the absorbing state, given the starting cell. This provides the desired weighting of cell usage. The contact avoidance measure of interest is the mean number of times critical Cells 1, 2, 3, and 7, 8, 9 are entered given the process starts in Cells 5, 11, and 17.

Calculation of the measure requires formulation of a matrix (Q) which is identical to the transition matrix P except that Row 21 and Column 21 (corresponding to the absorbing cell) have been removed. The desired measure is given by matrix R (a 20 x 20 matrix):

$$R = (I - Q)^{-1}$$

where I is the identity matrix, "-1" represents the matrix inverse operation, and elements r_{ij} of R are the mean number of times the process enters Cell j given the process starts in Cell i.

Since the measure of interest is the mean number of times that the process enters the critical cells, given the process starts in Cell 5, plus those means given the process starts in Cell 11, and again for Cell 17, the specific performance measure of interest is

$$P_m = \sum_{\substack{i=5,\ 11,\ 17 \\ j=1,\ 2,\ 3,\ 7,\ 8,\ 9}} r_{ij}$$

Thus, the measure includes six values for each of three initial conditions for a total of 18 terms.

When a comparison of the contact avoidance performance is made (i.e., comparing performance of a subject using two different displays or comparing performance of a subject with the performance of an OMAC) the differences in the mean number of times in the critical cells is used. Each difference is squared and the sum of squares used for the difference measure. This difference measure is given by:

$$DM = \sum_{\substack{i=5,\ 11,\ 17 \\ j=1,\ 2,\ 3,\ 7,\ 8,\ 9}} d_{ij}^2$$

where

$$d_{ij} = r_{1ij} - r_{2ij}$$

r_{1ij} = mean number of times in Cell i given that the initial cell is Cell j for Case 1

r_{2ij} = mean number of times in Cell i given that the initial cell is cell j for Case 2

2.2.4 Candidate OMAC's

OMAC's are defined by the parameters of the criteria and constraint functions. The following criterion function was selected to include the factors identified as important in the task instructions.

$$C = A \times T + B \times f(2 - CPA)/TCPA$$

where

T is total transiting time,

f is a function defined by Figure 10,

CPA is closest point of approach to a contact, and

TCPA is time to CPA.

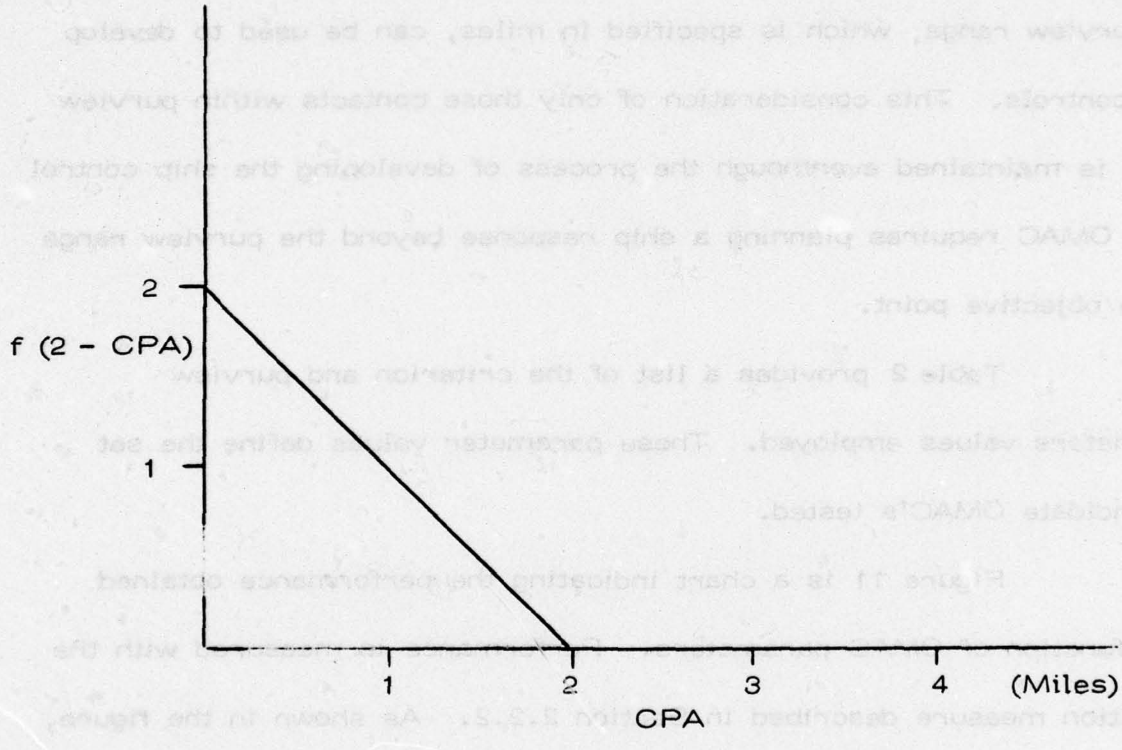


FIGURE 10 CRITERION FUNCTION

Weighting coefficients A and B are limited as follows:

$A, B \geq 0.0$

$A + B = 1.$

In addition to the criterion function given above, a purview constraint is employed. A purview constraint requires that only contacts within the purview range, which is specified in miles, can be used to develop ship controls. This consideration of only those contacts within purview range is maintained eventhough the process of developing the ship control using OMAC requires planning a ship response beyond the purview range to the objective point.

Table 2 provides a list of the criterion and purview parameters values employed. These parameter values define the set of candidate OMAC's tested.

Figure 11 is a chart indicating the performance obtained as a function of OMAC parameters. Performance is measured with the transition measure described in Section 2.2.2. As shown in the figure, performance improves with increasing purview up to 12.5 miles. At the greater purview tested (16.67 miles), performance decreased. Performance with a purview of 16.67 miles was evaluated with two time weighting values (.01 and .25). As shown in Figure 11, a time weighting of .01 results in poor overall performance. With this result that weighting was not evaluated with other purview values. But, the 16.67 mile purview was evaluated with a time weighting of .25. The figure shows performance

OMAC IDENTIFICATION	CRITERION PARAMETERS A	CRITERION PARAMETERS B	PURVIEW RANGE (MILES)
OMAC 1	.40	.60	6
2	.25	.75	6
3	.10	.90	6
4	.25	.75	8.3
5	.10	.90	8.3
6	.05	.95	8.3
7	.40	.60	10.5
8	.25	.75	10.5
9	.10	.90	10.5
10	.05	.95	10.5
11	.40	.60	12.5
12	.25	.75	12.5
13	.10	.90	12.5
14	.25	.75	16.67
15	.01	.99	16.67

TABLE 2 CRITERION AND PURVIEW PARAMETERS

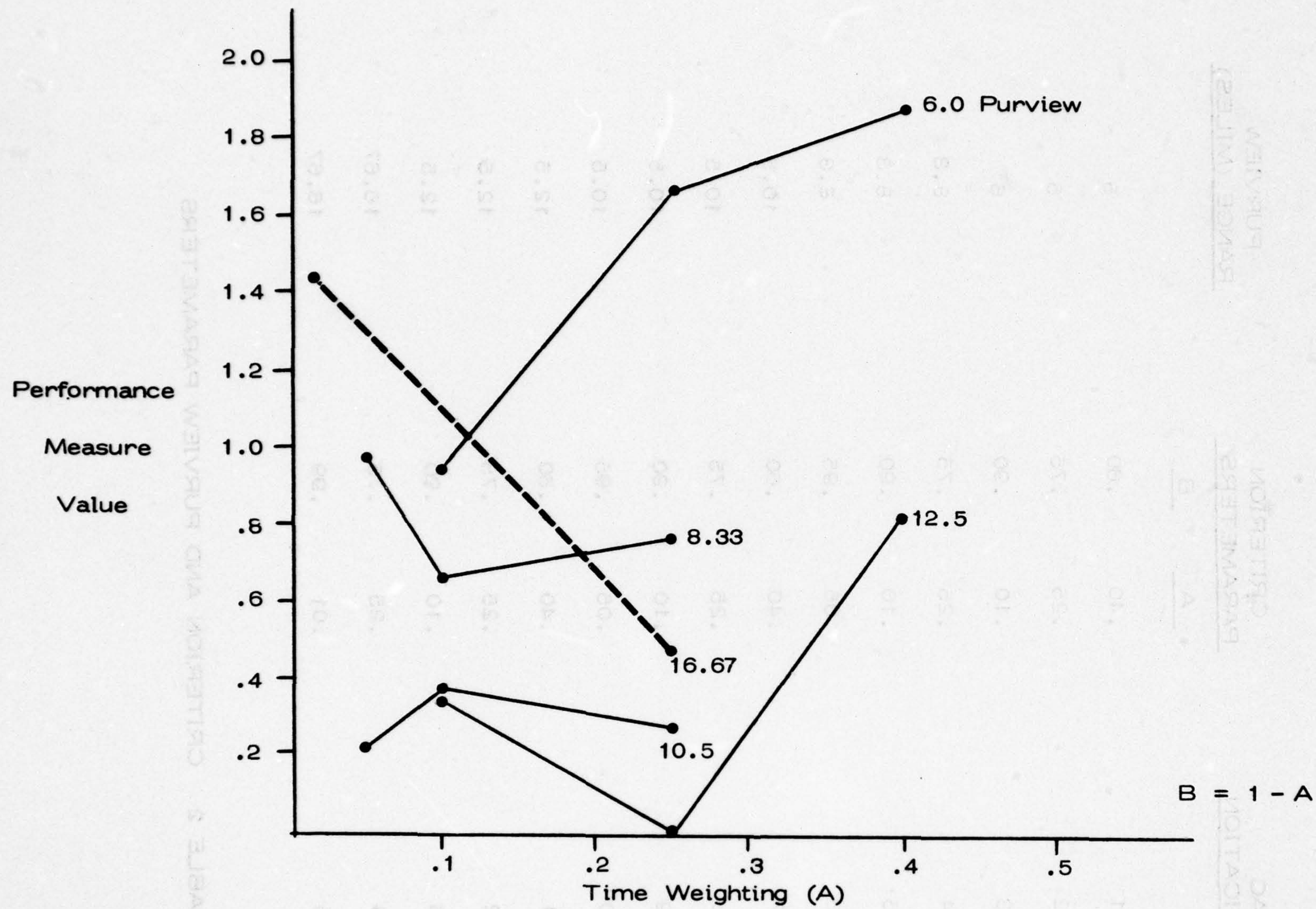


FIGURE 11 PERFORMANCE AS A FUNCTION OF OMAC PARAMETERS

improvement as purview increases from 6 to 8.3, 10.5, and 12.5; but, decreases for the 16.67 purview value. This is because the 16.67 purview required contact avoidance maneuvering far in advance of that required by the performance measure. With this excessive contact avoidance maneuvering, an excessive time penalty is accumulated. Apparently the 12.5 mile purview does not require excessive contact avoidance maneuvering and therefore provided best performance.

2.3 Method of Analysis

2.3.1 Analysis I: Test of the Dynamic Performance Measure

The transition performance measure is described in Section 2.2.2. It is obviously related to the "static" measure, i.e., the count of the number of times critical cells are entered; and, prior to its use, it is desirable to test the relationship between the static and transition measures. This test, termed Analysis I, employs a regression analysis of subject performances with the static measure as the independent variable and the transition measure as the dependent variable. Two analyses are used. One employs data from subject performances using the PACS display and the other uses data obtained with the OLD display. The hypothesis is that the two measures indicate the same quantity.

2.3.2 Analysis II: OMAC Representation of Subject Performance

Contact avoidance performance of each OMAC is compared to the contact avoidance performance of each subject experimental trial in order to identify a representative OMAC for that trial. The OMAC with the performance closest to a subject trial (as indicated by the transition performance measure) is designated as the representative OMAC for that subject.

A test of that representation was made using a regression analysis where the performance of a representative OMAC is used to predict the performance of a subject using a particular display type. The analysis uses OMAC contact avoidance performance as the independent variable. The hypothesis is that OMAC contact avoidance predicts subject performance with a specified display type.

2.3.3 Analysis III: OMAC Parameters Representing Display Type

OMAC's representing OOD performance can be grouped according to the display type (design) used. Parameters of OMAC's identified for each display type can be analyzed to explain performance differences with different display types. OMAC parameters for two display types (PACS and OLD) are analyzed.

In addition to display type, OMAC parameters are affected by the subject performance level. In order to study this effect in combination with the effect of display type, a two variable analysis is used with two levels per variable. A possible third factor, accuracy of OMAC models in representing subject performance, is not used in the analysis because the accuracy of the OMAC representation (i.e., the difference between OOD performance and the performance of the OMAC selected as representative) is correlated with OOD performance. This relationship is illustrated in Table 3.

In order to establish two performance categories for subjects, the superior half of the subject trials with the OLD display are classified as superior and the other half as less than superior. With this classification, the performance score for the superior subject trials was .526 or less. This score level was then taken as the superior performance criterion level and applied to identify superior performances with the PACS display. With this selection criteria, nine of the total 11 subject trials with the PACS display were rated superior.

From this two factor analysis, estimates are developed of OMAC parameters for each display type and performance category. Finally, the OMAC parameters are analyzed using a t test for significant differences with display type.

2.3.4 Analysis IV: Display Information and Ship Control Performance

Each type of display presents information to the subject in a different form. The information and the form of the information in advanced displays such as the PACS display can eliminate the need for the OOD to perform certain information processing tasks. The OOD is then presumably free to perform other processing tasks. Relating this change of the information processing requirement to a change in contact avoidance performance is the purpose of this analysis.

Subject	Difference in Scores Between Subject Performance and OMAC Representing Subject Performance	Subject Performance Score	
A12	.027	.036	Superior Performers On OLD Display
B7	.097	.228	
B4	.126	.240	
B14	.276	.422	
A4	.229	.526	
A10	.478	.623	
B10	.535	.754	
A8	.686	.777	
A6	.891	1.389	
B6	1.222	1.966	
A14	2.900	5.061	

TABLE 3 ORDERING OF PERFORMERS WITH THE OLD DISPLAY

The portion of the OOD's ship control task that is expected to be affected by a display design is the information processing component. This component is composed of a set of subtasks which are taken as: locate contact on display, determine contact course and speed, project contact position as a function of future time, identify possible CPA violations, determine time to CPA for CPA violations, evaluate alternative speeds to avoid CPA violations, and select course and speed. Each display design can provide information that can simplify or even supplement one or more of these information processing subtasks. For analysis in this study, specific subtasks are categorized as follows:

1. Determine course and speed required to reach objective position independent of contact positions, courses, and speeds.
2. Detect CPA violations and estimate time to CPA
3. Identify alternative courses and/or speeds that will avoid CPA violations.
4. Select alternative course and/or speed to avoid CPA violation based on transiting objectives, to obey rules of the road, and to conserve fuel.
5. Perform other information processing tasks not related to contact avoidance.

The analysis is to identify, for each display type, the processing provided by the display. In an additional analysis, the average number of contacts within purview is determined in order to establish the average number of contacts processed as a function of purview.

3.0 RESULTS

3.1 Analysis I Results: Test of the Dynamic Performance Measures

Results of the regression analysis using the transition and static performance measures are given in Tables 4 and 5. The results show that the static measure predicts the transition measure and that the prediction is significant at the $\alpha \leq .001$ and .05 levels for the PACS and OLD displays respectively.

3.2 Analysis II Results: OMAC Representation of Subject Performance

Tables 6a and 6b give the results of the comparison of each subject trial performance with each OMAC. Each subject provided two performances - one using the PACS display and the other using the OLD display. Entries indicated by a "*" identify the representative OMAC selected.

Results of the comparison between the representative OMAC and the represented subject trial according to contact avoidance performance are shown in Tables 7 and 8. The regression is significant at the $\alpha \leq 0.001$ level for both PACS and OLD displays. A scatter diagram for these regressions is given in Figure 12.

3.3 Analysis III Results: OMAC Parameters Representing Display Type

Table 9 presents the results of the analysis of OMAC parameters as a function of all performances (Case I) and superior performances (Case II), and two display types (OLD and PACS).

SOURCE OF VARIATION	SS	df	MS	F ratio
Explained - due to linear regression $\hat{Y} - \bar{Y}$	7.92	1	7.92	12.68*
Unexplained - error around regression line	5.61	9	0.62	
TOTAL	13.53	10		

$F(.001, 1, 9) = 9.5^{*}$

Significance of Regression Coefficient

$t_s = 45.2, \quad t(.001, 9) = 4.7$

Regression Coefficient $b_{y \cdot x} = 0.280$

Y intercept $a = 0.092$

TABLE 4 REGRESSION ANALYSIS
PACS DISPLAY

SOURCE OF VARIATION	SS	df	MS	F ratio
Explained - due to linear regression $\hat{Y} - \bar{Y}$	10.55	1	10.55	6.77*
Unexplained - error around regression line	14.01	9	1.55	
TOTAL	24.56	10		

$F(.05, 1, 9) = 5.12^{*}$

Significance of Regression Coefficient

$t_s = 2.6, \quad t(0.5, 9) = 2.2$

Regression Coefficient $b_{y \cdot x} = 0.35$

Y intercept $a = 0.28$

TABLE 5 REGRESSION ANALYSIS
OLD DISPLAY

OLD DISPLAY

Subject	6^{2}	6	6	8.3	8.3	8.3	10.5	10.5	10.5	10.5	12.5	12.5	12.5	16.6	16.6
	$.4^{1}$	.25	.1	.25	.1	.05	.4	.25	.1	.05	.4	.25	.1	.25	.01
A4	.48	.60	*.22	.38	.27	.44	2.84	.35	.42	.47	.67	.52	.46	1.02	.62
A6	1.07	*.89	*.89	.92	1.00	1.00	1.73	1.10	1.22	1.34	1.47	1.38	1.31	1.27	1.49
A8	1.65	1.58	.98	1.00	.84	1.06	2.47	.74	.73	.73	*.68	.77	.71	.87	.71
A10	1.33	1.22	.73	.77	.63	.74	2.40	.56	.49	.54	.51	.62	*.47	.79	.58
A12	1.41	1.23	.50	.51	.29	.55	2.26	.10	.05	*.02	.08	.03	.03	.41	.08
A14	3.08	3.68	3.75	4.13	4.11	4.16	*2.90	4.58	4.74	4.88	4.96	5.06	4.88	3.79	5.13
B4	.90	.57	.25	.22	.16	.31	2.51	*.12	.17	.22	.39	.24	.22	.75	.34
B6	1.29	*1.22	1.36	1.46	1.57	1.40	3.51	1.67	1.67	1.85	1.74	1.96	1.86	2.34	1.77
B7	.86	.61	.20	.17	.11	.21	2.07	*.09	.12	.19	.32	.22	.17	.55	.30
B10	2.17	1.74	1.23	1.19	1.00	1.26	1.31	.82	.76	.74	.63	.75	.74	*.53	.72
B14	1.07	.88	.41	.40	.30	.38	1.93	.30	*.27	.36	.47	.42	.34	.64	.46

* Indicates Best Performance Comparison

1 Time Weighting Factor

2 Purview

TABLE 6a COMPARISON OF SUBJECT AND OMAC PERFORMANCE

PACS DISPLAY

Subject	6	6	6	8.3	8.3	8.3	10.5	10.5	10.5	10.5	12.5	12.5	12.5	16.6	16.6
	.4	.25	.1	.25	.1	.05	.4	.25	.1	.05	.4	.25	.1	.25	.01
A4	1.51	1.33	.58	.56	.35	.64	2.14	.16	.11	.09	.15	.09	*.08	.40	.14
A6	1.07	.81	.42	.43	.30	.45	2.47	.27	*.24	.29	.35	.33	.30	.81	.33
A8	1.39	1.22	.46	.46	.24	.53	2.49	.06	.04	.00	.15	*.00	.01	.51	.10
A10	1.17	.97	.35	.32	.17	.40	2.40	.05	.05	.05	.21	.06	*.04	.54	.17
A12	1.41	1.25	.48	.48	.25	.55	2.53	.07	.04	.00	.15	*.00	.01	.51	.10
A14	1.32	1.06	.71	.67	.64	.68	.90	.65	.67	.77	.73	.82	.74	*.37	.87
B4	1.42	1.25	.48	.48	.25	.55	3.02	.07	.04	.00	.15	*.00	.01	.51	.10
B6	1.13	1.15	*1.07	1.17	1.24	1.11	3.08	1.35	1.42	1.58	1.61	1.66	1.48	1.75	1.73
B7	.90	.85	*.53	.55	.54	.60	3.11	.57	1.35	.72	.92	.78	.66	1.28	.88
B10	1.44	1.27	.50	.51	.28	.55	2.54	.09	.03	*.01	.04	.02	.02	.53	.06
B14	1.30	1.13	.41	.41	.21	.45	2.46	.05	.02	.01	.12	.02	*.00	.49	.10

*Indicates Best Performance Comparison

[1] Time Weighting Factor

[2] Purview

TABLE 6b COMPARISON OF SUBJECT AND OMAC PERFORMANCE

SOURCE OF VARIATION	SS	df	MS	F ratio
Explained - due to linear regression $\hat{Y} - \bar{Y}$	10.37	1	10.37	29.50*
Unexplained - error around regression line	3.16	9	.35	
TOTAL	13.53	10		

$F(.001, 1, 9) = 22.9^{*}$

Significance of Regression Coefficient

$t_s = 5.4$, $t(.001, 9) = 4.7$

Regression Coefficient $b_{y \cdot x} = 3.0$

Y intercept $a = -0.1$

TABLE 7 REGRESSION ANALYSIS OMAC/SUBJECT CONTACT AVOIDANCE PERFORMANCE PACS DISPLAY

SOURCE OF VARIATION	SS	df	MS	F ratio
Explained - due to linear regression $\hat{Y} - \bar{Y}$	20.83	1	20.83	50.14*
Unexplained - error around regression line	3.73	9	.41	
TOTAL	24.56	10		

$F(.001, 1, 9) = 22.9^{*}$

Significance of Regression Coefficient

$t_s = 7.08$, $t(.001, 9) = 4.78$

Regression Coefficient $b_{y \cdot x} = 1.41$

Y intercept $a = 1.02$

TABLE 8 REGRESSION ANALYSIS OMAC/SUBJECT CONTACT AVOIDANCE PERFORMANCE OLD DISPLAY

	PURVIEW			WEIGHTING ON TRANSIT TIME	
	OLD	PACS	Significance test t_s Ratio	OLD	PACS
CASE I					
Mean	10.20	11.33	0.84 (NS)	0.211	0.15
Variance	9.56	9.49		0.18	0.006
CASE II					
Mean	9.60	12.00	2.51* significant	0.15	0.15
Variance	4.05	0.85	at $\alpha \leq .1$	0.008	0.007

$^*t' \ (\alpha = .1) = 2.096$

$t' \ (\alpha = .05) = 2.717$

Case I - All subjects using both OLD and PACS display

Case II - Only subjects providing superior performances

TABLE 9 OMAC PARAMETERS vs. DISPLAY TYPE AND PERFORMANCE

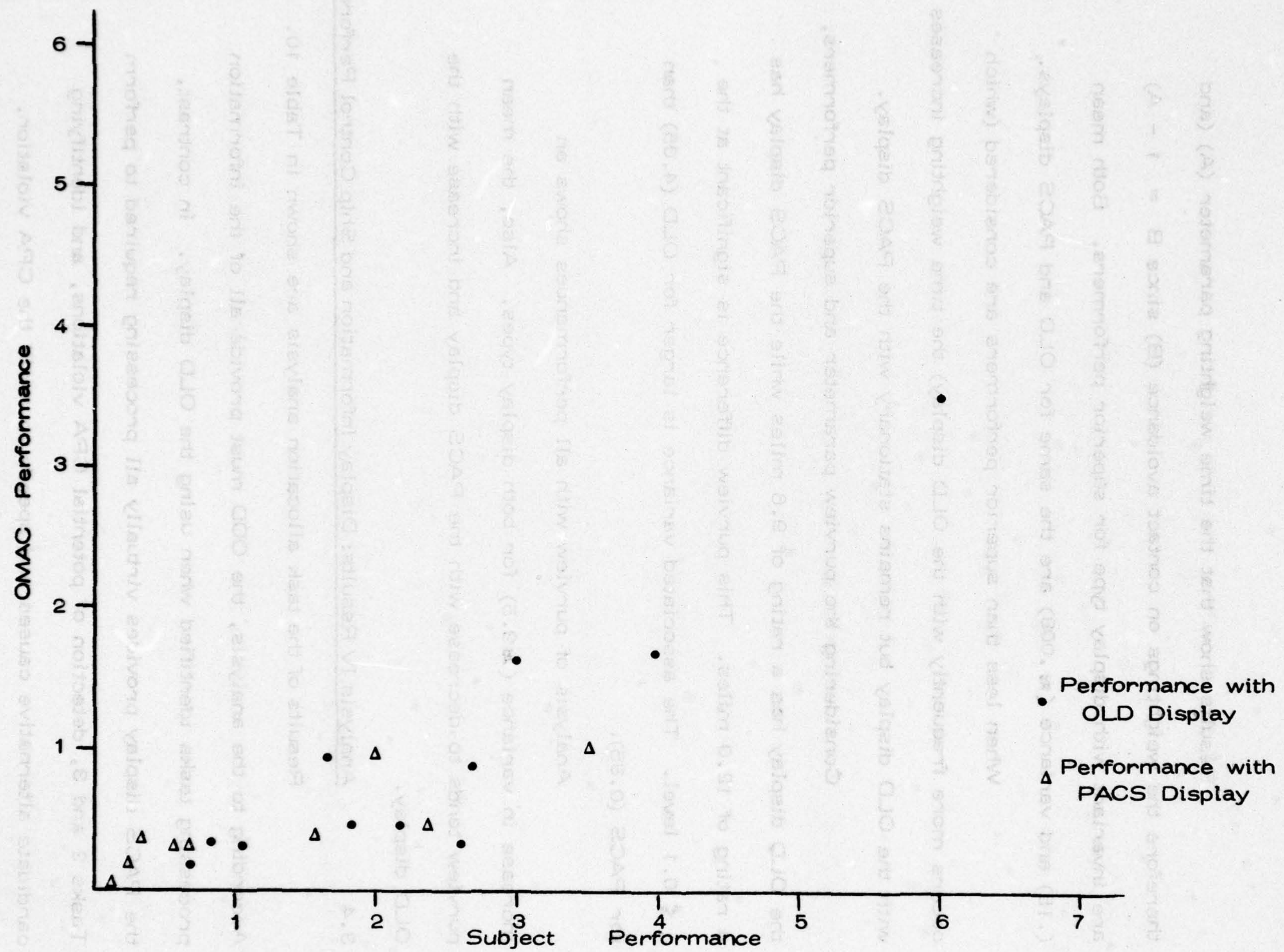


FIGURE 12 SCATTER DIAGRAM

Results show that the time weighting parameter (A) (and therefore the weightings on contact avoidance (B) since B = 1 - A) are invariant with display type for superior performers. Both mean (.15) and variance ($\approx$.008) are the same for OLD and PACS displays.

When less than superior performers are considered (which occurs more frequently with the OLD display) the time weighting increases with the OLD display but remains stationary with the PACS display.

Considering the purview parameter and superior performers, the OLD display has a rating of 9.6 miles while the PACS display has a rating of 12.0 miles. This purview difference is significant at the $\alpha \leq 0.1$ level. The associated variance is larger for OLD (4.05) than for PACS (0.85).

Analysis of purview with all performances shows an increase in variance ($\approx$9.5) for both display types. Also, the mean purview tends to decrease with the PACS display and increase with the OLD display.

3.4 Analysis IV Results: Display Information and Ship Control Performance

Results of the task allocation analysis are shown in Table 10. According to the analysis, the OOD must provide all of the information processing tasks identified when using the OLD display. In contrast, the PACS display provides virtually all processing required to perform Tasks 2 and 3, detection of potential CPA violations, and identifying candidate alternative causes and speeds to avoid the CPA violation.

	TASK	ALLOCATION OLD DISPLAY	 PACS DISPLAY	TYPE TASK ID
1.	Determine course and speed to objective	OOD**	OOD	T_1
2.	Detect CPA violations and determine time to violation	OOD	D*	t_1
3.	Identify alternative course and speeds to avoid CPA violations	OOD	D*	t_2
4.	Select alternative	OOD	OOD	t_3
5.	Other information processing	OOD	OOD	T_2

*Display provides substantially the total effort required by these tasks.

**Tasks requiring information processing by the Officer of the Deck (OOD).

Lower case t represents tasks where the information processing required is a function of the number of contacts.

Upper case T represents tasks where the information processing required is not a function of the number of contacts.

TABLE 10 INFORMATION PROCESSING TASK ALLOCATION

Analysis of the average number of contacts in purview as a function of purview reveals that the average number of contacts is proportional to area within purview. This implies that a constant contact density can be used to predict number of contacts in a given purview. This result is shown in Figure 13. The contact density for the ship control problem is approximately 0.012 contacts per square mile.

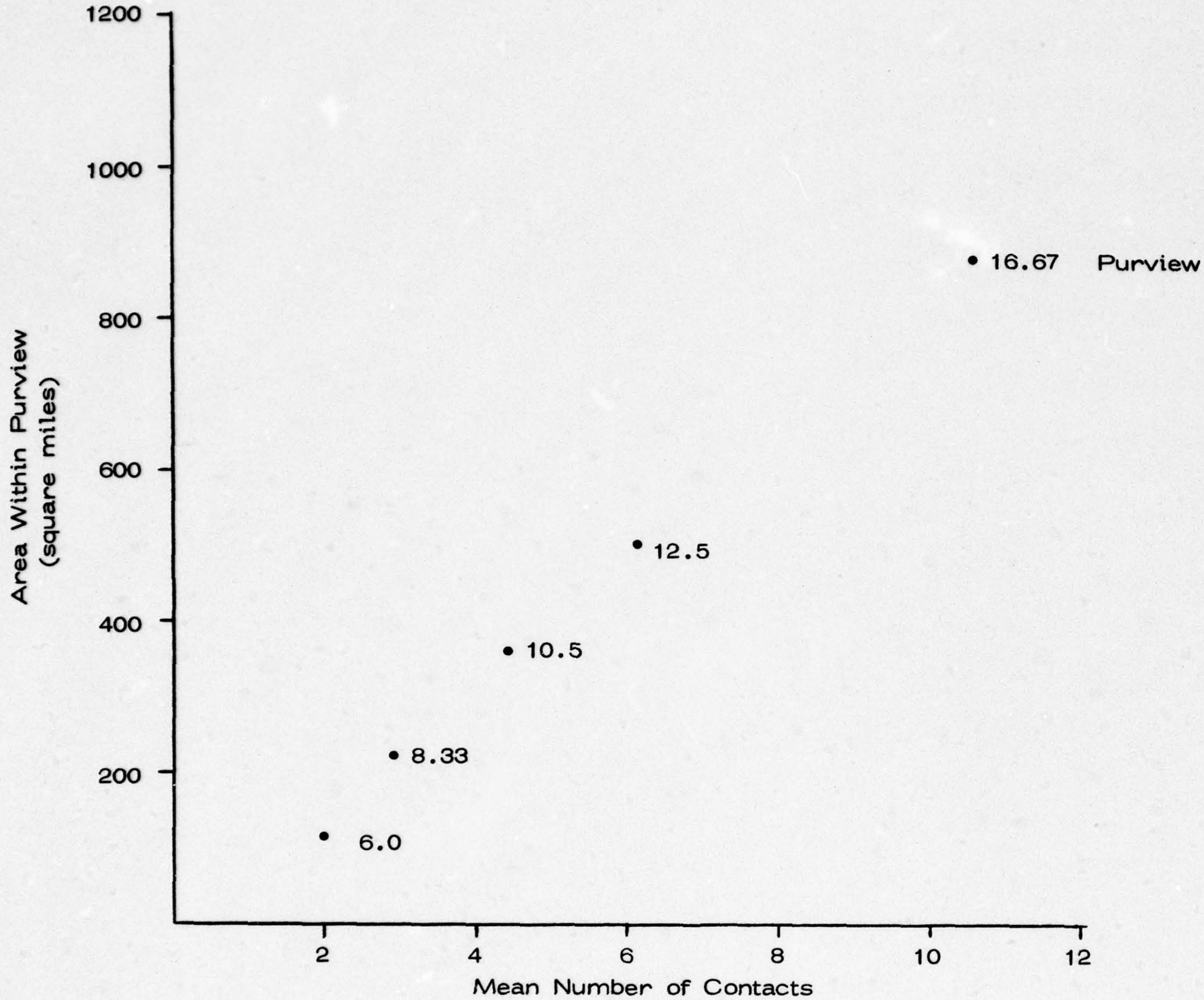


FIGURE 13 RELATIONSHIP BETWEEN PURVIEW AREA AND NUMBER OF CONTACTS

4.0 DISCUSSION AND CONCLUSIONS

4.1 Products of the Research

Performance Measurement

Results of the comparison of the transition and static measures (Analysis I) provide convincing evidence of the validity of both the transition measure and the transition matrices used to compute the transition measure. In this study, the transition measure was used extensively to compare OMAC performance to subject performance. This validation of the measure is fundamental to the other results obtained in the study. The transition matrix probabilities reveal the nature of the performance differences obtained with different display types. Analysis of the transition probabilities was used in this study to illustrate the nature of the performance differences. A more extensive analysis could reveal control pattern tendencies for each display type.

The transition performance measure is a sensitive indication of contact avoidance performance. Its sensitivity comes from detection of the relative ship states that lead to collisions rather than detection of just collision or near collisions.

OMAC Representation of Subject Performances

Analysis II results identify an OMAC for each subject performance. Two factors are of immediate interest with this identification. First, the ability of the OMAC's to represent subject performances is a function of the level of subject performance, i.e., superior performers were represented more accurately than were lesser performers. This suggests the need to introduce additional factors in candidate OMAC's in order to more accurately represent the lesser performers.

A second factor of interest is that, in spite of difference in accuracy of representation, the representation is sufficiently accurate to permit prediction of subject performance, i.e., prediction of subject performance using OMAC's in a statistically significant manner.

OMAC Representation of Performance with OLD and PACS Displays

Analysis III is an analysis of OMAC's representing two different display types (OLD and PACS) for two subject population groups (all subjects and superior subjects). From the results, several conclusions are possible:

1. A greater proportion of subject performers are rated superior with the PACS display than with the OLD display. This suggests that with the PACS display there would be more superior performers in the general OOD population.

2. Superior performers with PACS and OLD displays are represented by the same OMAC criteria (the relative weighting between contact avoidance and transit time). The average performance level with the two displays is different but the criteria optimized are the same. This suggests that consistent "target" criteria (the criteria sought by the subject) was the goal of superior performers with both displays; but, the subjects

were better able to reach that performance goal with the PACS display. This result suggests that the "target" criteria might be used in training where subjects could be rated not only on performance but also on the criteria they apparently optimize.

3. Performance differences with different display types obtained from the superior performances are explained by a difference in purview (the range from own ship within which the subject processes contacts). The logic is: OMAC predicts subject performance; OMAC has two parts: criteria and purview; but, the criteria is constant while purview changes with changes in display. Indeed, the OMAC performance data show clearly the effect of purview on performance.

4. Since the average number of contacts within purview in the experiment problem is a linear function of purview area (a result of Analysis IV), OOD ship handling performance may be a function of the number of contacts that the OOD can process with a given display design. If a display feature automates one or more information processing tasks, the OOD may be able to process more contacts, thus expanding h's purview. According to the results discussed above (3), this would result in improved performance. This logic suggests that an analysis of the information processing required of the OOD per contact may permit direct prediction of OOD ship handling performance.

4.2 Concepts Suggested by the Research

Prediction of Performance From Display Analysis

Analysis IV provides identification of information processing provided by the OLD and PACS displays. The PACS display automates two types of tasks: "detect CPA violations and determine time to violation" and "identify alternative course and speeds to avoid CPA violations." In contrast, the OLD display does not automate those tasks and thus they must be performed by the OOD.

As stated previously, an analysis of the processing required of the OOD per contact for a given display design may permit direct prediction of total system performance. In order to construct such a prediction methodology, assume that the processing (WL) workload equals the sum of the efforts required to process information for each component sub-task - an initial assumption that no parallel processing is used. Thus, with this assumption WL can be expressed as

$$WL = \sum_i T_i + \sum_j t_j N$$

where T_i represents the effort required for information processing sub-task (i) that is not a function of the number of contacts, t_j represents the effort required for information processing sub-task (j) for each contact, and N is the number of contacts.

It is also assumed, in order to form the above expression, that effort required to process information for each contact times the number of contacts (N) can be represented by, or approximated by, the linear term ($t_j N$). Rearranging the expression and solving for N yields:

$$N = \frac{WL - \sum_i T_i}{\sum_j t_j}$$

This is a general expression which gives the number of contacts (N) processed by the OOD as a function of the information processing sub-tasks that must be performed by the OOD.

Numeral values for WL, T_i, and t_i are required to compute N. One way to determine the numeral values is to conduct performance tests with several types of displays and determine the apparent N for each display. If a display provides automatic calculation of one or more sub-tasks, the representation of the effort for those sub-tasks is set to zero (i.e., $T_i = 0$, or $t_j = 0$).

The theory of equations says that if there are K variables then K equations are required to solve for each variable. Thus, with this method, the number of different types of displays tested must be equal to the number of sub-tasks plus one. The additional test permits solving for the WL factor.

As an example, consider the results of Analysis IV (shown in Table 10). According to the analysis, the OOD must provide all of the information processing tasks identified when using the OLD display. In contrast, the PACS display provides virtually all processing required to perform Tasks 2 and 3: "detection of potential CPA violations," and "identification of candidate alternative courses and speeds to avoid the CPA violation." Thus, the information processing workload with the OLD display can be expressed by:

$$WL = T_1 + t_1 (NO) + t_2 (NO) + t_3 (NO) + T_2$$

where

NO is the number of contacts in the purview associated with the OLD display. The terms T_1, T_2, t_1, t_2, and t_3 are defined in Table 10. Thus:

$$NO = \frac{WL - (T_1 + T_2)}{(t_1 + t_2 + t_3)}$$

Likewise, the information processing workload with the PACS display can be expressed by:

$$WL = T_1 + t_3 (NP) + T_2$$

where NP is the number of contacts in the purview associated with the PACS display. Thus:

$$NP = \frac{WL - (T_1 + T_2)}{t_3}$$

The absence of tasks t_1 and t_2 in the PACS workload expression reflects the PACS display feature that provides virtually all the computation required to perform those tasks.

Representation of Human Performance by the OMAC Optimized

Based on the overall results obtained with the OMAC, it is concluded that the criteria modeling approach offers a practical way to model human performance in an operational or near operational problem setting. The method seems to be applicable to any manned system problem.

With this modeling method, the subject's output at each instant of time is represented by taking into account both the instantaneous problem state and future planned subject outputs as a result of projections of controlled device responses. Projections of controlled device responses are the expected future responses of the device(s) or expected behavior of disturbing factors such as the contacts of the ship control problem.

Representative OMAC's reveal the target criteria of the human controller and permit evaluation of his ability to perform according to that criteria. OMAC's also reveal the constraints that may be selfimposed or are inherent but limit the subject's performance capability.

OMAC's can be developed for subjects working with complex and non-linear tasks. The complexity of the task or the device being controlled does not limit the identification of the apparent OMAC.

APPENDIX

DESCRIPTION OF DISPLAYS

INTRODUCTION

This Appendix provides a description of the center CRT display used for the experiments at NSRDC. Figures A1, A2 and A3 are sketches of the display format for the OLD, RVV, and PACS display types respectively. Table A1 identifies the features available with each display. A description of the features follow.

Explanation of Display Symbols

1. Contact symbol - 1/8 inch square marks the position of each contact
2. Heading marker - heading cursor of own ship

   OLD - solid line from center to edge of display

   RVV - dashed line from center to edge of display

   PACS - solid line from center to length defined by "leaders adjust"[1] or "unit length" and then dashed to edge of display
3. Upper left corner - northup or headup[2]
4. Range - 3, 6, 12, 24 miles - lower left corner 'Range XX'

[1] "leaders adjust" and "unit length" refer to controls which govern the length of the heading marker.

[2] "northup" and "headup" refer to the orientation of the display. With northup mode the display is rotated so that North is always vertical. With "headup" the display is rotated so that ship heading is vertical.

5. Ranger rings - 0, 1, 5, 10, 20 - lower right corner 'Range Rings XX'

6. Tab symbol '+' - the tab position is controllable by the subject to facilitate acquiring or dropping contacts, and determine contact range and bearing.

7. Contact Projections

TVV - With this display function, true velocity vectors are displayed for all acquired contacts provided "leaders adjust" or "unit length" is on and set at other than zero. A line is presented from the contact symbol with a length defined by leaders adjust or unit length. An arrow on end of the line represents the predicted position of the contact at a specified future time. The words "true vectors" appear upper right of the center display.

RVV - With this display, relative velocity vectors replace the true velocity vectors. The words "relative vector" appear upper right of the center display.

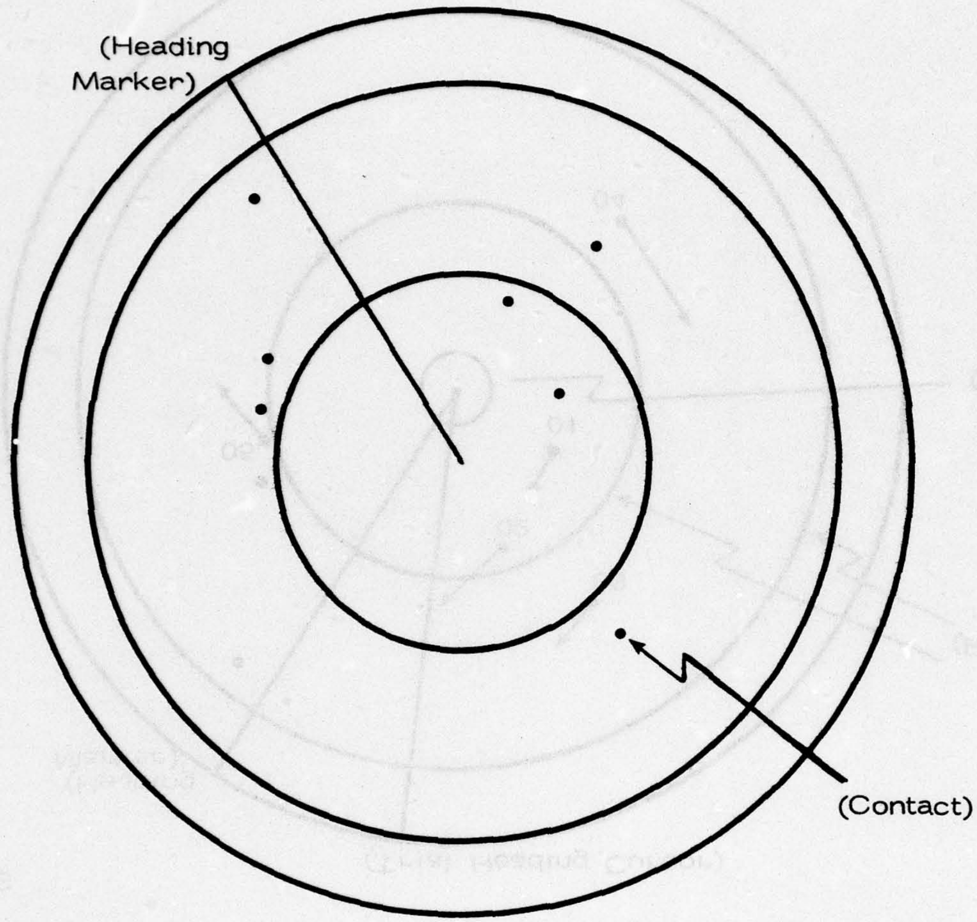
Trial Heading - When activated by the subject, a cursor line appears extending from the center to edge of the display. The line may be rotated under control of the subject. The words 'TRIAL HDC' appear left side of the center display.

Trial Speed - When activated by the subject, the words 'Trial Speed' appear left side of the center display.

PACS - With this display function, the center display shows the locus of points of contact violations (passing with 4,000 yards from a contact) for present and alternative own ship courses.

8. CPA Ring for RVV - Range ring at minimum miss distance.

NORTHUP



RANGE 24 Miles

RINGS 10 Miles

FIGURE A1 OLD DISPLAY FORMAT

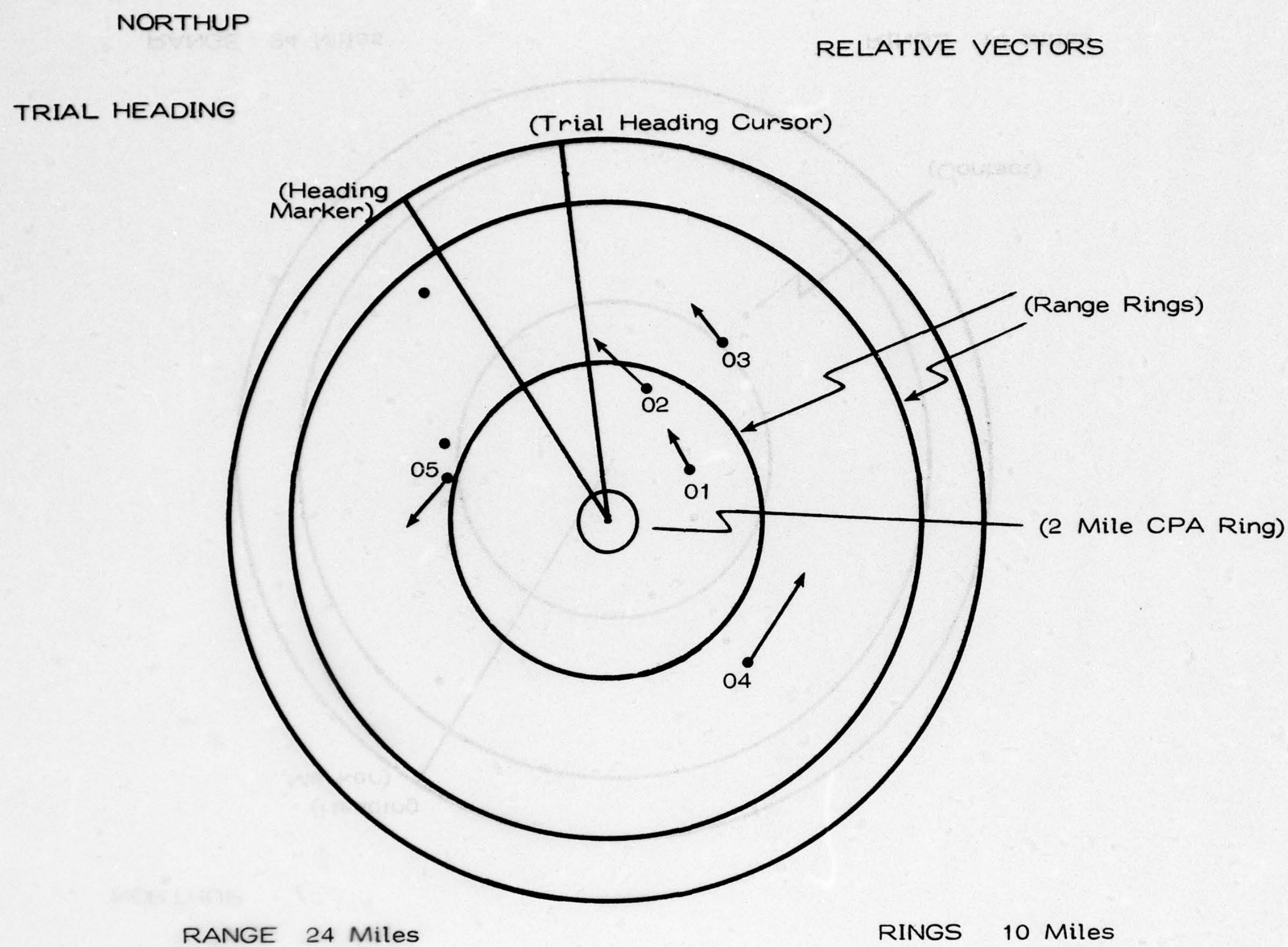


FIGURE A2 RVV DISPLAY FORMAT

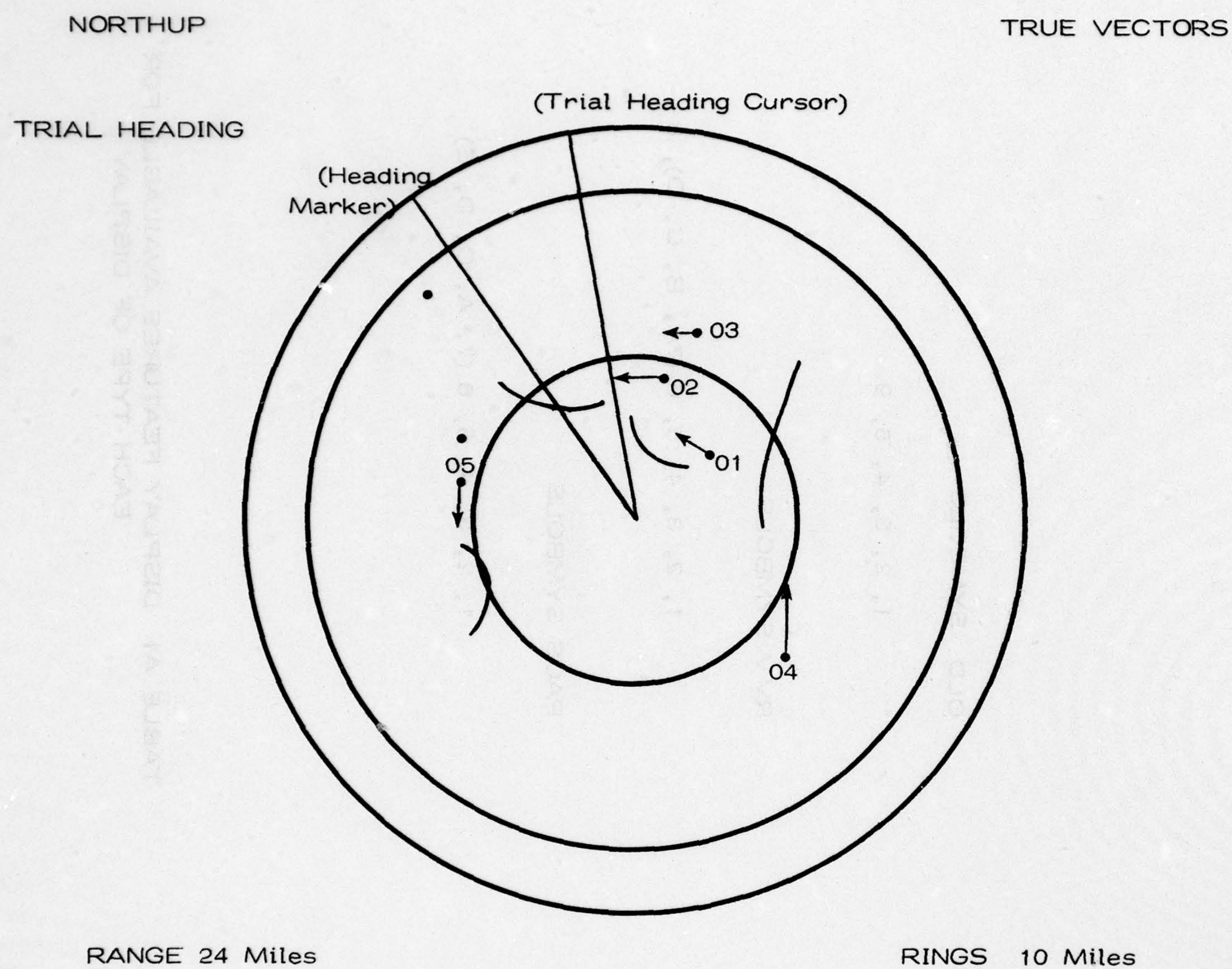


FIGURE A3 PACS DISPLAY FORMAT

OLD SYMBOLS

1, 2, 3, 4, 5, 9

RVV SYMBOLS

1, 2, 3, 4, 5, 6 (7A, B, C, D), 8

PACS SYMBOLS

1, 2, 3, 4, 5, 6 (7, A, C, D, E)

TABLE A1 DISPLAY FEATURES AVAILABLE FOR EACH TYPE OF DISPLAY

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