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APPLICATION OF MULTIDIMENSIONAL SCALING TO DECISION SITUATION P--ETC(U)

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Technical Report
1366-B

APPLICATION OF MULTIDIMENSIONAL SCALING TO DECISION SITUATION PRIORITIZATION AND DECISION AID DESIGN

25 August 1980

Submitted to:
Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974
and
Engineering Psychology Programs
Office of Naval Research
Arlington, VA 22217

Contract No. N00014-78-C-0743
Work Unit NR 199-003

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ANALYTICS

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 1366-B	2. GOVT ACCESSION NO.: AD-A091 956
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Application of Multidimensional Scaling to Decision Situation Prioritization and Decision Aid Design	5. TYPE OF REPORT & PERIOD COVERED: Technical Report 8/79-4/80
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Wayne Zachary	8. CONTRACT OR GRANT NUMBER(s): N00014-78-C-0743
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Analytics, 2500 Maryland Road, Willow Grove, Pa. 19090	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 199-003
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research Code 455, 800 N. Quincy St., Arlington, VA 22217	12. REPORT DATE: August 1980
	13. NUMBER OF PAGES: 147
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Naval Air Development Center, Aircraft and Crew Systems Engineering Directorate, Warminster, Pa. 18974	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Multidimensional Scaling, Unfolding Analysis, Priority Mapping, Decision Aids, Air ASW, Prioritization, Tactical Coordinator, TACCO, P-3C, Decision Situations, Decision Aid Design

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

This report describes one phase of an on-going effort to apply decision aiding technology to Naval Air ASW. Previous portions of the effort have identified key decision-making situations in Naval Air ASW to which decision-aiding is applicable, and specified the decision-aiding techniques that are most appropriate for each of them. This report considers the problem of prioritizing those situations for actual decision aid development, and initiates the aid design process for those situations found to have the highest priority.

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Initial attempts at prioritizing the decision situations pointed out the need to treat priority as an explicitly multidimensional measure, and to incorporate the judgement of experienced Air ASW personnel into the prioritization procedure. These two requirements led to the development of a novel prioritization methodology termed Priority Mapping. The technique utilizes non-metric Multi-Dimensional Scaling (MDS) and Coombsian Unfolding Analysis to create quantitative priority scores for decision situations from qualitative judgement about them by experienced Air ASW personnel. MDS is first used to identify the underlying dimensions with which experienced personnel perceive ASW decision-making. Unfolding Analysis is then used to model priority in term of these underlying dimensions; the unfolding analysis model provides the desired numerical priority scores.

Two types of data for the prioritization are collected from 32 highly experienced P-3C Tactical Coordinators (TACCOs) at NAS Moffett Field: 1) judgements about the basic similarities/differences among a sample of TACCO decision functions, and 2) rankings of the same decision functions according to their perceived importance in two major types of ASW missions -- attack missions and surveillance missions. MDS is applied to the first type of data (judged similarities) to dimensionalize ASW decision-making. Three dimensions are identified from the MDS analysis: 1) degree of uncertainty, 2) information processing load, and 3) complexity of the alternatives involved. Unfolding Analysis is applied to the three dimensional MDS solution and to the second type of data (rankings) to create a mathematical model of priority as a function of the three MDS dimensions. This model is used to generate numerical priority scores for the decision functions in two types of missions (attack and surveillance) which are then aggregated and normalized to construct priority scores for the decision situations.

For both attack and surveillance missions, the Contact Classification/Verification decision situation achieves the highest priority. The Surveillance Tracking situation has second highest priority for Surveillance Missions, while the Attack Planning situation has second highest priority for Attack Missions.

Decision aids designs for two of the highest priority situations--Contact Classification/Verification and Attack Planning--are initiated. An Optimal Mode-Selection decision aid is outlined for the Contact Classification/Verification situation. This aid uses a dynamic programming algorithm and a multiattribute utility model together with computational algorithms for determining the probability of correctly identifying a signal from a particular target (given a signal-processing mode and environmental conditions) to help the TACCO or Sensor Operator (SENSO) select an optimal processing mode for his acoustic signal processing equipment. An Attack Criteria/Weapon Placement decision aid is outlined for the Attack Planning decision situation. This aid uses a real-time information processing algorithm to automate the determination of attack criteria attainment and uses a probabilistic model outcome calculator, a nonlinear value model, and a nonlinear programming algorithm to optimize the tactics for anticipated attack

ACKNOWLEDGEMENTS

The research presented in the report was jointly supported by the Engineering Psychology Program, Office of Naval Research and the Human Factors Division, Naval Air Development Center. In addition to the author, major contributions to the effort were made by Messrs. James Kelley, Melvin Strieb, and Dr. Robert Wherry. We would like to acknowledge the important critical contributions of Dr. Martin Tolcott and Mr. Gerald Malecki of the Office of Naval Research, and Dr. Julie Hopson, LCDR. Tommy Morrison, CDR. Michael P. Curran and CDR. Norman Lane of the Naval Air Development Center. Additional thanks are due to Mr. Robert Lawson of the Office of Naval Research and CDR. David Stromberg and SQ.LDR. Jon Child of COMPATWINGSPAC for their assistance in arranging the interviews at Moffett Field. Last, but certainly not least, we would like to thank the TACCOs from squadrons 19, 31, 40, 46, 47, and 50 at NAS Moffett Field for their time and effort in providing the inputs for this research that only they could.

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EXECUTIVE SUMMARY

The application of decision aiding technology to Naval Air ASW requires a broad range of analytic tools. This report presents the results of the current phase of Analytics' effort to define a structure for applying these tools within the context of Naval Air ASW. Previous phases of this effort have analyzed Naval Air ASW platforms and missions, identified six key decision making situations which arise in these missions, determined the decision aiding techniques which are best suited to improving decision making performance in each of them and made an initial attempt at decision situation prioritization. The selection of an appropriate decision situation for decision aid design and implementation must be based upon an accurate prioritization of the decision situations according to their importance to the Naval Air ASW mission. Our initial ASW decision situation prioritization effort pointed out the need to treat priority as a multidimensional measure, and the need to incorporate the judgments of experienced operational ASW personnel into the prioritization procedure. The objective of the current effort reported here has been to develop and apply a prioritization methodology which meets these requirements.

A prioritization technique called Priority Mapping was developed in the course of this research. This technique uses Multidimensional Scaling and Unfolding Analysis to translate non-quantitative judgements about the similarity among, and relative importance of, a number of decision functions performed by the Tactical Coordinator (TACCO) into numerical priority scores for the decision situations in which these decision functions arise.

Two types of basic data for this effort were collected through interviews with 32 highly experienced P-3C TACCOs stationed at NAS Moffett Field. Data on the perceived similarities among fourteen decision functions were gathered and processed to produce numerical measures of their dissimilarity. These data were subsequently input to a Multidimensional Scaling program.

Additional data were collected on the perceived importance of the decision functions in missions with and without attack phases, on the perceived urgency of the decision functions, and on the TACCOs' perceptions of their relative workload during each of the decision functions. These data were subsequently used as inputs to the Unfolding Analysis procedure.

A Multidimensional Scaling analysis of the perceived similarities data identified the ASW decision space as three dimensional. The three dimensions were interpreted as representing:

- the degree of uncertainty in the information used to make a decision
- the information processing load a decision placed on the TACCO
- the complexity of the alternatives which the TACCO considers in making the decision.

Unfolding Analysis was conducted to assess the relative ability of four models of priority to represent the preceived importance of the decision functions rated by the TACCOs at Moffett Field. The most complex model, known as the generalized distance model, was selected as the most appropriate. Two mathematical formulae which represented decision priority as a function of the three dimensions uncovered by the Multidimensional Scaling procedure were constructed according to the generalized distance model. The first formula represented the decision functions' priority in attack missions while the second represented their priority in surveillance missions. The resulting decision function priority scores were aggregated to produce priority scores for the six decision situations previously identified. For attack missions the prioritization of those decision situations (in order of descending priority) is:

- Contact Classification/Verification
- Attack Planning
- Localization

- Surveillance Tracking
- Lost Contact Reacquisition
- On-Station Search

For surveillance missions, the prioritization is:

- Contact Classification/Verification
- Surveillance Tracking
- Lost Contact Reacquisition
- Localization
- On-Station Search
- Attack Planning

High level decision aid designs are presented for two of the situations with highest priority (Contact Classification/Verification and Attack Planning). An Optimal Mode-Selection decision aid is outlined for the Contact Classification/Verification situation. This aid uses a dynamic programming algorithm and a multiattribute utility model together with computational algorithms for determining the probability of correctly identifying a signal from a particular target (given specific signal-processing modes and environmental conditions) to help the TACCO or SENSO select an optimal processing mode for his acoustical signal processing equipment. An Attack Criteria/Weapon Placement decision aid is outlined for the Attack Planning decision situation. This aid uses a real-time information processing algorithm to automate the determination of attack criteria attainment, and uses a probabilistic model outcome calculator, a nonlinear value model, and a nonlinear programming algorithm to optimize the tactics for anticipated attack.

This effort has resulted in three primary products:

1. Dimensionalization of ASW decision-making as perceived by experienced ASW decision makers,

2. Prioritization of ASW decision situations and decision functions in two kinds of ASW missions, and

3. Construction of high level decision aid designs for two of the decision situations with highest priority.

Even the most carefully chosen mix of decision aiding techniques applied to the highest priority decision situations, however, can not be guaranteed to improve materially the quality of the decision made in that situation. The degree of uncertainity inherent in a problem, the required response interval, or other such limiting factors could impose such severe constraints that, in practice, even the best decision aid could have only minimal impact on given decision situation. It still remains to be demonstrated that the highest priority decisions are in fact amenable to aiding by the decision aiding approaches selected here.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLES

1. INTRODUCTION AND METHODOLOGICAL OVERVIEW

The rapid increase in the technological sophistication of Naval Air ASW in recent years has brought with it growing demands for quicker and higher quality decisions from ASW aircrews. This report describes the current Analytics research effort in investigating the application of decision aiding to Naval Air ASW. The project reported here concerns the prioritization of Air ASW decision situations for decision aiding design.

Analytics' previous investigation into Air ASW decision aiding (see Zachary, 1980) has focused on three issues:

- the definition of the decision points within the generic Air ASW mission to which decision aiding could be applied,
- the identification of state-of-the-art decision aiding techniques which could be applied to each of these decisions, and
- the prioritization of Air ASW decision making situations according to their criticalities in the overall mission.

These issues are reviewed below, as background for the remainder of this report.

1.1 REVIEW OF PREVIOUS RESEARCH

An analysis of the commonalities among the missions flown by the three principal ASW platforms of the 1980-1985 time frame -- P-3C, and S-3A, and the LAMPS MK III -- has resulted in the construction of a generic Air ASW mission profile. From this generic mission structure, the various decisions made by the Tactical Coordinator (TACCO) nave been identified and investigated. It was found that similar decision processing is performed by the TACCO throughout the mission, but with different end results, depending on the particular objective of the mission phase. For example, the goal event sought by the TACCO in the on-station search portion of the mission is gaining contact with a hostile submarine. In the attack planning portion of the mission, the goal event is the destruction of the submarine. The differing goal events of the different mission phases give rise to complex decision making contexts, which constrain the way in which the TACCO's primary decision functions are carried out. These contexts, termed decision making situations, were identified as the principal units to which decision aiding should be applied. The six specific decision situations defined are listed in Table 1-1, along with their goal events.

Table 1-1. ASW Decision Situations and Goal Events

DECISION SITUATION	GOAL EVENT
ON-STATION SEARCH	GAIN CONTACT WITH TARGET OF INTEREST
CONTACT CLASSIFICATION/VERIFICATION	IDENTIFY SOURCE OF CONTACT
LOCALIZATION	DETERMINE LOCATION, COURSE, SPEED AND DEPTH OF TARGET
SURVEILLANCE TRACKING	MAINTAIN LOCALIZED CONTACT WITH TARGET
ATTACK PLANNING	PLACE OPTIMAL ATTACK AGAINST HOSTILE TARGET
LOST CONTACT REACQUISITION	REGAIN AND LOCALIZE CONTACT WITH A LOST TARGET

Existing decision aids were reviewed and analyzed to determine the range and characteristics of state-of-the-art decision aiding technology. Complete existing decision aids were found to be highly specialized, and not directly generalizable to the ASW decision situations. However, the existing decision aids were found to be composed of similar decision aiding techniques; these individual techniques were found to be extremely general. Analysis of the functions these individual techniques played in the various aids showed there were many fewer functional categories of techniques than techniques themselves. These categories were used to group the techniques into a functional taxonomy of decision aiding methods. The categories in the taxonomy (shown below as Table 5-1) were used as the basis of a descriptive framework for the six decision situations. This framework permitted the situations to be described analytically so the relevant decision aiding techniques could be matched with specific aspects of each decision situation.

Finally, the decision situations were prioritized according to their need or priority for decision aid design. A two factor scheme was developed for prioritizing the situations which considered the relative operator workload during each situation and the positional importance of each situation. (Positional importance refers to the interdependencies among the situations caused by the sequential nature of the ASW mission; if early situations are not successful, then later situations may never even occur.) The prioritization achieved by this procedure is as follows:

- Lost Contact Reacquisition
- Contact Classification/Verification
- On-Station Search
- Localization
- Surveillance Tracking
- Attack Planning

In constructing this priority scale, two critical problems emerged. First, it became clear that many more factors potentially contributed to priority then the two used. There appeared to be no simple way, however, to determine which factors were actually relevant to priority and how they contributed to it. Second, the prioritization was analytical (rather than experimental) and therefore did not incorporate the knowledge, judgements, and intuition about ASW decision making possessed by experienced operational ASW personnel. The importance of this second problem became clear when an attempt was made to validate the prioritization by comparing it with rankings produced by a small number of operational ASW personnel at the Naval Air Development Center (NADC). Although only a small sample of ranking data was collected (i.e. N=4), there were large differences between the individual rankings which all differed substantially from the analytically produced rankings.

Given the likelihood that significant factors had been excluded from the original prioritization and given the inability to validate it with operational personnel, it was imperative to validate the prioritization with a more sophisticated methodology that would overcome the two problems of the original analysis. The majority of the effort reported here was devoted to this task.

1.2 METHODOLOGY FOR DECISION SITUATION PRIORITIZATION

In validating the previously constructed prioritization, a methodology was sought which could simultaneously treat the multidimensional nature of decision priority, as well as incorporate the knowledge, judgements and intuitions of experienced ASW personnel. In particular, the methodology was required to provide means for

- identifying the factors relevant to ASW decision priority,
- determining the manner in which these factors combined to yield priority, and
- constructing priority scores for the decision situations.

The requirement that experienced ASW personnel be incorporated into the analysis necessitated a psychometric approach to the problem. After many standard techniques were reviewed and judged to be unsatisfactory, a new prioritization methodology was developed based on Multidimensional Scaling.

In this methodology, the underlying dimensions which experienced ASW personnel find relevant to ASW decision-making are identified through a Multi-Dimensional Scaling (MDS) analysis of basic judgemental data supplied by these personnel. Next, Unfolding Analysis is used to determine the way in which these dimensions combine to produce a scale of priority in the minds of these individuals. Finally, a technique known as Priority Mapping is used to construct numerical priority functions for the decision situations in terms of the dimensions in the MDS solution. This overall methodology is pictured in Figure 1-1. The various steps in this methodology, as well as a brief review of the result of its application are discussed below.

1.2.1 Collecting the Data for the Prioritization

The Multidimensional Scaling and Unfolding Analysis techniques both require as inputs psychometric data collected from individuals highly familiar with the items being scaled. In the case of ASW decision making, this meant that the data for the effort had to be collected from experienced ASW decision makers. For this study, an "experienced" individual was operationally defined as one who has served at least one year or one full deployment as a TACCO. The largest available pool of individuals with this level of TACCO experience was at NAS Moffett Field, so the data needed for the prioritization procedure were collected there.

Two basic types of data were collected from each experienced TACCO through the vehicle of psychometric tasks. The first task performed by each individual was an *unconstrained sorting* of a sample of fourteen decision functions: a grouping of TACCO decision functions such that all "similar" decisions are grouped together. No restrictions were placed on the number or size of groups that could be formed. The decision functions (individual decisions made by a TACCO in the course of a mission) were used instead of the six decision situations for two reasons:

1) The original prioritization was based on decision function priority scores aggregated across decision situations. This required the decision function to be the basic unit of the present prioritization in order to ensure comparability between the two analyses.

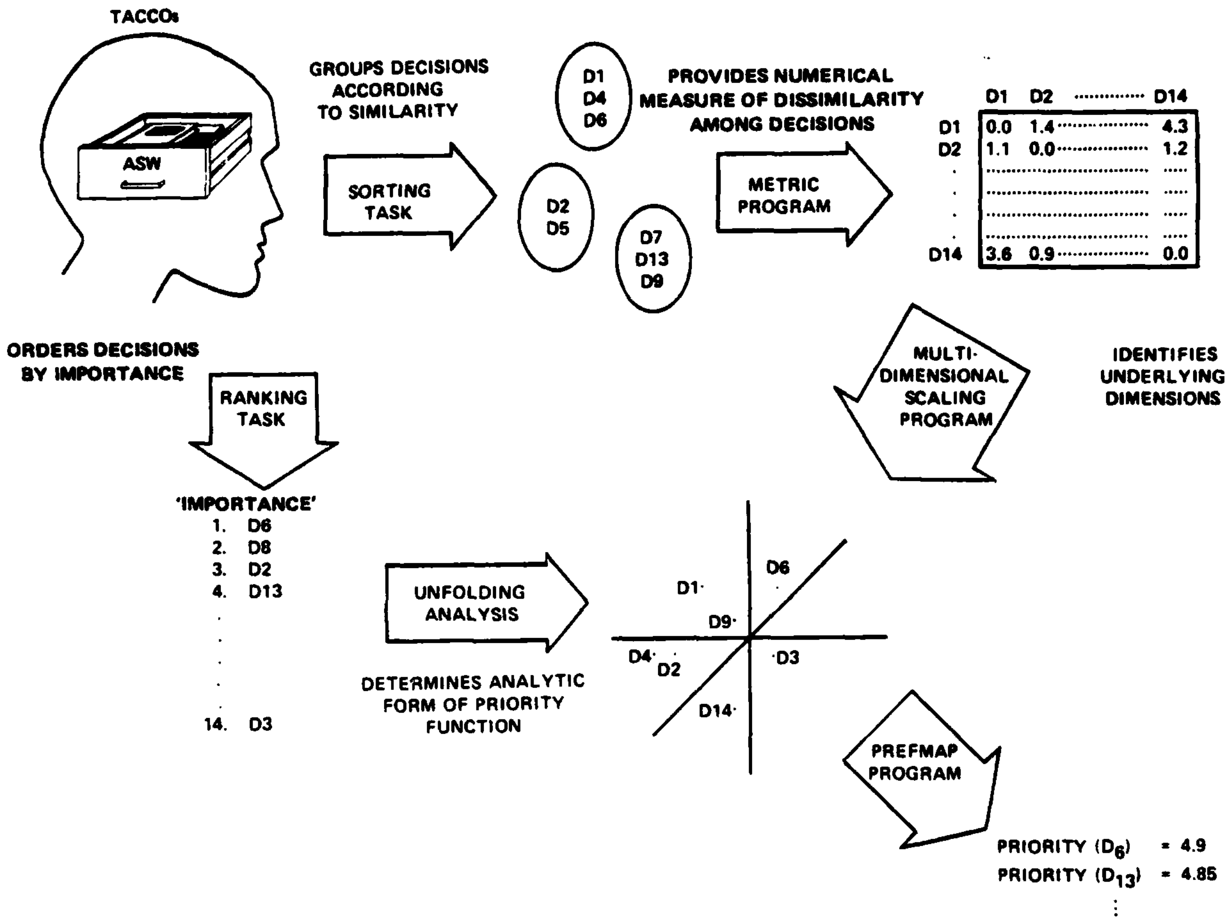


Figure 1-1. Multidimensional Scaling Prioritization Procedure

2) The decision situations were analytical constructs which were not likely to be immediately familiar to the TACCOs without considerable explanation. The decision functions on the other hand, were directly recognizable by the TACCOs because they refer to specific tasks actually performed by them.

The fourteen decision functions selected were chosen because they occurred in several of the decision situations and because they represent a sample of all types of tactical decisions which arise in the course of a mission.

The unconstrained sorting task provides basic information as to the perceived similarities among the decision functions. This information could be preprocessed and used as input to an MDS program. The unconstrained sorting task was selected over other tasks (such as paired-comparisons or triads) because it is relatively easy to apply and it permits a powerful mathematical analysis (see Section 2.2.2.1).

The second task performed by each TACCO was a series of rankings of the decision functions by several different criteria. The criteria were:

- importance of the decision function in a mission whose objective is to attack the hostile submarine,
- importance of the decision function in a mission whose objective is only to achieve surveillance on the hostile submarine,
- urgency of the decision function, and
- TACCO workload during the decision function.

The ranking task provides basic information on the perceived relationships among the decision functions with regard to each of these criteria. The ranking results are used as input to the Unfolding Analysis.

The two psychometric tasks were presented to the experienced TACCOs in the context of an interview. This interview began with a briefing on the Navy's effort to develop decision aids for Naval Air ASW and was followed by the introduction of the ranking and unconstrained sorting tasks. The interview ended with an open discussion of decision aids and human engineering issues in ASW. Further details on the data collection procedures for this effort are presented in Section 2.

1.2.2 Preprocessing the Unconstrained Sorting Data

The unconstrained sorting task is designed to capture, in a non-quantitative manner, the TACCO's perception of the interrelationships among the decision functions being considered. The information contained in the sorting results needs to be represented quantitatively before it can be used as an input to a Multidimensional Scaling program. This can be accomplished with a computer program named METRIC which is based on algorithm developed by Burton (1975). From the results of an unconstrained sorting, METRIC computes an indicator or measure of the dissimilarity of each pair of decision functions used in the unconstrained sorting. The measure is expressed as a square matrix in which each decision function is represented by one row and column. The dissimilarty matrix can be directly input to an MDS program. Since fourteen decision functions were used in the unconstrained sorting task, the dissimilarity matrix which results from the application of METRIC to the data colllected at Moffett Field contains fourteen columns and fourteen rows. This preprocessing step is described in more detail in Section 2.3.

1.2.3 Multidimensional Scaling of the Decision Functions

The groupings of the decision functions formed by the TACCOs in the unconstrained sorting task reflect the underlying distinctions or features which these experienced TACCOs use to organize their thinking about ASW decision making. Multidimensional Scaling is a technique which 'reconstructs' or identifies these underlying features by analyzing a dissimilarity matrix created from the results of an unconstrained sorting. MDS does this by defining the objects being scaled as points in a multidimensional topological space and "building" the space which best represents the objects in it. The quality of the representation is determined by a comparison of the *distances* of the objects in the space with the *dissimilarities* of the objects used as input to the procedure. In non-metric MDS, the most general type of MDS, the fit is considered perfect if the dissimilarities are a monotonic transformation of the distances. Thus, only the ordinal properties of the dissimilarity matrix are used in the MDS rather than the actual numerical values in the matrix. This is desirable because the numbers in the matrix have no psychological interpretation, and should not be assumed to represent a precise ratio measurement scale (see Section 3.1).

In an MDS solution, the items being scaled (here, the ASW decision functions) are represented as points in some multidimensional space. Each dimension or axis in this space represents a distinctive feature used to organize the scaled items (called stimuli) in the minds of the individuals doing the unconstrained sorting. The meaning of each dimension is then interpreted by examining the projections of each of the stimuli onto it. The features represented by the MDS dimensions are the only ones which are actually used by experienced personnel to "think about" the items involved. Therefore, they should be the only factors required in the computation of a scale of priority.

The dissimilarity matrix constructed from the unconstrained sortings gathered at Moffett Field was input into a Multidimensional Scaling program named MINISSA. The program identified the ASW decision space as three dimensional. Plots of the various decision functions on these three dimensions are given below in Figure 3-2. These dimensions were tentatively interpreted as follows:

- *Dimension 1* - the uncertainty in the information used to make a decision,
- *Dimension 2* - the information processing load the decision imposes on the TACCO, and
- *Dimension 3* - the complexity of the alternatives the TACCO considers in making the decision.

Further details on the MDS analysis are given below in Section 3.

1.2.4 Unfolding Analysis of the Ranking Criteria

The MDS analysis identifies the underlying dimensions of the perceptual space of ASW decision making from the results of the TACCO's unconstrained sortings. Other features of the ASW decision functions, such as their perceived importance values, must therefore be combinations for functions of these three main dimensions. Unfolding Analysis is a technique for determining the specific form of the function which best represents a derivative feature (e.g. importance) as a combination of the independent features of the perceptual space (i.e. the dimensions of the MDS solution). In Unfolding Analysis, the ability of four different models of dimensional combination to represent a given ranking of the stimuli are tested and compared. The model which is simplest and which has the best fit with the ranking is then selected as the form by which the ranking criterion is mapped into the multidimensional space. A general discussion of Unfolding Analysis is given in Appendix F.

Two of the rankings collected at Moffett Field were used along with the three dimensional MDS solution in the Unfolding Analysis. The ranking criteria considered were those relating to importance (in missions with an attack phase and in missions without an attack phase) because preceived importance was considered equivalent to priority. The average of the rankings produced for each of the two criteria by all the 32 TACCO's interviewed were used as the input to the Unfolding Analysis. The most powerful of the four models, called the generalized distance model, produced the best fit of the rankings in the multidimensional space for both criteria, accounting for the 99% of the variance in both cases. The Unfolding Analysis procedure is summarized in Section 4.1; details of calculations are given in Appendix G.

1.2.5 Priority Mapping of the Decision Functions and Decision Situations

The analytical form of the function which expresses the criteria of importance in missions with and without attack in terms of the three MDS dimensions is determined by the Unfolding Analysis. Next, a regression-like procedure, called Priority Mapping is used to specify the values of the coefficients in a specific priority function for each criterion. The result of Priority

Mapping is a complete formula which can generate numerical priority scores for the decision functions, given their locations on each of the dimensions in the MDS solution. The procedure is regression-*like* because it fits coefficient in an analytic function to ordinal data (the rankings on each criterion). Rather than using a standard least-squares estimation, it employs a two-step iterative procedure. It first computes a least-squares estimation using the ranks and then adjusts the results to fit the ordinal properties of the solution back to the original data. The two steps are iterated until either an acceptable fit is achieved or it becomes clear that no progress toward a solution is being made. A program named PREFMAP is used to carry out the Priority Mapping procedure (see Section 4.1).

Priority Mapping was used to generate representations of the two importance ranking criteria as functions of the three MDS dimensions according to the generalized distance model. The priority function for the criterion of importance in a mission with attack is given in Appendix G, and the numerical decision function priority scores generated by this formula are given in Table 4-1. The priority function for the criterion of importance in a mission without attack is given in Appendix G, and the decision function priority scores generated by this formula are given in Table 4-2.

The decision function prioritizations were converted into decision-situation prioritizations by summing the priority scores of the decision functions which comprised each decision situation. These "raw" decision situation priority scores were then normalized by dividing each of them by the number of decision functions summed to produce it. The normalized priority scores for the decision situations were used as the final priority values. The final ranking of the decision situations in each type of mission are shown in Table 1-2. A complete presentation of the Priority Mapping analysis is given in Section 4.2 and Appendix G.

Table 1-2. ASW Decision Situation Prioritizations in Two Types of ASW Missions

RANK IN MISSION WITH ATTACK OBJECTIVE	DECISION SITUATION	DECISION SITUATION	RANK IN MISSION SURVEILLANCE OBJECTIVE
1	CONTACT CLASSIFICATION/ VERIFICATION	CONTACT CLASSIFICATION/ VERIFICATION	1
2	ATTACK PLANNING	SURVEILLANCE TRACKING	2
3	LOCALIZATION	LOST CONTACT REACQUISITION	3
4	SURVEILLANCE TRACKING	LOCALIZATION	4
5	LOST CONTACT REACQUISITION	ON-STATION SEARCH	5
6	ON-STATION SEARCH	ATTACK PLANNING	6

1.3 DECISION AID DESIGN

The prioritization given in Table 1-2 indicates the order in which the six decision situations should be considered for decision aiding applications. As an initial step in this direction, high level decision aid designs were constructed for two of the decision situations. For the Contact Classification/ Verification decision situation (which ranked first in both types of mission) an Optimal Mode Selection decision aid is outlined. This aid helps the TACCO and/or the SENSO (Sensor Station Operator) select the optimal combination of processing modes for the acoustical signal processing equipment based on a set of targets-of-interest and the in-situ environmental conditions. For the Attack Planning decision situation (which ranked second for missions with an attack phase) an attack criteria/attack plan decision aid is outlined. This decision aid helps the TACCO in attaining attack criteria on the submarine as quickly as possible and, once they are obtained, assists him in selecting and implementing the optimal tactics for the actual attack. The full outline of these decision aids are presented in Section 5.

1.4 ORGANIZATION OF THE REPORT

The remainder of this report presents the results of the prioritization analysis and decision aid design in greater detail. Section 2 discusses the data collection procedures, and the preliminary analyses of the data gathered at Moffett Field. Section 3 discusses the application of Multidimensional Scaling to dimensionalize the ASW decision space using the data collected at Moffett Field. Section 4 discusses the application of the Unfolding Analysis and Priority Mapping procedures to the prioritization of the six Air ASW decision situations. Section 5 presents initial high-level decsion aid designs for two of the highest priority situations. Section 6 presents conclusions and recommendations based on the results of the effort. The materials used in the Moffett Field interviews and the raw data gathered from them are presented in the appendices to this report.

2. DATA COLLECTION FOR THE MULTIDIMENSIONAL SCALING AND UNFOLDING ANALYSIS PROCEDURES

This research is based on the assumption that a prioritization of Air ASW decisions must incorporate the knowledge, opinions, and intuitions of experienced air ASW decision-makers. Multidimensional scaling and unfolding analysis provide a mechanism for numerically prioritizing the six decision situations on the basis of structured but fundamentally judgemental inputs from experienced ASW personnel. This section describes the procedures used to obtain and preprocess the judgemental data needed to perform the MDS and unfolding analysis. The characteristics of the personnel from whom data were collected, and the choice of a location for the data collection procedure are discussed in Section 2.1. *In Section* 2.2, *the structure* of the interview used to obtain the data is described. The data which were collected, and the techniques used to preprocess them for the MDS and unfolding analysis are reviewed in Section 2.3.

2.1 AIR ASW PERSONNEL REQUIREMENTS

In the earlier effort (Zachary, 1980), three air ASW platforms were identified as the focus of the investigation -- P-3C, S-3A, and LAMPS MK III. Only the first two of these are currently operational, so the personnel to be interviewed were restricted to those currently working on the P-3C and the S-3A. The previous effort also identified the Tactical Coordinator or TACCO as the principal decision-maker of interest, further restricting the population to individuals serving as TACCOs on these two platforms. The motivation for the approach taken in the effort, as well as the underlying assumptions of the psychometric procedures used, required that the TACCOs interviewed be highly experienced at their job. An experienced TACCO was operationally defined as someone who had served as a designated or a crew-flying (airborne) TACCO aboard the P-3C or S-3A for at least one year or one full deployment. Prospective interviewees, then, were defined as individuals having that type of TACCO experience.

Five possible sources of interviewees within the continental US were identified. Three of these provided P-3C populations (the airwings at Brunswick, Maine, Jacksonville, Florida, and Moffett Field, California), and two provided S-3A populations (the airwings at Cecil Field, Florida and San Diego, California). The scope of the present effort allowed interviews to be conducted at only one of these sites. It was initially decided to restrict the candidate sites to the P-3C locations, to accommodate the need for a preliminary or pilot data collection procedure (see Section 2.3). This pilot procedure was conducted to allow deficiencies in the interview method to be identified and corrected prior to the principal data collection effort. The preliminary procedure was to be conducted at NADC where the preponderance of available interviewees had a P-3C, rather than an S-3A, background.

Of the three possible sources of P-3C interviewees, Brunswick was immediately eliminated because their transition to the P-3C (from A and B) was sufficiently recent that the criteria of experience could not be met. Of the remaining two, Moffett Field was chosen because it had available the largest pool of potential interviewees during the timeframe in which the interviews were to be conducted.

2.2 STRUCTURE OF THE MULTIDIMENSIONAL SCALING INTERVIEW

The data for the MDS and unfolding analysis were collected through several psychometric tasks presented as part of a structured interview. The format of the interview allowed several TACCOs to be interviewed in the same room simultaneouly. The overall interview had three parts. Initially, a briefing was provided on the history of the ASW decision aids effort and its goals. Next, a series of structured psychometric tasks were presented to, and performed by, each interviewee. Finally, an open-ended discussion among the interviewers and interviewees concerning decision aids and general human factors engineering problems in the P-3C was held. Each of these portions of the interview is discussed in further detail below. The interviews are designed to be completed in a single morning or afternoon, scheduled as follows:

- One hour was allocated to initial briefing and questions-and-answers;
- One half hour was allocated to the first of the psychometric tasks (unconstrained sorting);
- Forty-five minutes was allocated to the second of the psychometric tasks (ranking); and
- Two hours were used for the final discussion session.

2.2.1 Initial Briefing

At the start of each interview session, a short introductory briefing was given. The first part of this briefing covered the work and data on this project, emphasizing the notion of a decision aid, the interest the Navy has in decision aids, and prior analysis of a generic Air ASW mission into mission segments, decision functions, and decision situations. The second part of this briefing covered the need to order (prioritize) these decision situations as a way of identifying the one(s) to which decision-aiding should be applied. The need and desire to base this prioritization analysis on the experience and knowledge of operational personnel was emphasized.

During the third portion of the briefing the subjects were introduced to the tasks they would be asked to perform. They were assured their responses would remain anonymous and not be taken as a statement of official Naval or air-wing policy. The full text of the briefing is given in Appendix A. Questions, comments, and other spontaneous discussion were then solicited and responses provided prior to the beginning of the first of the psychometric tasks.

2.2.2 Psychometric Tasks

The TACCOs were asked to perform two psychometric tasks, the purpose of which was to provide information that could be used to derive numerical indicators of various subjective aspects of their ASW knowledge. The first task, an unconstrained sorting task, provided the inputs needed for the multidimensional scaling. The second task, a simple rank-ordering, provided the inputs to the unfolding analysis and was performed in four different ways as described in the following subsections.

2.2.2.1 The Unconstrained Sorting Task

The techniques of unconstrained sorting, also known as the "Q-sort," was first developed by George Miller (1969). In this task, the subject is asked to place the items being scaled (called collectively the stimuli) into an arbitrary number of groups of unspecified size. The stimuli may be organized into as many groups as is necessary to place all similar items together, without any restrictions on how many items may be placed into each group. The basis on which the items are grouped is established by the instructions for the task.

The unconstrained sort is only one of many psychometric methods used to collect data for multidimensional scaling. Other commonly used methods are the triads test, paired comparisons, and conjoint measurement. Unconstrained sorting was chosen over these other techniques for two reasons. First, it is the only technique which allows the levels of distinction drawn among the stimuli by different subjects to be explicitly controlled in the processing of the task results. Individuals performing any of the above tasks will place varying emphasis on the underlying distinctions which interrelate stimuli. The algorithms used to process the results of all of the above tasks control for this type of between-subject variance. However, individuals will also vary in the level of detail they consider when performing the task. For example, some will utilize only broad distinctions and find all the stimuli either very different of very similar, while others will utilize very few distinctions and find each pair of stimuli similar in a different degree. It is useful to be able to focus on a specific level of distinction in processing the results of the task. If only the most general dimensions are sought from the MDS, then broad distinctions should be emphasized. If all possible dimensions are sought from the MDS, than fine-grained distinctions should be emphasized. This can be done only with unconstrained sorting data.

Second, the unconstrained sort is the simplest and fastest means of obtaining data for MDS. The TACCOs being interviewed could provide the needed data for MDS in half an hour if the Q-sort were used, but if any other techniques were employed, several hours could be required, just to obtain the MDS data. Moreover, because paired comparisons, tracks, etc., require direct interaction between the interviews and the interviewees, only one TACCO could be interviewed at a time. The limited amount of time available to interview each TACCO, and the need to interview several TACCOs simultaneously, favored the use of the unconstrained sort.

Extensive investigation of Burton (1969) and M. Miller (1975) has shown that unconstrained sorting produces equivalent results to other techniques, although two general rules-of-thumb should be obeyed in its application. The first is that the number of stimuli must be greater than ten, and the second is that there must be more than twice as many subjects performing the sort as there are stimuli being sorted. The first condition was met, as a total of 14 decision functions were used in the analysis (see Section 2.2.2.2). The second condition was also met in that a total of 32 TACCO's were utimately interviewed.

2.2.2.2 Stimulus Set

In Zachary (1980), the six Air ASW decision situations were organized into individual decision functions which arise in the generic Air ASW mission. These decision functions were then related to individual tasks which they required on the part of the operator. The original prioritization of the six decision situations (ibid: Section 6) was based on these individual decision functions. In order to establish comparability between the previous prioritazation and that derived in this effort, it was necessary to use these same decision functions as the stimulus set for the unconstrained sorting task. An even more important reason for using the decision functions as the stimuli instead of the decision situations was that the decision situations are analytic constructs. They represent complex sets of interrelated decision-making, information processing, and communication functions on the part of the TACCO. The decision situations were likely to have little intuitive meaning for the TACCOs, without considerable definition and explanation. The basic decision functions, on the other hand, were directly relevant to the experience of the TACCOs because they represent specific problems which the TACCOs can associate to their on-platform operations. As a result, the TACCOs can apply their detailed knowledge and intuition about the decision functions, which they would be unable to do in the decision situations.

Fourteen decision functions were selected. Each is described below, along with a two-letter code used to identify it on the response forms for the sorting task and the subsequent ranking task. The decision functions used in the sorting are:

- ADJUST PATTERN TO SENSOR FAILURE (AP) - replacement of faulty sensors or adjustment of aircraft track due to equipment/sensor failure.
- EXTEND EXISTING SENSOR PATTERN (EP) - determine orientation and settings of sensors to be added to existing pattern with no contact.
- ANTICIPATE TARGET MOVEMENT (AM) - predict future location, course, speed, and depth of target based on intelligence and actual tactical situation.
- CONSTRUCT SENSOR MONITORING PATTERN (MP) - determine where to position the aircraft to obtain maximum reception from sensors, and sequence in which to monitor deployed (acoustic) sensors if number of sensors exceeds number of aircraft receivers.
- COORDINATE HAND-OFF (CH) - transmit data to relief platform for continuation of prosecution.
- DETERMINE SIGNAL IS A VALID CONTACT (VC) - reduce false alarm rates of sensor system (e.g., clouds on radar, random noise on MAD or acoustic).

- DETERMINE WEAPON AND SETTING FOR ATTACK (DS) - select weapon to be used for the attack, and its optimum weapon settings (e.g., search depth, minimum/maximum search limit).

- GAIN ATTACK CRITERIA (AC) - interpret sensor data to determine when target is localized sufficently to place an attack.

- DETERMINE TARGET FIX (TF) - use incoming sensor data to establish the location of the target.

- CREATE SENSOR PATTERN (CP) - determine pattern, spacing, orientation and/or utilization for all sensor types for each phase of the mission.

- MANAGE EQUIPMENT/STORES TO ACCOMODATE PRESENT AND FUTURE NEEDS (ME) - monitor inventory of sensors and equipment status for application for future tactics and resources.

- CLASSIFY SIGNAL (CS) - determine if signal (primarily acoustic) may be originating from the target of interest.

- COMPENSATE FOR ACOUSTIC/ATMOSPHERIC PROPAGATION CONDITIONS (PC) - determine the adjustments in sensor spacing, aircraft track, aircraft altitude, etc., that must be made when actual atmospheric and bathythermal conditions are different from their forecast.

- DETERMINE AIRCRAFT WEAPON LAUNCH POSITION (LP) - determine factors to place the aircraft in an optimum attack position.

The 14 decision functions are summarized in Table 2-1.

2.2.2.3 Task Instructions and Materials

Each individual performing the sorting task was presented with the stimuli in the form of a deck of three by four inch cards. In the center of each card (in bold type) was the name of the decision. Immediately under the name was a short explanation of the decision problem, printed in a lighter type face. The two-letter code used to identify each decision on the response-recording sheet was located in the upper right corner of the card. The two letter codes are mnemonics, derived from the first letters of keywords in the decision name. The mnemonic codes are given in Table 2-1 next to the name of each decision. Mnemonic codes were selected over numeric or alphabetic codes to identify the

Table 2-1. Fourteen ASW Decision Functions and Alphabetic Codes

CODE	DECISION FUNCTION
AP	ADJUST PATTERN TO SENSOR FAILURE
EP	EXTEND SENSOR PATTERN
AM	ANTICIPATE TARGET MOVEMENT
MP	CONSTRUCT SENSOR MONITORING PATTERN
CH	COORDINATE HAND-OFF
VC	DETERMINE SIGNAL IS A VALID CONTACT
DS	DETERMINE WEAPON AND SETTING FOR ATTACK
AC	GAIN ATTACK CRITERIA
TF	DETERMINE TARGET FIX
CP	CREATE SENSOR PATTERN
ME	MANAGE EQUIPMENT/STORES TO ACCOMODATE PRESENT AND FUTURE NEEDS
CS	CLASSIFY SIGNAL
PC	COMPENSATE FOR IN SITU ACOUSTICAL AND ATMOSPHERIC PROPAGATION CONDITIONS
LP	DETERMINE AIRCRAFT LAUNCH POSITION FOR ATTACK ON TARGET

decisions because number or letter codes could affect the way of sorting was conducted by suggesting an implicit order which was not intended.

The sorting task was performed as follows. After the initial briefing, each TACCO was given a pack of cards and a set of response forms (reproduced in Appendix B). The first response sheet requested background data on the experience of the respondent; the interviewees were asked to fill in these data before proceeding. They were then required to read the instructions on their response forms (see Appendix B) and perform the sorting task. There were no time limitations; no subject required more than 30 minutes.

2.2.2.4 The Ranking Task

The second of the two psychometric tasks performed by the TACCOs was to rank order the stimuli used in the unconstrained sorting. The subjects were presented with a criterion and asked to rank order the items according to that criterion. This task was repeated four times, using four different criteria:

- Importance of the decision in a mission with an attack on the submarine,
- Importance of the decision in a mission with only surveillance of the submarine,
- Urgency of the decision, and
- TACCO workload during the decision.

The first two rankings provided the primary inputs for the unfolding analysis. These two rankings used the same criterion -- the perceived importance of the decision functions to the mission. The difference between the two rankings was the type of mission used as a reference. In the first ranking the objective of the mission was to locate, attack, and destroy the hostile submarine. In the second ranking the objective of the mission was to locate, track, and handoff the hostile submarine to a relief platform. In both of these rankings, the criterion of importance was defined as the degree to which a less-than-optimal decision would negatively impact on the achievement of the mission objective.

The third ranking was performed using a criterion of urgency. Urgency was defined as the relative speed with which the decision had to be made, once it became apparent that the decision was required. The fourth ranking used a criterion of workload. The term workload was only minimally defined. The subjects were instructed to consider mental (cognitive) workload as well as manual (physical) workload. These last two rankings were included to allow future MDS analysis of perceived decision aiding needs against perceived time and operator workload constraints during the air ASW mission, and to provide supplemental information which could aid in the interpretation of the MDS solution derived here.

In performing the ranking task, the subjects used the same cards containing the decision function descriptions that they used in performing the unconstrained sorting task. Their instructions simply identified the criteria on which they were to rank the stimuli. The instructions and response forms are contained in Appendix B.

2.2.3 Final Discussions

Following the final ranking tasks, the response forms were collected and comments were solicited from the TACCOs with regard to:

- decision aids in general, and the Naval Air ASW decision aid effort in particular,
- the tasks which they had just performed and the decision functions used in the tasks, and
- general comments/suggestions concerning decision making and human factors engineering problems on-board the P-3C aircraft which they have flown.

Most of the discussions focused on the last topic lasted above. The points made in these the discussions are summarized in Appendix E.

2.3 INTERVIEW RESULTS AND PRELIMINARY ANALYSIS

Prior to the interviews at Moffett Field, a series of preliminary interviews were conducted at the Naval Air Development Center (NADC). The interviewees were NADC personnel with subtantial experience as TACCO's on the P-3C. One individual with S-3A experience was also interviewed. These interviews were conducted to identify and correct in advance any problems in the multidimensional scaling interview structure. The inteviewees were asked to identify any errors or inadequacies in either the interview structure or the interview material. As problems were identified, they were corrected before the next set of preliminary interviews. This procedure produced the following change in the interview structure and materials:

- Several decision functions were added and/or deleted from the stimulus set, e.g. Damage Assesment was deleted and Coordinate Handoff was added,
- More details were added to the initial briefing, e.g. more examples of decision aids were included,
- A single ranking by importance was replaced by dual rankings considering ASW missions with and without attack on the submarine,
- Importance and urgency were included as separate ranking criteria, and
- The final definition of importance was constructed.

All of these changes are reflected in the description of the interview procedure given in Section 2.2 above.

2.3.1 Preprocessing of Sorting Data for MDS Program

Interviews were conducted with a total of 32 TACCOs at NAS, Moffett Field over a five day period (10 December 1979 to 14 December 1979). A separate interiew session was conducted each morning and afternoon. Sorting data were obtained from 31 of the 32 interviewees; one person misinterpreted the instructions and produced unusable data. These 31 sortings are listed in Appendix C.

The sortings were prepared for input to the MDS computer program by an algorithm developed by Burton (1975), which processes unconstrained sorting data to produce a dissimilarity measure among the decisions in the stimulus set. In general, a dissimilarity measure is a binary mapping from the set of objects scaled to some numerical scale. For any two objects i and j, the dissimilarity between i and j is written as d_{ij}. Dissimilarity measures are analogous to topological metrics, and have three main properties:

(1) $d_{ij} = 0$ iff: $i=j$, $d_{ij} \geqslant 0$ otherwise (positivity)

(2) $d_{ij} = d_{ji}$ for all i,j (symmetry)

(3) $d_{ik} \leq d_{ij} + d_{jk}$, for all i,j,k (triangle inequality)

Dissimilarity measures are normally represented as a square matrix of values (with each row/column representing one of the stimuli from the sorting) so the terms dissimilarity "measure" and dissimilarity "matrix" are used here interchangeably.

Burton's algorithm computes the dissimilarity between two stimuli according to the number of individuals who placed them in different groups, and the values that are assigned to two parameters, α and ε. The first parameter, α, represents the level of discrimination selected for the analysis (see Section 2.2.2.1 above). The second parameter, ε, represents the minimal dissimilarity between two stimuli (i.e., that dissimilarity which results when two simuli are placed in the *same* group by one individual). The algorithm is based on the mathematical principle that each individual induces a partition on the set of stimuli by placing them into mutually exclusive groups. R_i is defined as the number of groups formed by individual i, (i.e. the number of cells in the partition induced by subject i), and M_{ik} is defined as the number of stimuli placed in group k by subject i. If the number of subjects is T, then dissimilarity between stimuli x and y is:

$$d_{xy} = \sum_{i=1}^{T} (C - S_i(x,y)),$$

where $S_i(x,y) = A_{ik}$ if subject i placed stimuli x and y in cell k of the partition,

$= B_i$ if subject i placed stimuli x and y in different cells of the partition

$= C$ if $x = y$.

There are two constraints on d:

1) $B_i < \min(A_{ik})$, over all k

2) $C > \max(A_{ik})$, over all i,k

A useful measure is obtained by defining

$A_{ik} = (M_{ik})^{\alpha}$

$B_i = 0$

$C = 1 + \varepsilon$, if $\alpha < = 0$

$= N + \varepsilon$, if $\alpha > 0$

$= 2 + \varepsilon$, if $\alpha < 0$

Since ε is a minimum value used to differentiate items placed together by a given individual, it should be very small. α represents the level of distinction used by the individuals doing the sortings. If α is greater than zero, a greater weight is given to sortings using a few, large cells, and the resulting distance measure tends to be the lower dimensionality when subjected to multidimensional scaling. If α is less than 0, then a greater weight is given to partitions which include a greater number of small cells, and the measure results in higher-dimensional multidimensional scaling solutions. When α is 0, there is equal weight given to large and small cell sizes, as 1 is always added to d_{xy} whenever x and y are placed in different cells, and ε is always added to d_{xy} when they are placed in the same cell.

A computer program named METRIC which performs this algorithm was used to produce a dissimilarity measure from the results of unconstrained sortings. Because the intent is to identify only the most salient, important dimensions in ASW decision-making, an α value of -.5 was used. The resulting dissimilarity matrix is shown in Table 2-2. The decision functions are identified in Table 2-2 by the two-letter codes depicted earilier in Table 2-1. Only the lower triangle of the matrix is shown because the matrix is symmetrical and the diagonal contains only zeroes.

2.3.2 Preliminary Analysis of Ranking Results

Rankings of the 14 decision functions by the four criteria were obtained from all 32 TACCOs interviewed at Moffett Field. These rankings are given in Appendix D. The sorting task data required preprocessing via Burton's algorithm before they could be used in the MDS analysis, but the ranking task data could be input directly, to the unfolding analysis procedure. It was possible however, to perform several useful preliminary analyses of the rankings prior to their use in the unfolding analysis.

The first preliminary analysis allowed the statistical significance of the ranking data to be assessed. Kendall's W, the coefficient of concordance, is a statistic which measures the degree of agreement among K rankings of the same set of N objects. A test of significance of the concordance among the rankers (here, the TACCOs) can be based on the value of W (Kendall, 1962). This test uses the null hypothesis that there is no agreement among the different rankings, and is based on the fact that K(N-1)W is asymptotically distributed according to the Chi-Square distribution with N-1 degrees of freedom (Gibbons, 1971).

The coefficient of concordance was computed and its significance tested for each of the four rankings obtained from the TACCOs at Moffett Field. The results are shown in Table 2-3. All four rankings were found to be significant

Table 2-2. Dissimilarity Matrix for ASW Decision Functions

DECISION FUNCTION	AP	EP	AM	MP	CH	VC	DS	AC	TF	CP	ME	CS	PC
EP	64.065												
AM	115.809	110.017											
MP	64.843	70.994	112.896										
CH	115.541	117.541	115.092	117.541									
VC	117.541	117.541	115.541	117.541	115.809								
DS	112.896	114.896	89.235	117.541	113.092	117.541							
AC	114.896	112.250	73.929	114.896	115.092	117.541	76.197						
TF	114.896	110.518	67.956	114.896	115.092	112.077	90.322	71.869					
CP	69.671	64.701	112.896	65.076	117.541	117.541	115.809	114.896	114.896				
ME	86.114	93.764	115.541	84.114	112.713	117.541	115.541	117.541	117.541	87.528			
CS	117.541	117.541	115.541	117.541	115.809	73.258	117.541	117.541	112.077	117.541	117.541		
PC	66.767	64.884	114.896	66.490	117.541	114.395	113.164	112.250	112.250	63.293	85.796	115.809	
LP	114.896	114.896	87.235	116.127	115.092	117.541	69.394	74.197	88.322	117.541	117.541	117.541	114.896

DECISION FUNCTION

at the .01 level, allowing the null hypothesis to be rejected with greater than 99% confidence. These tests indicated that

- The TACCOs were not performing the ranking tasks in a random or careless fashion, and
- The TACCOs were ranking the tasks in a consistent way for each criterion.

The rankings were thus shown to contain significant data for the unfolding analysis.

Table 2-3. Significance of Inter-Subject Agreement in Four Ranks of ASW Decisions

RANKING CRITERION	KENDALL'S W (COEFFICIENT OF CONCORDANCE)	X^2 (CHI-SQUARE) BASED ON W	REJECTION LEVEL FOR NULL HYPOTHESIS OF NO AGREEMENT AMONG RANKINGS
IMPORTANCE IN MISSION WITH ATTACK	0.39496	164.305	<.001
IMPORTANCE IN MISSION WITHOUT ATTACK	0.49067	204.118	<.001
URGENCY	0.50768	211.196	<.001
WORKLOAD	0.28419	118.221	<.001

The second preliminary analysis conducted on the ranking results provided an overall pattern of responses for each criterion. Average rankings were constructed for each criterion by simply averaging the ranks assigned to each decision function by each of the 32 TACCOs. These average rankings are shown in Tables 2-4 through 2-7. As these tables show, each criterion produced a substantially different ranking, confirming the assumption that multiple criteria were needed to map the implicit prioritization of the decision functions by the TACCOs.

Table 2-4. Average Ranking of Decisions in Mission With Attack

DECISION NAME	AVERAGE RANK	
CLASSIFY SIGNAL	3.63	(INCREASING)
GAIN ATTACK CRITERIA	4.19	↑
DETERMINE TARGET FIX	4.94	
DETERMINE AIRCRAFT WEAPON LAUNCH POSITION	5.78	
DETERMINE SIGNAL IS VALID CONTACT	6.25	
CREATE SENSOR PATTERN	6.31	
ANTICIPATE TARGET MOVEMENT	6.44	IMPORTANCE
DETERMINE WEAPON AND SETTING FOR ATTACK	6.84	
COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS	8.34	
MANAGE EQUIPMENT/STORES	9.44	
CONSTRUCT SENSOR MONITORING PATTERN	9.75	
EXTEND SENSOR PATTERN	9.97	
ADJUST PATTERN TO SENSOR FAILURE	10.50	↓
COORDINATE HAND-OFF	12.63	(DECREASING)

Table 2-5. Average Ranking of Decisions in Mission Without Attack

DECISION NAME	AVERAGE RANK	
CLASSIFY SIGNAL	3.25	(INCREASING)
CREATE SENSOR PATTERN	4.76	
ANTICIPATE TARGET MOVEMENTS	4.97	
DETERMINE TARGET FIX	5.22	
COORDINATE HAND-OFF	5.34	
DETERMINE SIGNAL IS A VALID CONTACT	5.41	
COMPENSATE FOR IN-SITU PROPAGATION CONDITION	7.09	IMPORTANCE
MANAGE EQUIPMENT/STORES	7.44	
EXTEND SENSOR PATTERN	8.13	
CONSTRUCT SENSOR MONITORING PATTERN	8.16	
ADJUST PATTERN TO SENSOR FAILURE	8.62	
GAIN ATTACK CRITERIA	10.81	
DETERMINE AIRCRAFT WEAPON LAUNCH POSITION	12.88	
DETERMINE WEAPON AND SETTING FOR ATTACK	12.94	(DECREASING)

Table 2-6. Average Ranking of Decisions By Urgency

DECISION NAME	AVERAGE RANK	
DETERMINE AIRCRAFT WEAPON LAUNCH POSITION	2.59	(INCREASING)
GAIN ATTACK CRITERIA	3.19	
DETERMINE WEAPON AND SETTING FOR ATTACK	4.56	
ANTICIPATE TARGET MOVEMENT	5.25	
DETERMINE TARGET FIX	5.66	
DETERMINE SIGNAL IS VALID CONTACT	6.63	URGENCY
CLASSIFY SIGNAL	7.09	
MANAGE EQUIPMENT/STORES	7.94	
ADJUST PATTERN TO SENSOR FAILURE	8.56	
COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS	9.97	
CREATE SENSOR PATTERN	10.22	
EXTEND SENSOR PATTERNS	10.38	
COORDINATE HAND-OFF	11.09	
CONSTRUCT SENSOR MONITORING PATTERN	11.88	(DECREASING)

Table 2-7. Average Ranking of Decisions By Workload

DECISION NAME	AVERAGE RANK	
GAIN ATTACK CRITERIA	3.94	(HIGHER)
DETERMINE AIRCRAFT WEAPON LAUNCH POSITION	4.66	↑
DETERMINE TARGET FIX	5.13	
ANTICIPATE TARGET MOVEMENT	5.94	
COORDINATE HAND-OFF	6.00	
DETERMINE WEAPON AND SETTING FOR ATTACK	6.44	WORKLOAD
MANAGE EQUIPMENT/STORES	6.56	
CREATE SENSOR PATTERNS	7.94	
ADJUST PATTERN TO SENSOR FAILURE	9.31	
COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS	9.34	
EXTEND SENSOR PATTERNS	9.38	
DETERMINE SIGNAL IS VALID CONTACT	9.66	
CLASSIFY SIGNAL	10.09	↓
CONSTRUCT SENSOR MONITORING PATTERN	10.63	(LOWER)

3. DIMENSIONALIZING THE ASW DECISION SPACE

The unconstrained sorting task provides data on the differences perceived by TACCOs among a sample of fourteen ASW decision functions. The judgments on the similarities and differences of the decisions reflect the underlying distinctive features or dimensions by which the TACCO organize their perceptions of ASW decision making situations. The interrelationships of the 14 decisions in the stimulus set on these underlying dimensions are reconstructed from the unconstrained sorting data through Multidimensional Scaling techniques. These mathematically reconstructed relationships identify the basic principles which the experienced TACCOs used when they performed the sortings, and thus dimensionalize the TACCOs' perceptual decision space.

This section details the MDS procedures used to dimensionalize the ASW decision space and presents the results of that dimensionalization. Section 3.1 briefly reviews the principals of metric and non-metric MDS. Section 3.2 presents the results of the MDS analysis of the Moffett Field data and Section 3.3 provides some interpretations of the three dimensions that were obtained.

3.1 NON-METRIC MULTIDIMENSIONAL SCALING TECHNIQUES

Multidimensional Scaling techniques are mathematical procedures that reconstruct a topological space (i.e. a set of real-valued orthogonal dimensions and a distance metric) which best models a set of observed inter-object distance measurements for some group of objects. If, for example, three objects are observed to be one unit apart from one another, then their interrelationships can be optimally represented as the vertices of an equilateral triangle. Since a triangle is two-dimensional, the underlying topological space is two-dimensional. A one-dimensional space could not be used because it is impossible to place three points on a line such that they are one measurement unit apart. A three or higher dimensional solution is possible but not optimal because the distances in the example can be modeled completely in two dimensions so additional dimensions would be extraneous. It is therefore possible to represent the three objects as points in a two-dimensional space such that two conditions are met:

1. the distances between the pairs of the objects are all equal to the values originally observed, and
2. the space is unique up to a translation or rotation of axes.

These conditions are the goals of an MDS analysis. They are thus also the criteria by which an MDS result is evaluated. In this simple example, the actual numerical values assigned to the original (observed) distances are crucial to determining and verifying the solution, so this approach is known as *metric* MDS.

Metric MDS is similar to factor analysis and has been in use for over 50 years. Its use requires that the numerical values which represent the observed distances have the properties of a true ratio scale. This condition is seldom met in psychological and decision science research; often the best available data have only the properties of ordinal scales. Therefore, in the mid 1960's several researchers independently developed a non-metric version of Multidimensional Scaling. Non-metric MDS, unlike metric MDS, uses only the ordinal properties of the observed distances between the objects being scaled. This allows a more general interpretation of the distance values. In non-metric MDS, any measure of *dissimilarity* can be used as an estimate of the true interobject distances as long as it is monotonically related to a true distance measure.

Non-metric MDS permits reconstruction of a real-valued multidimensional structure from *ordinal* data through the use of *ordinal* constraints. In general, when only ordinal properties of data are used in a geometrical procedure, it is possible to define a solution only in terms of possible *regions* of the solution space. But as additional constraints are placed on the problem (even ordinal constraints) it becomes possible to further restrict the region of the solution space where the true solution exists. If a great many constraints are involved, it may be possible in practice to restrict the solution region so much that it can be treated as a specific point in the solution space, i.e. as an absolute solution. This is how non-metric MDS works.

The constraints arise from the nature of the dissimilarity measure. If there are n objects being scaled, then there will be $\binom{n}{2}$ unique dissimilarity measurements among them. However the direction of relationship (i.e. less than, greater than, or equal) between each pair of these measurements must be maintained in any MDS solution. These pairwise measurements comparisons are (by definition) the ordinal structure of the data. Each comparison thus represents an ordinal constraint on the MDS procedure, since it is an ordinal relationship which must be preserved in the solution. Because there are $\binom{n}{2}$ unique measurements, there are $\binom{\binom{n}{2}}{2}$ unique ordinal constraints, a very large number when compared with the number of objects being scaled (n). In an MDS problem, the number of constraints is usually so much larger than n that a unique MDS solution can be computed without using the actual numerical values of the dissimilarities.

MDS algorithms operate in a three-stage iterative procedure. In the first stage, the dissimilarity matrix for the stimuli (e.g. Table 2-2) is used to construct an initial representation of the stimuli as points in a multidimensional space. This is termed the initial configuration. The dissimilarity measure is also used to construct the set of ordinal constraints which will govern the remainder of the procedure.

In the second stage, the algorithm measures the goodness of the fit between the present configuration of the stimuli in the space and the ordinal constraints through some statistical or heuristic criterion. A heuristic criterion is one that has proven useful in identifying improvement in one solution over another but which has no statistical basis and which has no known sampling distribution. Thus, a change in a heuristic criterion can be easily interpreted as indicating an improvement (or deterioration, depending on the direction of the change) in the solution but can not provide an indication of the significance of the change. A statistical criterion is one that provides a statistical measure of improvement. The most common statistical criterion is the coefficient of variation (r^2) which measures the proportion of the variance in the data that is accounted for in the solution. Since non-metric MDS algorithms do not use the actual dissimilarity *values* in testing the goodness of fit, statistical criteria such as r^2 are usually impossible to compute.

In the third stage of an MDS algorithm the location of each stimulus on each dimension is adjusted so as to increase the goodness of the fit on the next iteration. The second and third stages are iterated until either the criterion reaches some threshold value or a predefined number of iterations has been completed.

The most commonly used criterion in non-metric MDS is a heuristic criterion termed "stress." Stress is a measure of the relative number of ordinal constraints that are violated by the current solution. The primary MDS algorithm used in the present analysis employed the following stress criterion:

$$\text{STRESS} = \sqrt{\frac{\sum_{ij} \left(d_{ij} - f(\hat{d}_{ij})\right)^2}{\sum_{ij} d_{ij}^2}} \qquad (i>j)$$

where d_{ij} is the distance between stimuli i and j in the multidimensional scaling solution, $\hat{d}_{ij}$ is the dissimilarity between stimuli i and j used as the input to the MDS procedure, and $f(\hat{d}_{ij})$ is a monotonic tranformation of $\hat{d}_{ij}$, subject to the general constraint:

$$f(\hat{d}_{ij}) > f(\hat{d}_{kl}) \text{ whenever } \hat{d}_{ij} > \hat{d}_{kl}.$$

The function $f(d_{ij})$ can be obtained in a variety of ways, but in the algorithm used in this study, it was calculated through Kruskal's monotone regression procedure (see Roskam 1977).

Some MDS algorithms use a metric procedure similar to factor analysis to derive the initial configuration but then proceed nonmetrically through the remainder of the algorithm. These algorithms are termed "quasi-metric" MDS algorithms. True non-metric algorithms obtain the initial configuration either through a random procedure or directly from the user.

The configuration of the stimuli in the multidimensional space when the algorithm terminates constitutes the MDS solution. This final configuration represents the placement of the stimuli in the space which best fits the constraints on their interrelations imposed by the original dissimilarity measure. The criterion for algorithm termination is based only upon the comparison of the distances between the stimuli in the MDS solution and the original dissimilarities. These comparisons are independent of the placement of the axes in the multidimensional space. It is therefore sometimes appropriate to rotate the axes of the MDS solution to obtain a placement of the stimuli with regard to the axes which permits easier interpretation.

An MDS algorithm can only compute a solution for a space with a predefined dimensionality. It is thus necessary to perform the analysis for spaces of varying number of dimensions and afterward select the solution which is best. This selection is normally made on the basis of a plot of the criterion (e.g. stress) against the dimensionality of the space. The stress associated with an MDS solution will normally be lower when more dimensions are used but the rate of decrease of stress with regard to dimensionality will vary. There will usually be some point (i.e. number of dimensions) where the curve created by the connecting points in the plot inflects or "elbows." The dimensionality at this point is taken as representing the best solution. When the stress/dimensionality plot shows a constant (linear) decrease, it indicates that the data being scaled do not have an underlying multidimensional structure and MDS analysis is inappropriate.

3.2 APPLICATION OF MDS ALGORITHM TO THE MOFFETT FIELD TACCO DATA

The dissimilarity matrix for the fourteen ASW decision functions (Table 2-2) constructed from the unconstrained sortings of the TACCOs interviewed at Moffett Field was used as input to a Multidimensional Scaling program. The MDS analysis was conducted on the University of Pennsylvania Wharton School's DEC-10 computer using the MDSX package of Multidimensional Scaling programs (Coxon *et al* 1977). This package contains several different MDS algorithms. Specifically, it includes the MINISSA algorithm of Lingoes and Roskam (1975), the INDSCAL algorithm of Carroll and Chang (1970), and Young's (1968) TORSCA IV algorithm. Initially, each of those algorithms were used on the Moffett Field data to test for convergent validity among the various programs. Virtually identical results were obtained from all three algorithms. In the prioritization analysis in Section 4.2, the output from MINISSA is used as the primary MDS solution (i.e. in place of the solutions provided by TORSCA IV and INDSCAL) because TORSCA IV and INDSCAL algorithms are both quasi-metric, whereas MINISSA is totally non-metric.

Each MDS algorithm was used to construct successive solutions from one to five dimensions. The plot of the stress against the dimensionality for MINISSA, shown in Figure 3-1, indicates that a three dimensional solution is best. Roskam (1977) provides some "rules-of-thumb" for assessing the goodness of a MINISSA solution according to the stress of the final configuration. He indicates that a stress between .05 and .01 should be considered as "good," while stress less than .01 should be considered the very best quality, in other words "execellent." Thus, with a stress of .002, the three dimensional MINISSA solution can be evaluated as excellent.

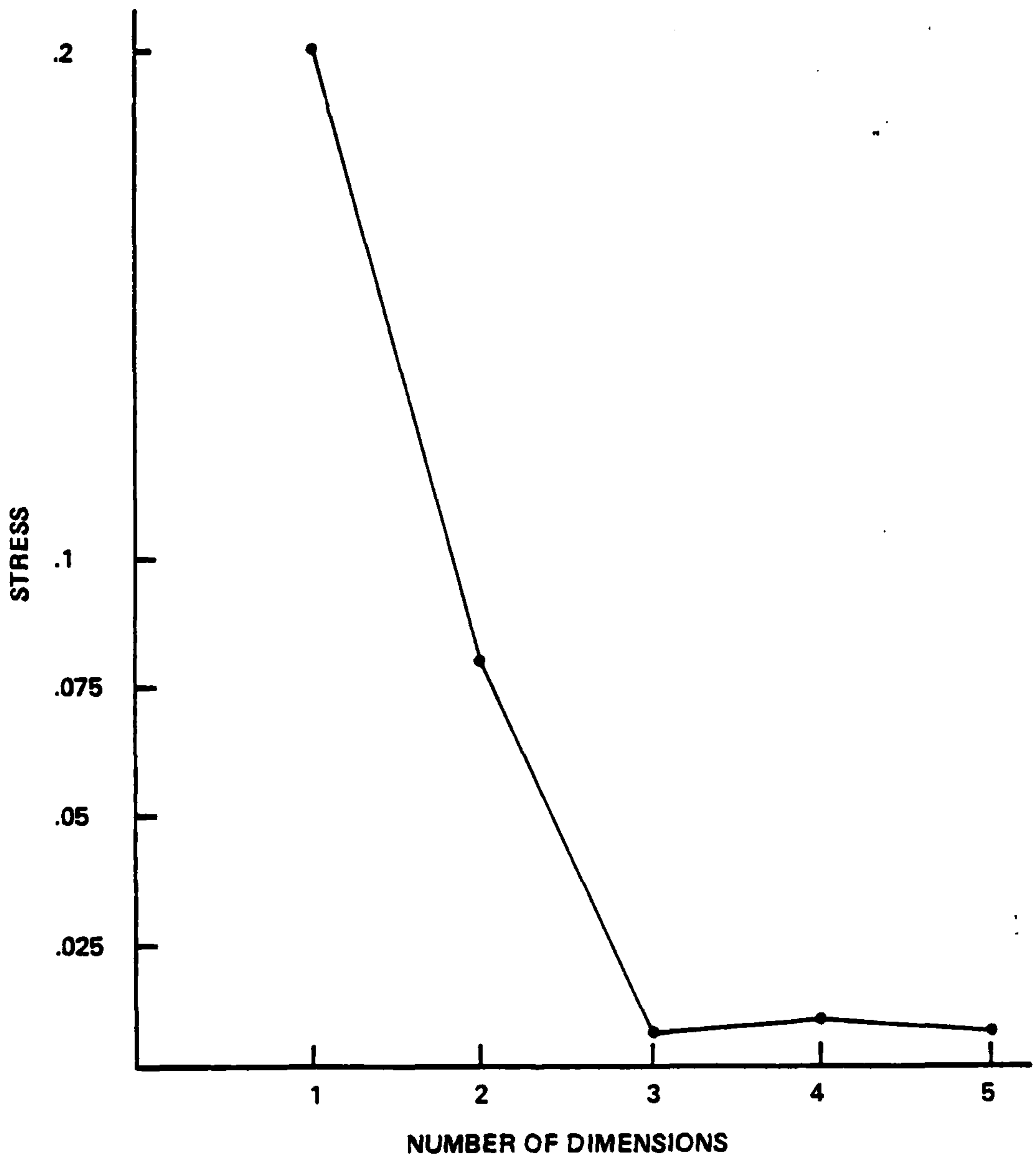


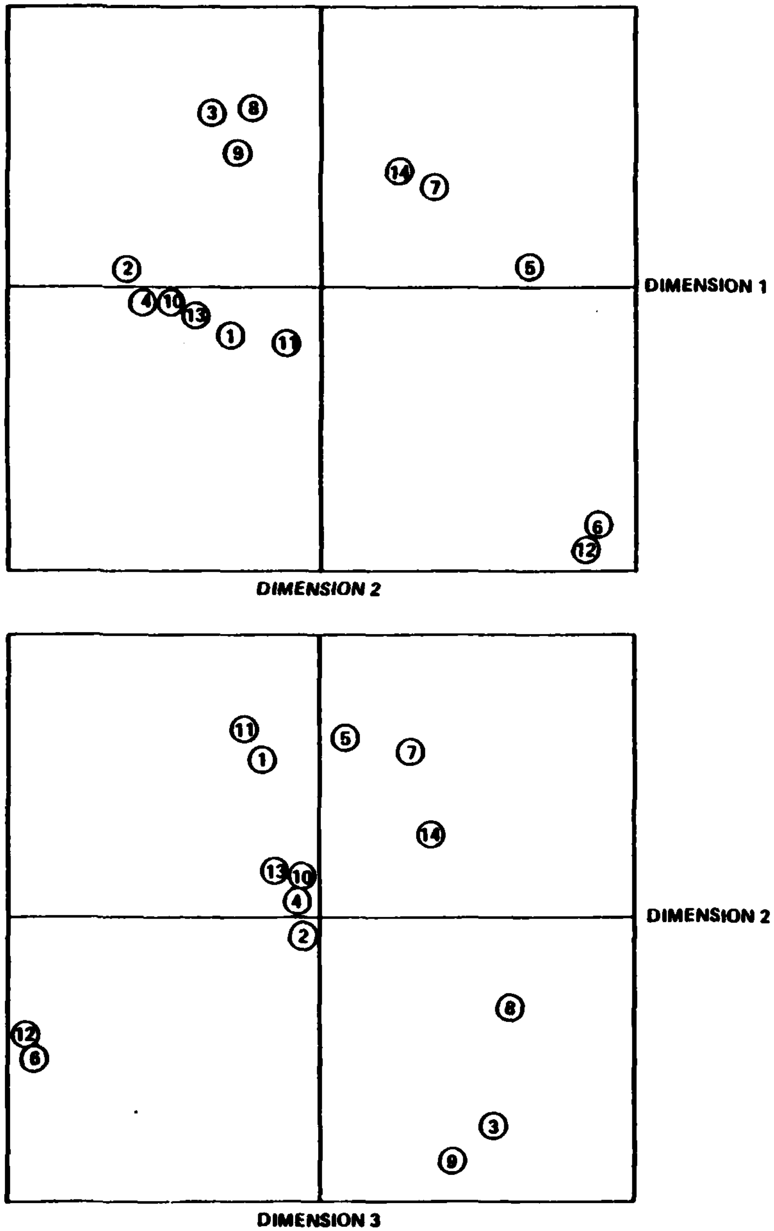
Figure 3-1. Minissa Stress Vs. Dimensionality Plot

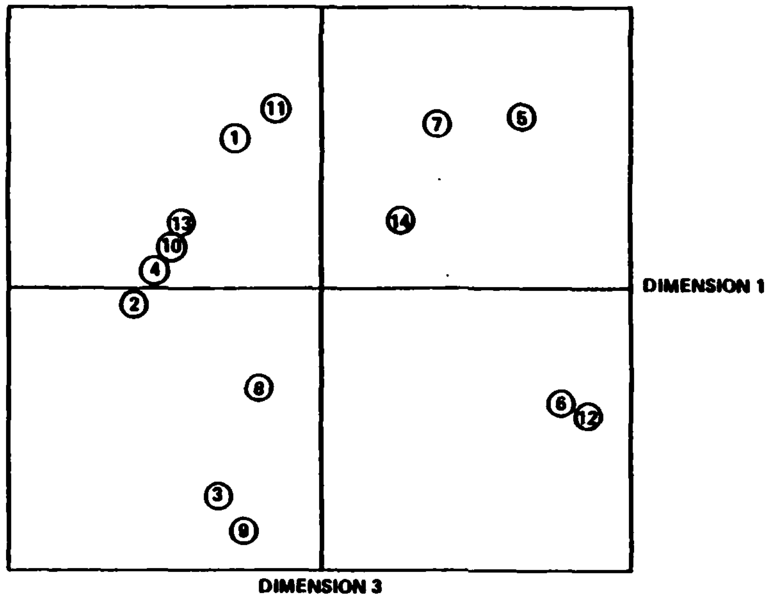
The parallel analysis of this data with the INDSCAL algorithm allowed a statistical estimate of the goodness of the three dimensional solution as INDSCAL uses the statistical criterion of r^2 (the coefficient of variation) for evaluating a configuration. The three dimensional INDSCAL solution was found to account for 76.2% of the variance in the original dissimilarity data. This figure was in keeping with the evaluation of the MINISSA solution.

The three dimensional MINISSA solution is plotted in Figure 3-2. This figure shows two dimensional plots of each possible pair of the three MINISSA dimensions. The locations of the decision functions within this multidimensional space are shown in Figure 3-2 only relative to each other -- no numerical values are provided for any of the dimensional scales. The actual coordinates of the fourteen decision functions on these three dimensions are shown in Table 3-1.

Table 3-1. Coordinates of Decision Functions in Three-Dimensional Solution

DECISION NAME	LOCATION ON DIMENSION 1	LOCATION ON DIMENSION 2	LOCATION ON DIMENSION 3
ADJUST PATTERN TO SENSOR FAILURE	–.14	–.08	.27
EXTEND SENSOR PATTERN	–.32	.02	–.02
ANTICIPATE TARGET MOVEMENT	–.16	.33	–.41
CONSTRUCT SENSOR MONITORING PATTERN	–.27	–.02	.06
COORDINATE HAND-OFF	.36	.05	.33
DETERMINE SIGNAL IS VALID CONTACT	.47	–.55	–.26
DETERMINE WEAPON AND SETTING FOR ATTACK	.21	.17	.29
GAIN ATTACK CRITERIA	–.10	.35	–.21
DETERMINE TARGET FIX	–.13	.26	–.47
CREATE SENSOR PATTERN	–.27	–.02	.07
MANAGE EQUIPMENT/STORES	–.03	–.11	.35
CLASSIFY SIGNAL	.47	–.55	–.26
COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS	–.23	–.05	.10
DETERMINE AIRCRAFT WEAPON LAUNCH POSITION	.15	.21	.14





KEY

1. ADJUST PATTERN TO SENSOR FAILURE
2. EXTEND SENSOR PATTERN
3. ANTICIPATE TARGET MOVEMENT
4. CONSTRUCT SENSOR MONITORING PATTERN
5. COORDINATE HAND-OFF
6. DETERMINE SIGNAL IS A VALID CONTACT
7. DETERMINE WEAPON AND SETTING FOR ATTACK
8. GAIN ATTACK CRITERIA
9. DETERMINE TARGET FIX
10. CREATE SENSOR PATTERN
11. MANAGE EQUIPMENT/STORES
12. CLASSIFY SIGNAL
13. COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
14. DETERMINE AIRCRAFT WEAPON LAUNCH POSITION

Figure 3-2. Plots of Decision Functions on Three Dimensions

3.3 DIMENSIONAL INTERPRETATIONS

The MDS algorithm reconstructs the key underlying features or characteristics of the decision functions in the stimulus set which the TACCO's used in performing the unconstrained sorting task. The algorithm represents these underlying features as the dimensional axes in the MDS solution. The algorithm cannot identify the *meaning* of these dimensional axes, however. The meanings must be interpreted through a careful examination of the way in which the decision functions in the stimulus set project onto each axis of the MDS solution. These projections are the dimensional coordinates given in Table 3-1. In the following sections each of the dimensions is analyzed and a tenative interpretation offered.

It should be noted that the multidimensional space constructed by an MDS algorithm is unique only up to a translation or rotation of the axes. Thus, the three dimensions in the MINISSA solution for the Moffett Field unconstrained sorting data can be rotated to any orientation in that space in order to obtain a more interpretable set of projections. The interpretations given below are based on the "unrotated" orientation given in Table 3-1 and Figure 3-2 for two reasons. First, that solution actually represents an implicit rotation performed by the MDS program to minimize the correlation between dimensional axes. This provides the orientation of the dimensions in which the axes are most independent in terms of the decision functions in the stimulus set. This in turn, enhances the interpretation of the dimensions as independent features. Second, a parallel analysis was conducted in which the dimensions were heuristically rotated to increase their interpretability. This analysis did not result in axis orientations that were more interpretable than those in the unrotated solution. Because the unrotated orientation is based on a statistical criterion (minimizing the inter-dimensional correlations) whereas the rotated orientation was based only on a heuristic approach, the unrotated placement of the dimensions is used in the interpretations below.

3.3.1 Interpretation of Dimension One: Degree of Uncertainty

This dimension was interpreted as referring to the degree of uncertainty in the information associated with the decision function. At one extreme of the dimension were the two signal processing decision functions -- Determine Signal is a Valid Contact, and Classify Signal. In both of these cases, the inputs to the TACCO's decision --acoustic signals -- are well defined and precise. The uncertainty in these decision functions lies principally in the interpretation or analysis of these signals. At the other end of the dimension there is a cluster of decision function relating to search patterns -- Extending the Pattern, Constructing the Pattern, Constructing the Monitoring Pattern, and Compensating for in-situ Propagation Conditions. There are many inputs to these decisions and each of these inputs may contain a great deal of uncertainty or "noise." Also, these decision functions are concerned with negative information, that is, information which is gained when something is observed *not* to occur. For example, the failure to gain a contact from certain sensors provides negative information on the target's location. There is a great deal of uncertainty associated with incorporating negative information into a decision. Thus, the decision functions on either end of this dimension represent extremes in the degree of uncertainty in the inputs to the decision.

The order of the decisions between these extremes also supports this interpretation of the dimension. Highest on the dimension after the signal processing functions are (in order) Coordinate Hand-off, Determine Weapon and Setting, and Determine Aircraft Weapon Launch Position. These three decision functions all involve little input uncertainty. In a hand-off the number, types, and settings of the deployed sonobuoys are all known precisely, and their locations are known to at least some degree. Since there currently is only one available weapon with two possible settings on the P-3C, there is also little input uncertainty in determining the attack weapon and its setting. The aircraft weapon launch position involves more uncertainty because it must be calculated on the basis of estimates of the target's present and future course, speed and location. These estimates always contain an element of uncertainty since they are predictions of future action.

Near the zero point on the dimension is the Managing Equipment and Stores decision function. This decision has two inputs, one of which (the stores remaining) is somewhat certain and the other of which (possible future needs for these stores) is highly uncertain (and thereby subject to over-estimation).

The remaining decision functions are located in a cluster near the negative extreme of the dimension. All of these relate in some degree to target movement. Anticipating Target Movement explicitly involves predicting the future location, course, depth, and speed of the target using (as inputs) the present estimate of the target's location, course, depth, and speed. Because they are estimates, these inputs are always subject to some degree of uncertainty (as are all appraisals of enemy intent). These same inputs are used in two other decision functions in the cluster -- Gaining Attack Criteria and Determining a Target Fix. The fourth decision function in this group is Adjusting the Sensor Pattern to Sensor Failure. There are several inputs which the TACCO must consider in making this decision. The characteristics of the current sensor pattern -- the geometry of the pattern and the setting, type and depth of existing sensors -- must obviously be considered. But the anticipated movement of the target is also an input, since the TACCO may desire to extend the pattern in the direction of future target movement rather than just replace a faulty sensor in the area from which the target is moving. Also, the likely remaining lifespan of the other sensors in the pattern must be considered in adjusting the pattern to the failure of a sensor. These last two types of input (anticipations of target movement and estimates of remaining sensor lifespans) both contain a good deal of uncertainty and thus justify the placement of adjusting the Sensor Pattern to Sensor Failure decision function with the others in this cluster.

3.3.2 Interpretation of Dimension Two: Information Processing Load

This dimension was interpreted as representing the relative information processing load the decision placed upon the TACCO. At the lower extreme of this dimension are the two signal processing decisions (Determine Signal is a Valid Contact and Classify Signal). On the P-3C these decisions are primarily made by the Sensor Station Operators (SENSOs) and are merely accepted or rejected by the TACCO. Thus, they present a very light information processing load for the TACCO. At the other extreme are five decision functions -- Gaining Attack Criteria, Anticipating Target Movement, Determining Target Fix, Determining Aircraft Weapon Launch Position, and Determining Weapon and Setting for Attack -- which must be made in short periods of time and require the integration of information of *many* types of information from many sources. For all these decisions information from the different sensors and different sensor types must be correlated and compared to obtain estimates of the targets' location, course, depth, and speed. Also, information on the sensor types and sensor capabilities must be considered together with environmental information to construct assessments of the likely error or uncertainty in those estimates. All of these five decision functions thus place a heavy information processing load on the TACCO.

The remaining decision functions on this dimension fall near each other in a cluster with its center near the origin. These seven decision functions -- Coordinating Handoff, Extending Sensor Pattern, Constructing Sensor Monitoring Pattern, Creating Sensor Patterns, Compensating for in situ Propagation Conditions, Adjusting Sensor Pattern and Managing Equipment/Stores -- represent decisions with multiple and complex inputs. They are, however, less time constrained than those decisions at the positive end of this dimension. In most cases, the same information must be processed by the TACCO in these decisions as in the decision functions placed at the high end of the dimension. Environmental *conditions, sensor capabilities* and placements, and target location estimates must be considered in some or all of the decisions in this group, and multi- and cross-sensor inputs must also be compared and correlated. But because the decisions in this cluster do not require as rapid solutions, the TACCO has more time to process this information. Thus, the relative information processing load is reduced.

This interpretation of dimension two is subject to some degree of independent validation by comparing it to the ranking associated with the judged criterion of workload. Comparing the order of the decision functions on this dimension with their order in the average ranking for TACCO workload in Table 2-7, a rank order correlation of .8 was obtained. This high correlation supports the interpreation of dimension two as an information processing load dimension.

3.3.3 Interpretation of Dimension Three: Complexity of Alternative Structure

Dimension three proved the most difficult to interpret and its analysis here should be considered as only tentative. The third dimension was finally concluded to represent the relative complexity of the alternative structure of the decision function. Complexity of the alternative structure refers to the number of alternative approaches the TACCO has toward performing the decision function. At the postive extreme of this dimension were three decision functions which can be approached in a relatively straight forward manner -- Managing Equipment and Stores, Coordinating the Handoff, and Determining Weapon and Setting for Attack. Each of these decision functions can be performed by standard procedures and do not present a large number of alternative choices to the TACCO. In coordinating a handoff, for example, the information which the TACCO must manage and transmit to the relief platform is well defined and there are only a few different ways in which he may do so.

The placement of the Adjusting Sensor Pattern to Sensor Failure decision function with this group is somewhat anomalous, as there are many alternate ways in which this decision function may be approached. If the TACCOs were considering it as a straight sensor *replacement* decision, however, its location on this dimension is more understandable.

On the opposite end of this dimension are five decision functions relating to signal processing and target movement--Determining Target Fix, Anticipating Target Movement, Classifying a Signal, Determining the Signal is a Valid Contact, and Gaining Attack Criteria. Each of these decision functions has many complex inputs and can be approached in a variety of different ways. In determining a target fix, for example, the TACCO may rely on information from any combination of sensors (of the same or of differing types) to determine the precise location of the submarine. The number of possible locations for the target is theoretically infinite and even in practice it is very large. Thus, the TACCO may take any of a variety of approaches to select from among the large and complex set of alternatives in these decisions. The remaining five decision functions on this dimension--Determining the Aircraft Weapon Launch Position, Compensating for in-situ Propagation Conditions, Creating a Sensor Pattern, Constructing a Sensor Monitoring Pattern, and Extending the Sensor Pattern -- are all located in a cluster near the zero-point of this dimension. These all seem to represent decisions which have a moderately large set of alternatives, but not as large or complex a set as the signal processing or target movement decisions.

An alternative interpretation of this dimension is to dichotomize the decision functions into tactical decisions and target management decisions. The tactical decisions are Manage Equipment/Stores, Coordinate Handoff, Determine Weapon and Setting for Attack, Adjust Sensor Pattern to Sensor Failure, Determine Aircraft Weapon Launch Position, Compensate for in-situ Propagation Conditions, Create Sensor Pattern, Construct Sensor Monitoring Pattern and Extend Sensor Pattern. All these decisions involve choices made by the TACCO concerning the selection and/or use of specific tactics to gain contact with or prosecute the submarine. These decisions are all located on the positive end of the dimension with the exception of Extend Sensor Pattern which has a value near zero (-.02).

The remaining decision functions (Gain Attack Criteria, Determine Signal as a Valid Contact, Classify Signal Anticipate Target Movement, Determine Target Fix) are all located on the negative end of the dimension, substantially away from the zero point. These decisions do not concern the selection or application of tactics but instead deal with interpretation and analysis of information that is received about a specific target as a result of previous tactical actions. These decisions affect the tactical decisions on the other half of the dimension, both in terms of allowing new tactics to be employed (as, for example, attainment of attack criteria permits the attack tactics selection to begin) and in terms of providing feedback on the effectiveness of previous tactics (as, for example, verifying a contact indicates that the current sensor pattern has been effective in achieving a contact from a target of interest).

4. PRIORITIZATION OF AIR ASW DECISION SITUATIONS

The three dimensions constructed by the Multidimensional Scaling analysis of the sorting data represent a geometric model of experienced TACCOs' conceptual framework for Air ASW decisions. Since these three dimensions represent the basic underlying characteristics which experienced TACCOs use to think about Air ASW decision making, other subjective characteristics should be representable as combinations of these underlying features. Priority or importance is one such characteristic. This section describes the procedures used to identify the particular combination of these three dimensions which the TACCOs interviewed at Moffett Field were implicitly using when they ranked the decision functions according to their importance in the mission. Also presented is the way in which the reconstructed combination rules or *priority functions* were used to numerically prioritize the six Air ASW Decision situations for decision aid design.

The basic technique used to determine the TACCOs' priority functions is termed Priority Mapping, and has been developed specifically for this effort. It is related to the psychometric technique known as Preference Mapping (Carrol and Chang 1967) and is based on Coombs (1950) and Bennett and Hays (1960) notion of Unfolding Analysis. Appendix F provides a review of Unfolding Analysis and its relation to Priority Mapping. Briefly, Priority Mapping is a means of "embedding" an ordinal priority scale of a set of items into a multidimensional model of the interrelationships among those items. Normally, the multidimensional model is a the result of an MDS analysis of a dissimilarity measure on a set of items, and the priority scale is a ranking of the items produced by one or more individuals according to some definition or criterion of priority. The scale is embedded into the multidimensional model by expressing the scale as some function of the dimensions in the model.

Unfolding Analysis determines which among four broad classes of functions provides the best representation of the ordinal scale in terms of the multidimensional model dimensions. These four classes of functions correspond to four increasingly complex multidimensional models of priority. In the simplest model, called the vector model, priority is modeled as the order of the projections of the items in the multidimensional space onto a vector through the space. The next simplest model is called the distance model, and in it priority is modeled as the order of the distances of the items in the multidimensional space from some "ideal" point representing the highest possible (or lowest possible) priority. The third model is called the weighted distance model. It is identical to the second (distance) model except that it allows the distance from the ideal point along some dimensions to contribute more to priority than the distance along others. Finally, the fourth and most complex model is termed the general distance model. It is identical to the weighted distance model except that it also allows the dimensional axes to be rotated prior to differential weighting. These four models are discussed in greater detail in Appendix F. Section 4.1 summarizes the Priority Mapping results for the importance rankings collected from the TACCOs at Moffett Field. Section 4.2 describes the manner in which these results were used to prioritize the six ASW decision situations.

4.1 UNFOLDING ANALYSIS AND PRIORITY MAPPING OF DECISION FUNCTIONS

Separate Unfolding Analysis procedures were conducted for the two rankings of decision functions by importance. The first analysis considered the rankings by importance in a mission where the objective was an attack on the submarine. The average ranking according to this criterion is given in Table 2-4, and the rankings by each of the individual TACCOs are given in Appendix D. The second analysis considered the ranking by importance in a mission where the goal was surveillance of the submarine. The average ranking according to this criterion is given in Table 2-5, and the rankings by each of the individual TACCOs are given in Appendix D. The Priority Mapping analysis was accomplished by using the PREFMAP program developed by Carroll and Chang (1967, 1977), which performs the procedures described in Appendix F. PREFMAP, like the MDS programs described in Section 3.2, is part of the MDSX package of Multidimensional Scaling programs (Coxon *et al.* 1977) available on the Wharton School's DEC-10 Computer.

PREFMAP performs Unfolding Analysis in two parallel manners. First, it conducts a separate analysis of each *individual* ranking against a multidimensional representation of the ranked stimuli provided by the user. Second, it performs an identical analysis on the aggregated (average) ranking of all the individuals. In the discussions of both of the Unfolding Analysis procedures below only the results of the aggregate analysis are considered because they were the ones that were used in the prioritization of the six decision situations.

4.1.1 Decision Function Prioritization for Attack Missions

The analyses of the decision function rankings for attack missions concluded that the most compex of the four models of priority--general distance model--was required to represent this criterion (i.e. importance in a mission with attack) as a function of the three dimensions discussed in Section 3. The detailed calculations in the Priority Mapping for this criterion are given in Appendix G. The result of the analyses is a formula for determining the *priority score,* $P_{WA}(d_j)$, of any decision function, d_j, in an attack mission from its coordinates in the multidimensional decision space (Figure 3-1) alone. This formula is also given in Appendix G. The numerical priority scores that were generated for the fourteen decision functions by the formula $P_{WA}(d_j)$ are given in Table 4-1.

The values in Table 4-1 represent the final prioritization of the decision functions in a mission with attack. It should be noted that in Table 4-1 lower values indicate higher priority, and higher values indicate lower priority. The interviewees were asked to assign the most important decision the lowest rank (i.e. 1), and the least important decision the highest rank (i.e. 14), and PREFMAP merely maintains this directionality in its computations.

Table 4-1. Decision Function Prioritization For Mission With Attack On Submarine

PRIORITY RANK	DECISION FUNCTION	PRIORITY SCORE	
1	DETERMINE SIGNAL IS VALID CONTACT	-.2219	(HIGHER)
2	CLASSIFY SIGNAL	-.2208	↑
3	COORDINATE HAND-OFF	-.1553	
4	DETERMINE TARGET FIX	-.1439	
5	ANTICIPATE TARGET MOVEMENT	-.1186	
6	CONSTRUCT SENSOR MONITORING PATTERN	-.0581	
7	COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS	-.0575	PRIORITY
8	CREATE SENSOR PATTERN	-.0350	
9	EXTEND SENSOR PATTERN	-.0293	
10	MANAGE EQUIPMENT/STORES	.0032	
11	ADJUST PATTERN TO SENSOR FAILURE	.0167	
12	GAIN ATTACK CRITERIA	.2098	
13	DETERMINE AIRCRAFT WEAPON LAUNCH POSITION	.4050	↓
14	DETERMINE WEAPON AND SETTING FOR ATTACK	.4322	(LOWER)

4.1.2 Decision Function Prioritization in Surveillance Missions

A parallel analysis was conducted for the rankings by importance in a surveillance mission--one without an attack segment. In this case also it was found that the generalized distance model was required to describe the TACCOs' rankings of priority. The Priority Mapping resulted in a formula for determining the priority score, $P_{WOA}(d_j)$, of a decision, d_j, in a surveillance mission from its location on the three dimensional space shown in Figure 3-1. This formula, and the details of the Unfolding Analysis and Priority Mapping for this criterion are also given in Appendix G. The priority scores for the fourteen decisions generated by the formula $P_{WOA}(d_j)$ are given in Table 4-2. These values represent the priorities of the decision functions in a surveillance mission.

As described above, smaller values indicate higher priority, and larger values cate lower priority.

Table 4-2. Decision Function Prioritization For Mission Without Attack On Submarine

PRIORITY RANK	NAME	PRIORITY SCORE	
1	GAIN ATTACK CRITERIA	-.21129	(HIGHER)
2	DETERMINE SIGNAL IS VALID CONTACT	-.186603	↑
3	CLASSIFY SIGNAL	-.17522	
4	DETERMINE AIRCRAFT WEAPON LAUNCH POSITION	-.15907	
5	DETERMINE TARGET FIX	-.14836	
6	ANTICIPATE TARGET MOVEMENT	-.08897	
7	DETERMINE WEAPON AND SETTING FOR ATTACK	-.02783	PRIORITY
8	COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS	.03061	
9	CREATE SENSOR PATTERN	.05525	
10	CREATE SENSOR MONITORING PATTERN	.06229	
11	EXTEND SENSOR PATTERN	.08192	
12	ADJUST PATTERN TO SENSOR FAILURE	.15309	
13	MANAGE EQUIPMENT/STORES	.15867	↓
14	COORDINATE HAND-OFF	.45690	(LOWER)

4.2 COMBINING PRIORITY SCORES ACROSS DECISION SITUATIONS

Tables 4-1 and 4-2 present the priority scores that were constructed for the fourteen decision functions in two types of missions -- missions with and without an attack on the submarine being prosecuted. These decision *function* prioritizations still remain to be translated into decision *situation* prioritizations. This is accomplished in a three step procedure. In the first step, the decision situations are broken down into their constituent decision functions. In the second step, the priority scores for all the decision functions which comprise each situation are combined to produce a raw priority score. And in the third step, the raw priority score for each situation is normalized to compensate for the differing number of functions used to represent each situation. Each of these steps is described in greater detail below.

4.2.1 Relating Decision Functions to Decision Situations

Initially, the decision functions which comprise each of the six decision situations were identified. An initial assessment of the relationship between the decision functions was made in the preceding effort (see Zachary 1980, Section 2.). The breakdown of decision situations into constituent decision functions presented there (*ibid:* Table 2-2) was refined through discussions with experienced Naval ASW personnel at the Naval Air Development Center (NADC). As a result of these discussions, the decision functions (from among the fourteen in the stimulus set) involved in each of the six decision situations (On-Station Search, Contact Classification/Verification, Localization, Surveillance Tracking, Lost Contact Reacquistion, and Attack Planning) were identified. The relationships between the decision functions and situations are given in Table 4-3. It should be noted that some of the decision functions are included in several of the decision situations. This reflects the conclusions of the previous effort that the decision situations reflect contexts in which specific decisions are made, and that the same decision function may be performed quite differently in different mission contexts.

4.2.2 Creating Raw Priority Scores For the Decision Situations

After the constituent decision functions of each decision situation were identified, raw priority scores for the decision situations were constructed. This was done by summing the priority scores of the constituent decision functions for each situation. Since each decision function, j, had two priority scores -- $P_{WA}(d_j)$ and $P_{WOA}(d_j)$ -- two corresponding raw priority scores were constructed for each situation. The first represented the situations priority in a mission whose goal was attack and destruction of the hostile submarine, and was computed as

$$P_{WA}(D_i) = \sum_{d_j \in D_i} P_{WA}(d_j)$$

Table 4-3. Decision Function Composition Of Six Air ASW Decision Situations

DECISION SITUATION	CONSTITUENT DECISION FUNCTIONS
ON-STATION SEARCH	CREATE SENSOR PATTERN MANAGE EQUIPMENT/STORES EXTEND SENSOR PATTERN ADJUST PATTERN TO SENSOR FAILURE CONSTRUCT SENSOR MONITORING PATTERN COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
CONTACT CLASSIFICATION/VERIFICATION	CLASSIFY SIGNAL DETERMINE SIGNAL IS A VALID CONTACT
LOCALIZATION	MANAGE EQUIPMENT/STORES ANTICIPATE TARGET MOVEMENT EXTEND SENSOR PATTERN GAIN ATTACK CRITERIA DETERMINE TARGET FIX COORDINATE HAND-OFF ADJUST PATTERN TO SENSOR FAILURE CONSTRUCT SENSOR MONITORING PATTERN COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
SURVEILLANCE TRACKING	CREATE SENSOR PATTERN MANAGE EQUIPMENT/STORES ANTICIPATE TARGET MOVEMENT EXTEND SENSOR PATTERN DETERMINE TARGET FIX COORDINATE HAND-OFF ADJUST PATTERN TO SENSOR FAILURE CONSTRUCT SENSOR MONITORING PATTERN COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
ATTACK PLANNING	CREATE SENSOR PATTERN MANAGE EQUIPMENT/STORES ANTICIPATE TARGET MOVEMENT EXTEND SENSOR PATTERN GAIN ATTACK CRITERIA DETERMINE TARGET FIX ADJUST PATTERN TO SENSOR FAILURE DETERMINE WEAPON AND SETTING FOR ATTACK CONSTRUCT SENSOR MONITORING PATTERN DETERMINE AIRCRAFT WEAPON LAUNCH POSITION COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS
LOST CONTACT REACQUISITION	CREATE SENSOR PATTERN MANAGE EQUIPMENT/STORES ANTICIPATE TARGET MOVEMENT EXTEND SENSOR PATTERN COORDINATE HAND-OFF ADJUST PATTERN TO SENSOR FAILURE CONSTRUCT SENSOR MONITORING PATTERN COMPENSATE FOR IN-SITU PROPAGATION CONDITIONS

where D_i is decision situation i, d_j is decision function j, and P_{WA} is as previously defined. The raw decision situation priority scores for a mission with attack are given in Table 4-4.

Table 4-4. Decision Situation Prioritization For Mission With Attack

RANK	SITUATION	RAW PRIORITY SCORE	NORMALIZED PRIORITY SCORE
1	CONTACT CLASSIFICATION/ VERIFICATION	-.36	-.181
2	ATTACK PLANNING	-.09	-.008
3	LOCALIZATION	+.49	+.055
4	SURVEILLANCE TRACKING	+.76	+.084
5	LOST CONTACT REACQUISITION	+.71	+.089
6	ON-STATION SEARCH	+.54	+.090

The second priority score for each decision situation represented its priority in a mission whose goal was surveillance of the hostile submarine, and was computed as

$$P_{WOA}(D_i) = \sum_{d_j \epsilon D_i} P_{WOA}(d_j)$$

where D_i, d_j, and P_{WOA} are as previously defined. The raw decision situation priority scores for a mission without attack are given Table 4-5.

Table 4-5. Decision Situation Prioritization For Mission Without Attack

RANK	SITUATION	RAW PRIORITY SCORE	NORMALIZED PRIORITY SCORE
1	CONTACT CLASSIFICATION/ VERIFICATION	-.44	-.221
2	SURVEILLANCE TRACKING	-.58	-.064
3	LOST CONTACT REACQUISITION	-.43	-.054
4	LOCALIZATION	-.33	-.037
5	ON-STATION SEARCH	-.16	-.027
6	ATTACK PLANNING	+.62	+.056

4.2.3 Normalizing the Raw Scores

The raw priority score assigned to each decision situation is influenced by two factors -- the priority scores of the constituent decision functions and the number of constituent decision functions. This second factor has a substantial effect on the raw score, because the greater the number of constituent functions, the larger the raw score. Unfortunately the effect of this factor is primarily to confound the effect of the first which is the principal concern in this prioritization procedure.

When the stimulus set for the MDS procedure was defined, it was not intended that it include every conceivable decision function which the TACCO performs in an Air ASW mission. Rather, it was simply constructed to include a representative sample of the decision functions which may arise in the course of a mission. The fourteen decision functions which were chosen are not evenly distributed across the six decision situations, as can be seen from Table 4-3. One situation (Contact Classification/Verification) was represented by as few as two functions, while another (Attack Planning) was represented by as many as eleven. The distribution of the sample of decision functions across the decision situations does not reflect the distribution of all decision functions over the situations and, therefore, does not meaningfully impact on situational priority. The number of decision functions in a decision situation affects the workload of the TACCO in that situation, but should not affect the priority of that decision situation in the mission. If it did, then the highest priority situation would be, by definition, the situation in which the TACCO is the busiest.

It was therefore necessary to control for the effect of the differing number of decision functions contributed to the raw priority score for each situation. This was done by normalizing the raw score -- dividing it by the number of terms in the sum from which it was computed. That is, the raw score was divided by the number of decision functions which comprise the decision situation. This normalization procedure was performed for both sets of raw scores. The normalized priority scores of each situation for the mission with attack are given next to the raw scores in Table 4-4. The normalized scores for the mission without attack are given next to the raw scores for each situation in Table 4-5.

4.2.4 Two Priorizations of Air ASW Decision Situations

The normalized scores for the decision situations in each type of mission were then used to rank the situations according to their overall priority. The orders in which the situations are shown in Table 4-4 and 4-5 reflect these rankings. In a mission with the goal of attacking the submarine the final prioritization of the decision situations is:

- Contact Classification/Verification
- Attack Planning
- Localization
- Surveillance Tracking
- Lost Contact Reacquisition
- On-Station Search

This order is intuitively attractive, since the Attack Planning situation is placed near the top, while Surveillance Tracking (which presumably would not occur in this type of mission) is near the bottom. In numerical terms, the bottom three situations are only separated by .006, indicating that they are equally low in priority (see Table 4-4).

In a mission with the goal of surveillance of the submarine, the final priorization of the decision situations is:

- Contact Classification/Verification
- Surveillance Tracking
- Lost Contact Reacquisition
- Localization
- On-Station Search
- Attack Planning

This order is also intuitively acceptable, with Attack Planning (which would not occur in this type of mission) at the bottom and Surveillance Tracking near the top.

5. DECISION SITUATION PRIORITIZATION AND DECISION AID DESIGN

The primary purpose for prioritizing the six decision situations is to determine the order in which decision aiding technology should be applied to them. In this section, the highest priority decision situations are analyzed and high level decision aid designs are constructed for them. Two specific situations will be considered, Contact Classification/Verification (which had the highest score in both types of mission), and Attack Planning (which had the second highest priority for the mission with attack).

5.1 CONTACT CLASSIFICATION/VERIFICATION: AN OPTIMAL MODE SELECTION DECISION AID

The Contact Classification/Verification situation was ranked first in the priority scales for both types of mission. Since this situation was represented by only two decision functions in the sample of fourteen, it is possible that this result is partially an artifact. It was clear from the interviews at Moffett Field, however, that the TACCOs felt this situation to be crucial to the ASW mission, for two specific reasons. First, they felt that the entire prosecution phase of the mission was dependent upon the correctness of the decisions in this situation. Second, they felt that there was very little room for error in the decisions in this situation. These comments, while explaining the high priority assigned to this situation, were not useful in determining what type of decision aid is needed for it. Information more pertinent to this end was obtained from the previous analysis and description of the Contact Classification/Verification decision situation (see Zachary 1980), the dimensional interpretations, and the additional rankings (urgency and workload) collected at Moffett Field.

The two decision functions in the sample of fourteen which contribute to this decision situation (Classify Signal and Determine Signal is Valid Contact) lay at or near an extremum of each of the three dimensions in the MDS solution. On the first dimension, degree of uncertainty, they are located at the end representing little information uncertainty. The situational inputs identified in the decision situation description confirm this. The primary inputs -- acoustical signals -- are tangible and lacking in uncertainty: it is the *processing* and interpretation of these signals which is more problematical.

On the second dimension, information processing load, the two decision functions relevant to this situation were located near the end representing a low processing load. This is presumably because the major part of the decisions made in this situation are made by the sensor station operators (SENSO) rather than the TACCO himself.* The workload rankings support this conclusion, as the two decision functions for this situation ranked twelfth and thirteenth in the average rankings (Table 2-7).

On the third dimension, complexity of alternative structures, these same two decision functions were located near the end of the dimension representing high complexity of alternative structure. This indicated that there is a large and complex set of alternative ways in which the TACCO or SENSOs can approach these decisions. The placement of the decision functions on dimension one (degree of uncertainty) confirms this. It was concluded from the placement on dimension one that the primary difficulty in these decision functions was in the analysis of the input data, rather than in the input data itself. This aspect of the decision situation provided the key to designing a decision aid. Further investigation of the detailed manner in which alternative ways of processing accoustic signals helped identify a key problem in need of aiding.

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*At least in the P-3C, the aircraft flown by the TACCOs interviewed at Moffett Field. On the S-3A, however, the TACCO can assume more of the workload in this situation.

The increasing sophistication of the on-board acoustic signal processing equipment (i.e. the current AQA-7(V7) system and the soon-to-be-implemented PROTEUS system) allows incoming sensor information to be processed in a wide variety of modes. Many of these modes can be employed simultaneously, resulting in a large number of possible processing mode combinations. The TACCO or SENSO must choose a specific processing mode, but currently has very little time and/or information on which to base this choice. Moreover, a choice of the correct processing mode is crucial to the successful identification and classification of a signal. Thus a decision aid is needed to assist the TACCO in selecting an optimal processing mode for the signal processing equipment.

This optimal mode selection decision aid will make suggestions as to processing-mode selection based on the following input information:

- Current environmental conditions, e.g. propagation-loss profile, bathythermal conditions, sea-state,
- Characteristic frequencies of the potential targets of interest,
- Type, placement, and setting of currently deployed sensors, and
- Stability of the various frequencies of the potential targets of interest.

The aid obtains some of the input information from the TACCO, and the remainder from other computer programs or databases on board the platform. In particular, the characteristic target frequencies and the stability of target frequencies will be obtained from an on-board database which is loaded prior to the start of the mission, according to the targets identified as likely to be encountered. The location, depth, setting and types of deployed sensors will be obtained from other operational programs on the aircraft. The specific targets of interest to the TACCO will be obtained directly from him, as will be the current environmental conditions. The aid will produce a single output from those inputs -- a suggested acoustical signal-processing mode.

The design for such an aid is described below in terms of the taxonomy of decision aiding techniques created by Analytics as a part of the previous effort. The taxonomy is shown here as Table 5-1. The specific techniques needed from each category of the taxonomy in the optimal mode selection aid are discussed below.

5.1.1 Outcome Calculators

As discussed in our previous report (Zachary 1980) there is no real-time process which underlies the decisions made in the Contact Classification/Verification situation. Therefore, no outcome calculator is needed by a decision aid for this situation.

5.1.2 Value Model

Central to the mode selection problem is a set of tradeoffs created by uncertainties about environmental conditions and by differing characteristics of the various targets of interest. For example, some processing modes may improve the probability of identifying some targets but decrease the probability of detecting others. Alternatively, some modes may improve the probability of detecting certain types of targets but only if specific environmental conditions prevail. A value model is thus needed to establish the preferred tradeoffs among such factors. The multiattribute utility model (MAUM) can be used effectively in this type of situation. A preference value or utility will be computed for each specific combination of processing modes, by the following MAUM:

$$U(i) = \sum_{j \in T} W_j P_i(j)$$

In the model, $U(i)$ is the utility of mode combination i, T is the set of targets of interest, j is a specific type of target, $P_i(j)$ is the probability of identifying a signal from target type j given the current sensor pattern and processing mode combination i, and W_j is a weight representing the relative importance of detecting a target of type j over all other target types. This

Table 5-1. Taxonomy of Decision Aiding Techniques

1.	OUTCOME CALCULATORS
1.1	Closed Form Analytic Models
1.2	Probabilistic Models
1.3	Deterministic Simulations
1.3.1	Mechanical
1.3.2	Differential Equation
1.4	Monte-Carlo Simulations
2.	VALUE MODEL
2.1	Multi-Attribute Utility Model (MAUM)
2.2	Adaptively Constructed MAUM
2.3	Direct Assignment of Utilities to Outcomes
2.4	Risk-Incorporating Utility Models
2.5	Non-Linear Utility Model
3.	DATA CONTROL TECHNIQUES
3.1	Automatic Data Aggregation
3.2	Data Management Techniques
4.	ANALYSIS TECHNIQUES
4.1	Optimization Techniques
4.1.1	Linear Programming
4.1.2	Non-Linear Programming
4.1.3	Dynamic Programming
4.1.4	Fibbonaci Search
4.1.5	Response Surface Methodology
4.2	Artificial Intelligence Techniques
4.2.1	Heuristic Search
4.2.2	Bayesian Pattern Recognition
4.3	Sensitivity Analysis
4.4	Intra-Process Analysis
4.5	Information Processing Algorithms
4.6	Status Monitor and Alert
4.7	Statistical Analysis
4.7.1	Distribution Comparison
4.7.2	Regression-Correlation
4.7.3	Discriminant Analysis
4.7.4	Bayesian Updating
5.	DISPLAY/DATA ENTRY TECHNIQUES
5.1	Display Graphics
5.2	Interactive Graphics
5.3	Windowing
5.4	Speech Synthesis/Recognition
5.5	Quickening
6.	HUMAN JUDGMENT AMPLIFYING/ REFINING TECHNIQUES
6.1	Operator-Aided Optimization
6.2	Adaptive Predictions
6.3	Bayesian Updating

MAUM incorporates the tradeoffs among target types through the W_j factors, and incorporate the tradeoffs among alternative environmental states implicitly through the $P_i(j)$.

5.1.3 Data Control

While the actual processing of the incoming acoustical signals may require sophisticated data control methods, the mode selection problem does not consider these signals per se. The information it does require (described above) can be obtained and managed with current standard techniques, so no data control techniques are needed in this aid.

5.1.4 Analysis

At the very heart of the mode selection decision is an optimization problem: the optimal processing mode must be chosen from among all possible combinations. This suggests the need for an optimization technique. The nature of the optimization problem is combinatorial, i.e. involves selecting an optimal combination of discrete characteristics, and this type of optimization is best handled with dynamic programming. The aid will contain a dynamic programming algorithm which "searches" the space of all possible combinations of processing modes. It would compare each combination and select the better one based on the MAUM described above.

The aid would also employ an information processing algorithm to construct the $P_i(j)$ values needed in the MAUM functions. This algorithm assesses the probability of identifying a signal from a specific type by using a given combination of processing modes. It combines pre-stored probability of identification values for specific environmental conditions and area-coverage factors across the probabilities of the various environmental conditions which may obtain for the current mission.

5.1.5 Display/Entry

The aid obtains the majority of the information it needs from other computer programs and on-board databases, and produces only a single output. This output, plus the few inputs required from the TACCO, can best be presented with standard alphanumeric display/entry techniques.

5.1.6 Human Judgment Refinement/Amplification

There is no need for any human judgment refining/amplifying techniques in this aid. This situation does not have an iterative type of task structure (the same task repeated over and over, as in tracking), so neither Bayesian Updating nor Adaptive Prediction techniques are appropriate. Although the problem does involve optimization, the operator-aided form of optimization is not well suited to combination problems of the sort involved here, because such optimization does not require the use of hill-climbing (i.e. convergence) algorithms.

5.2 ATTACK PLANNING: AN ATTACK-CRITERIA/WEAPONS PLACEMENT DECISION AID

The Attack Planning decision situation ranked second in priority for attack missions, directly behind the Contact Classification/Verification situation which ranked first for both types of missions. Five of the decision functions involved in attack planning -- Gaining Attack Criteria, Determining Aircraft Weapon Launch Position, Determining Target Fix, Anticipating Target Movement, and Determining Weapon and Setting For Attack -- ranked among the seven highest priority decision functions for the mission with attack (see Table 2-4). Interestingly, these same five decision functions were the highest five in the ranking for urgency (Table 2-6) and five of the highest six in the ranking for workload (Table 2-7). These placements characterize these aspects of attack planning as highly time-constrained and work-intensive decisions for the TACCO.

The placement of these decision functions in the MDS (Figure 3-2) solution space confirms this characterization. While they are positioned around or near the middle of dimension one (information uncertainty) and three (complexity of alternative structure), they are all located at the positive extremum of dimension two (information processing load). This indicates that they represent decisions which place a heavy information load on the TACCO. These characteristics of Attack Planning decision functions explain why the situation was assigned such a high priority by the TACCOs, and also suggest the type of decision aid required.

A decision aid for the Attack Planning situation should serve two specific functions. First, it should automate some of the information processing currently required of the TACCO, and second, it should speed the rate at which phases in the planning of an attack are accomplished. Specifically, the aid should assist the TACCO in gaining attack criteria, and once they are gained, in formulating the optimal tactics for an attack on the hostile submarine. Such an aid will have five primary features:

- *automation of attack criteria* - the aid automatically interrogates the incoming sensor data and continuously compares these data to a set of predefined attack criteria. When attack criteria are gained the aid immediately notifies the TACCO,

- *optimization of attack tactics* - after attack criteria are gained, the aid suggests the optimal location and time for an attack on the target given the present location and motion capabilities of the submarine,

- *optimization of weapon selection* - for the attack to be placed, the aid suggests the type of weapon that should be used, and the optimal engagement setting for it,

- *interface to pilot and navigator* - if the TACCO accepts the attack tactics (i.e. location and time) suggested by the aid, or if he enters alternate tactics of his own selection, the aid calculates fly-to-points and provides steering (navigational) commands to the pilot, and

- *suggestion of tactics for gaining attack criteria* - prior to the attainment of attack criteria, the aid suggests to the TACCO, if asked, specific tactics (e.g. deploying passive sonobuoys, deploying active sonobuoys, implementing MAD search patterns) that could speed the process of gaining attack criteria.

The Attack Planning aid would thus be used to alert the aircrew when attack criteria have been gained, recommend optimum weapon settings, determine weapon placement, and provide aircraft navigation commands to deploy the weapon. The aid will be initiated by the TACCO when he feels he is approaching the attainment of attack criteria.

There are many factors which affect the way in which the aid will perform these functions. Acoustic sensor information would be utilized to assist the aid in determining the attainment of attack criteria, in recommending optimum weapon settings, and in specifying optimal weapon placement. Oceanographic conditions can have major impact on a weapon's ability to detect and acquire the target. Although ASW weapons have specified acquisition ranges, these ranges are based upon a unique oceanographic conditions. Variations in conditions will impact upon the acquisition range of the weapon. The attainment of attack criteria can also be affected in other ways by oceanographic conditions, particularly when the aircrew is attempting to prosecute the target via passive acoustic sensors and it is difficult to determine the exact distance between the target and a sonobuoy.

During Attack Planning, the target (submarine) will either be alerted to the presence of the aircraft (and thus be trying to avoid the attack), or will be unaware of the aircraft (and thus be proceeding on its mission). If the aircrew prosecutes with active sonobuoy sensors it can be assumed the target has been alerted and will attempt to avoid further prosecution; otherwise it can be assumed that the target is unaware of the ASW aircraft. Depending upon the tactical situation, time may be an important factor in the attack planning. If the aircraft is running low on fuel, if the aircraft is approaching the end of its on-station period, or if the submarine is closing to within weapons range of the friendly force it is especially critical to expedite the attack.

The attack planning aid will therefore utilize several inputs to produce the outputs listed above. It will require information on:

- Characteristics and capabilities of the ASW aircraft and its weapons,
- Estimated capabilities of the submarine being attacked,
- Atmospheric and oceanographic conditions in the region of the attack,
- Type, location, depth and setting of the deployed sonobuoys,
- History of the contact with the target being attacked, and
- Overall tactical situation, including fuel and time onstation remaining for the ASW aircraft, the relative location of any friendly areas threatened by the submarine, and the offensive capabilities of the submarine.

All of these inputs can be obtained from either a prestored database or from other computer programs in the ASW aircraft. A brief description of the specific techniques the aid uses to produce its outputs from these inputs is given below, in terms of the categories in the decision aiding technique taxonomy (Table 5-1).

5.2.1 Outcome Calculator

Some form of outcome calculator is needed to predict the results of a potential attack on the hostile submarine by the ASW aircraft. The high urgency ratings assigned to the decisions functions in the attack planning decision situation require the use of an highly responsive outcome calculator. The analysis of decision aiding techniques in the previous effort (see Zachary 1980: Section 3) found that only the probabilistic, closed-form analytic, or deterministic simulation types of outcome calculators can be considered as computationally fast. The possible types of outcome calculators are therefore restricted to these three.

A primary function the outcome calculator must serve in the Attack Planning decision aid is to assess the impact of the great number of uncertainties in the attack scenario on its likely result. There is uncertainty in the target's location, course, speed, and depth, in the performance of the weapons that can be used, and in the TACCO's information concerning the oceanographic condition. The outcome calculator must therefore be able to accomodate uncertainty in its inputs, and incorporate uncertainty in its outputs. Of the three types of calculators listed above, only probabilistic models meet this criterion.

The probabilistic outcome calculator for the attack planning decision aid should accept probabilistic characterizations of the target's location, course, depth, and speed, capabilities of attack weapons (i.e. the weapon's probability of kill or P_K), and oceanographic condition data. From those inputs, it should produce a single, probabilistic output representing the outcome of the attack -- a probability of submarine kill (P_K).

5.2.2 Value Model

There are three criteria that contribute to the desirability, or utility of a given attack plan. The most important is the overall P_K for the submarine. Also important, however, are the time required (from the start of attack planning) to complete the attack, and the impact of the attack plan on the weapons inventory. For example, if the ASW aircraft is low in fuel, then it will be more desirable to attack sooner, even it this may require acting with a slightly lower P_K. Alternatively, if the ASW aircraft is low on weapons but has adequate fuel remaining, it will be more desirable to wait to obtain the highest possible P_K. These three factors -- P_K, time, and weapons inventory -- have a complex interrelationsip, and a value model which accurately models the necessary tradoffs among them will necessarily be nonlinear. Therefore, the attack planning decision aid will employ a nonlinear value model to select among the possible attack plans.

5.2.3 Data Control

As with the mode selection decision aid, this aid will obtain most of its input information from other computer programs in the aircraft's avionics suite. Since little or no input information will come directly from sensor or operator input streams, no automatic aggregation/disaggregation is necessary. Since the aid will not require a large database, specialized information management facilities are not required. Thus, no special data control techniques are needed for this aid.

5.2.4 Analysis

Several types of analysis techniques will be used by this decision aid. The first will be an information processing algorithm which computes the steering and navigation commands necessary to implement the selected attack plan. This algorithm incorporates a model of the ASW aircraft's motion and maneuvering capabilities. It accepts as inputs the current location, course, altitude and speed of the aircraft and the desired course, altitude and speed at the weapon release point, as well as the desired time of weapon release. From these, it calculates the steering commands and fly-to-points which will allow the aircraft to successfully capture the weapon release point, and sends these to the navigator and pilot.

The second analysis feature of the aid is an optimization of the attack plan -- the calculation of the optimal weapon, setting, time, and location for the attack on the submarine. The constraints on such an optimization problem can not be expressed as prestored linear equations, because they will change with each situation. Therefore, linear programming cannot be used. The nature of the optimization is continuous (at least with regard to location of the attack) rather than combinatorial, so dynamic programming is also inappropriate. The optimization will have to proceed by "probing" the space of possible solutions and moving in the apparent direction of improvement at each probe. At each point in the solution space probes, the probabilistic outcome calculator and the nonlinear value model would be used together to determine the effectiveness of the attack plan represented by that point, and the slope of the goodness function in that 'neighborhood'. *This is a classic nonlinear programming* formulation. If analysis can demonstrate that the value functions will always be monomodal over the space of all possible solutions, then the simpler and more efficient optimization technique of Fibbonacci search may be used instead of nonlinear programming.

The third analysis feature of the aid will make use of another information processing algorithm to determine automatically the attainment of attack criteria. This algorithm will utilize a prestored set of attack criteria and compare them to calculated probability areas for the target. It will also consider possible effects of oceanographic conditions on the probability area calculations. The algorithm will operate in real time, constantly comparing the latest calculated target probability area to the prestored attack criteria. When the criteria are met, the algorithm will alert the TACCO.

5.2.5 Display/Entry

This aid will require both alphanumeric and graphic display techniques. Graphic displays are needed to present the geometry of the attack to the TACCO, pilot, and navigator. They will also be needed to present suggested sensor deployments which could speed the achievement of attack criteria (see Section 5.2.6). Other inputs and outputs can be treated adequately with alphanumeric display/entry techniques.

5.2.6 Human Judgement Refinement/Amplification

The outputs provided by the attack planning decision aid include suggested tactics which could speed the attainment of attack criteria. The technique of Adaptive Prediction is used to provide this type of analysis. The Adaptive Prediction algorithm would record the various tactics applied by the TACCO during the localization phase of the mission and analyze them according to their relative success or failure. From these observations and analysis, it would construct a model of the tactical approaches that had highest probability of success for further localizing the target at the current point in the mission. When the TACCO desires the aid to suggest tactics for attaining attack criteria, the algorithm will use its adaptively constructed model to select the tactic that is most in keeping with the TACCOs own inferred tactical preferences and that also has the highest probability increasing the degree of target localization.

6. CONCLUSIONS AND RECOMMENDATIONS

This effort has produced a number of significant results from both an applications and a methodological prespective. It has generated a methodology for analyzing and prioritizing complex decision spaces, which allows:

- the identification of the key dimensions along which experienced decision makers perceive decisions in a specific tactical area,
- the determination of the way in which other characteristics of the decision space, such as priority, are constructed from these key dimensions, and
- the construction of a mathematical function which assigns real-valued priority scores to decisions according to their location on each of the key dimensions.

The research has also produced substantial progress in the effort to apply decision-aiding technology to Naval Air ASW. In particular, it has resulted in:

- The identification of three dimensions -- degree of uncertainty, information processing load, and complexity of alternative structure -- which underlie experienced ASW TACCOs decisions,
- the numerical prioritization of six Air ASW decision situations and the fourteen decision functions from which they were constructed, for two types of Air ASW mission (with and without attack on the submarine), and
- the construction of high level decision aid designs for two of the decision situations with highest priority.

The prioritization methodology developed here (Figure 1-1), *priority mapping,* represents a new approach to the problem of prioritization. The priority mapping approach is based on two basic assumptions about decision making in general, and Air ASW decision making in particular. First, it assumes that any area of decision making is a complex multidimensional domain and that all of the underlying dimensions in this domain are potentially relevant to the priority of the decisions involved. Second, it assumes that the prioritization of a set of decisions must incorporate the intuition, and judgements knowledge about the priority of those decisions held by individuals experienced in making them.

The application of the Priority Mapping methodology to the prioritization of Naval Air ASW decision situations demonstrated its feasibility and soundness. The methodology produced a highly useful dimensionalization of the ASW decision space (Figure 3-1) as well as mission-sensitive prioritization of the six decisions situations identified in the previous effort (Tables 4-8 and 4-9).

The successful prioritization of the decision situations allowed the initial steps to be taken in the design of decision aids for the highest priority situations. An Optimal Mode-Selection decision aid was outlined for the Contact Classification/Verification situation (which achieved the highest priority for both types of ASW mission). This aid uses a dynamic programming algorithm and a multiattribute utility model together with computational algorithms for determining the probability of correctly identifying a signal from a particular target given a specific signal-processing modes and environmental conditions to help the TACCO or SENSO select an optimal mode of processing for his acoustical signal processing equipment (Section 5.1). A decision aid was outlined for the Attack Planning decision situation, which achieved the second highest priority for missions with attack. This aid uses a real-time information processing algorithm to automate the determination of attack criteria attainment. It subsequently uses a probabilistic model outcome calculator, a nonlinear value model, and a nonlinear programming algorithm to determine the tactics for the optimal attack that can be placed on the hostile submarine (Section 5.2).

This effort has developed and applied a new methodology for determining which decisions in a specific context should have priority for decisions aiding. It has also begun the design of decision aids for the two most critical decision situations by identifying the specific techniques that are most applicable to those situations. But even though the suggested mix of techniques may be the best possible for each situation, it is not certain that even their optimal application can materially increase the quality of the decisions made. The degree of uncertainty involved in the problems, the required response times, or other factors could impose such severe constraints that in practice, these decision problems can not be substantially aided. Further investigation is needed to demonstrate that the highest priority decisions are in fact amenable to aiding by the selected decision aiding approach.

The discussions with the experienced TACCOs at Moffett Field, however, indicated that additional consideration should be given to the potential impact of the overall aid design on the human operator. Many TACCOs expressed a view that "they were working for the computer, rather than the other way around," and were concerned that the introduction of additional automation into their workstation might further aggravate this situation. It is clear, though often unrecognized, that decision aids do not "by definition" reduce the operator's workload. An aid introduces new tasks that must be performed, and if in doing so it does not obviate others, the net effect can be a worsening of an already difficult situation for the operator.

The *potential* improvement in decision performance that may result from a candidate decision aid must be considered in conjunction with the importance of the decision being aided in determining whether the full development of that decision aid is truly warranted. It is therefore recommended that future efforts also be directed towards determining the possible inputs that these candidate and designs could have on the operator in those high priority decision situations.

APPENDIX A

TEXT OF INTRODUCTORY BRIEFING GIVEN TO P-3C TACCOS PRIOR TO MULTIDIMENSIONAL SCALING INTERVIEWS

A. TEXT OF INTRODUCTORY BRIEFING GIVEN TO P-3C TACCOS PRIOR TO MULTIDIMENSIONAL SCALING INTERVIEWS

I would like to begin by thanking you all for coming here today to help us in this effort. You've been asked to come here because of your familiarity with ASW and ASW decision making. Before we ask you some specific questions about ASW, I'd like to begin by providing a brief background on what it is that we mean by decision aids and decision aiding, what the overall structure of our program is, where we have been, and why we have come here to talk to you. As good a place as any to begin is with the definition of a decision aid.

Very simply put, a decision aid is any kind of device that helps humans make better, more efficient, clearer, and faster decisions. Now, obviously, a wide range of possible things can be considered decision aids -- from a pencil and a sheet of paper which enable you to do calculations to large computer systems and programs. What we're most interested in are specific tools that will enable you as a TACCO to interact with your on-board computer system to help you make the kinds of decisions that you have to make in the course of an ASW mission.

The Navy's interest in decision aiding has been increasing significantly recently because of the realization that warfare, in general, and ASW, in particular, is becoming more automated and more highly technological. The speed and complexity with which decisions must be made is increasing constantly to a point where, in the not too distant future, you as TACCOs, will be overloaded, possibly beyond your capability to make the necessary decisions within a reasonable amount of time. Therefore, the Navy is interested in developing computerized systems of decision aids that will help you keep pace with the increasing automation onboard your aircraft. It should be pointed out that these decision aids will not take you out of the decision making process or automate your functions. Rather, they will provide you with better, more intelligent support from machines and will give you time to do what you do best -- think and make decision. The whole concept of decision aiding is based on the notion that the most complex, useful, and important piece of equipment on any platform is the human brain. Humans are onboard to make decisions; but computers and other kinds of devices can assist by managing information, making certain kinds of data available at your finger-tips, helping you remember things (like the procedures you must go through to accomplish a specific function), performing certain kinds of calculations for you, and so forth.

There are some simple examples of decision aids currently on-board ASW platforms such as the P-3C and S-3A. For example, the tactics pattern matrix feature of the I4.4 program on the P-3C supports you, as the TACCO, in your selection and deployment of patterns of sonobuoys through a series of cues. The basic pattern is then constructed automatically by the computer. Another example is the project position function which automatically establishes and displays a past or future projection of a target position.

Some high level decision aiding is also available in the ESM gear. You, as a TACCO, can, for example, select up to 20 signals to be automatically displayed. Only the pre-selected signals will then be reported to you if they are identified by the automatic signal processing equipment. The PROTEUS system, which is soon to be incorporated to the P-3C, contains a number of decision aids of this same variety as does the PAD/C system for passive acoustical signal processing.

Decision aids can work at a variety of levels. Simple decision aids can, for example, provide very rudimentary bookkeeping functions or provide checklists of things that must be done. More complex decision aids can "ask" you the questions that you should be asking yourself. Still more complex decision aids can anticipate some of the information that you may want, based on your past performance; they can perform certain kinds of calculations automatically so that the results of the calculations will be available when requested; they can make certain kinds of inferences about what might happen in the future enabling you to play "what if" games to find out what results might be obtained if a specific course of action is undertaken. These latter things, which are at the higher end of the spectrum of the capabilities of decision aids, are the ones that we're most interested in.

To give you a feeling for the types of aids that are possible, I'd like to review some of the other decision aid projects of this type that are on going today in the Navy. The largest decision aiding effort to date has been undertaken by the Office of Naval Research. Their program has concentrated on developing a variety of decision aids for carrier-based air strike operations. Some of the specific problems to be addressed by these decision aids are: planning the ingress route for an incoming carrier-based air strike or reconnaissance mission through a complex sensor field; determining the specific timing of alpha type air strikes; task force EMCOM planning; and overall air strike campaign planning. The decision aids being developed by ONR are very high level decision aids, both in the sense that they provide a great deal of assistance to the human and in the sense that they deal with very high level command and control decisions (at the task force commander level or higher).

More germaine to our discussion today is the effort that we have undertaken under the joint sponsorship of the Naval Air Development Center and the Office of Naval Research to identify possible decision aids for on-platform ASW operations. I'd like to review some of the earlier parts of this effort to clarify why we are here today.

We began our effort by looking at the ASW platforms that will be in use in the 1980-1985 timeframe -- the P-3C, the S-3A, and the LAMPS MK-III. We examined the specific missions that are undertaken by these three platforms in order to define a generic or generalized ASW mission, to identify commonalities

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in the missions flown by the three platforms, and to identify some fo the critical differences both in crew functions and in the details of the missions that were undertaken. We then constructed this flowchart* of the sequence of operations that takes place in the generalized mission. The mission was subdivided into very broad categories -- movement to the search area, on-station search, prosecution of the contract, possibly culminating in attack and destruction of a hostile submarine. These stages were then subdivided into the detailed steps that involved specific decisions about classification, and extension of search area, and anticipation of target movement. We identified the specific sequences in which these decisions were made, recognizing that the interrelations between these decisions are highly dependent on the sequential nature of the ASW mission. The decisions that take place in the attack phase, for example, are dependent upon the successful completion of those portions of the mission that relate to search and early prosecution of a contact. Ultimately, we identified six broad areas that we termed decision making situations. We defined a decision making situation as a portion of a mission in which a complex sequence of decisions has to be made by the TACCO. These situations were complex because they involved trading off a number of factors against one another. The six decision situations were:**

(1) On-Station Search,

(2) Contact Classification/Verification,

(3) Target Localization,

(4) Surveillance Tracking,

(5) Lost Contact Reacquisition, and

(6) Attacking Planning.

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*Figure A-1 displayed at this point.

**Figure A-1 removed, and Figure A-2 displayed at this point.

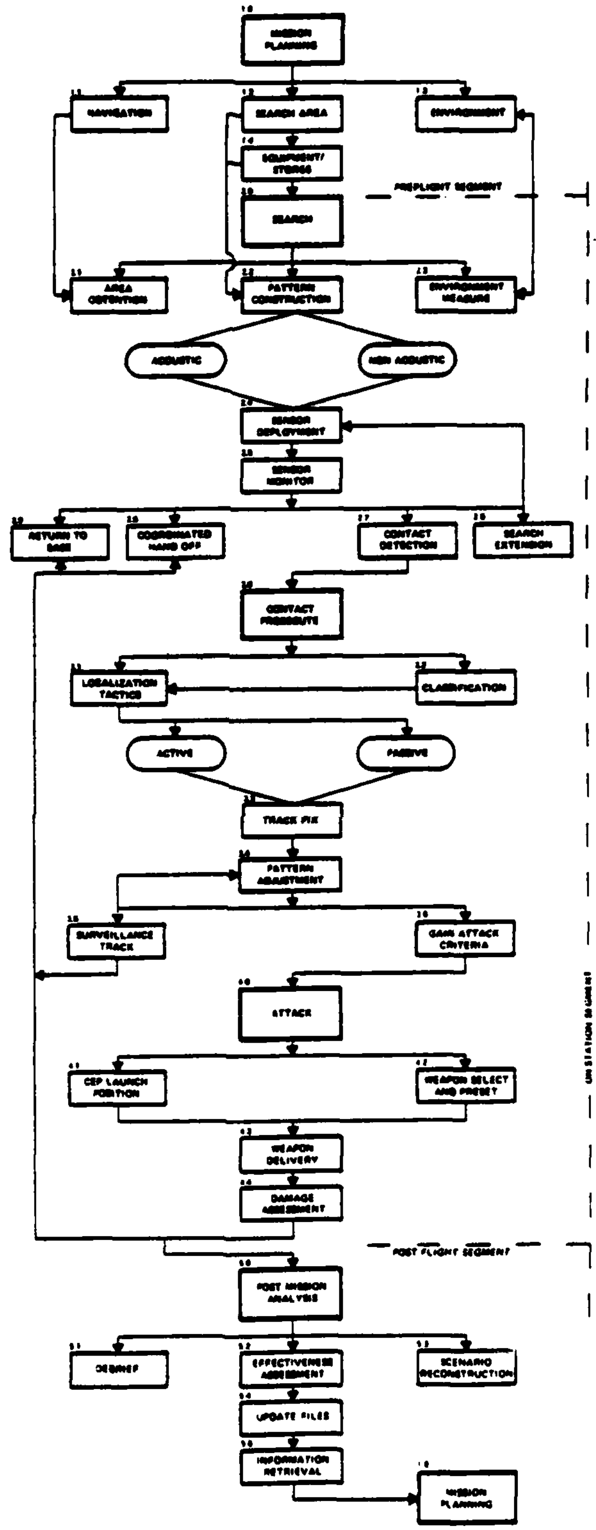

Figure A-1. Air ASW Mission Flow Vugraph

ASW PROBLEM-SOLVING DECISION SITUATIONS

- ON-STATION SEARCH
- CONTACT/CLASSIFICATION VERIFICATION
- CONTACT LOCALIZATION
- LOST CONTACT REACQUISITION
- SURVEILLANCE TRACK
- ATTACK PLANNING

Figure A-2. "ASW Problem Solving Decision Situations" Vugraph

The next issue we addressed in our program was the relative priority of each of these situations. By prioritizing the decision situations, we felt that we could determine which situation could most benefit from decision aiding. But we were immediately confronted by the problem that there was no single dimension, or criteria, by which we could prioritize the decision situations. They obviously are influenced by their sequence in the mission. They are also influenced by varying time constraints on the decisions that must be made in each situation and how busy the TACCO is in each situation. The more we thought about it, the more different criteria for prioritization we were able to define. It became clear to us that one of the problems was that we, as analysts, could not determine the prioritization. We decided that the only way to determine the specific criteria that were relevant to the prioritization of these decisions was to ask the people who made these kinds of decisions, people such as yourselves. That is why we are here today. We want to determine how the various decisions that you, as TACCOs make, should be prioritized. To do this, we have to determine the dimensions or criteria by which these decisions are interrelated in your minds. Then we have to determine the importance or priority of these decisions in a mission.

There are a number of techniques that can be used to do this. One way would be to ask you, in very lengthy and detailed discussions, to try to identify the dimensions which are salient to ASW decision making for you. But besides taking a lot of your time, it is not clear that that technique would work. People are often very unclear about the underlying principles they use to think about common, everyday things, like decision making. In addition, we would have the problem of resolving the differences we encountered between the various people we talked to. So instead, we have decided to use a more formal mathematical technique known as multidimensional scaling which will take less of your time and will enable us to determine both the dimensions and the relative importance of the various decisions from the same set of data. Multidimensional scaling uses the computer program to calculate the dimensions from very simple judgements made by you about the basic similarity or difference among these various decisions. We also decided that we wanted to address not just the broad analytic categories that we have called decision situations, but more precise, meaningful, specific decisions that are made by TACCOs. We identified 14 of these decisions, many of which occur in several of the decision situations. There are, of course, many more decisions that are made in the course of a mission but the 14 decisions that we chose were ones that appeared in more than a single decision situation or ones that seemed particularly amenable to decision aiding. The 14 decisions that we have chosen are shown in this vugraph.*

You have in front of you a set of cards.** Each card describes one of these decisions. We're going to ask you to make judgments about which decisions you feel are similar or dissimilar, and to rank them by various criteria. The results of these judged similarities and rankings will be used by the multidimensional scaling process to mathematically determine a set of relationships between these decisions that will help us in prioritizing them. It will also help us to understand the kinds of distinctions that you find most relevant among these various decisions. But, most importantly, we feel it will enable us to relate our analysis in a concrete way to your knowledge, experience, and intuition of the ASW mission. With your help, we will be able to determine the best places to apply decision aiding techniques in the ASW mission.

I'd like to add one other note about the way in which you should sort and rank these decision functions in later portions of this procedure. Do not sort or rank the decisions in terms of how you think a decision aid could help you make these decision nor in terms of how you think they could be made better, but rather in terms of how you currently go about making these decisions and how they currently are handled on the platforms on which you have worked.

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*Figure A-2 removed at this point, and Figure A-3 displayed and left on screen throughout the remainder of the procedures.

**Card-packs describing the 14 decision functions passed out to interviewees at this point.

DECISION FUNCTIONS PERFORMED BY THE TACCO

- CREATE SENSOR PATTERN
- CONSTRUCT SENSOR MONITORING PATTERN
- COMPENSATE FOR ACOUSTIC/ATMOSPHERIC PROPAGATION CONDITIONS
- ADJUST PATTERN TO SENSOR FAILURE
- DETERMINE SIGNAL IS A VALID CONTACT
- CLASSIFY SIGNAL
- MANAGE EQUIPMENT/STORES TO ACCOMMODATE PRESENT AND FUTURE NEEDS
- EXTEND SENSOR PATTERN
- ANTICIPATE TARGET MOVEMENT
- DETERMINE TARGET FIX
- GAIN ATTACK CRITERIA
- DETERMINE AIRCRAFT ATTACK LAUNCH POSITION
- DETERMINE WEAPON AND SETTING FOR ATTACK
- COORDINATE HAND-OFF

Figure A-3. "Decision Functions Performed by the TACCO" Vugraph

APPENDIX B

RESPONSE FORMS FOR MULTIDIMENSIONAL SCALING INTERVIEWS

B. RESPONSE FORMS FOR MULTIDIMENSIONAL SCALING INTERVIEWS

This appendix contains the forms on which the TACCO's interviewed at Moffett Field recorded the results of the unconstrained sorting and four rankings. All of the pages in the appendix were given to each interviewee as a stapled packet. The first page was used to record some general biographical information on the respondent. This information was used in grouping the unconstrained sorting responses for subgroup comparisions (see Section 3.3). The next two pages provided the instructions and response sheet for the unconstrained sorting of the ASW decisions. The remaining pages provided the instructions and response forms for four different rankings of the fourteen decisions.

BIOGRAPHICAL INFORMATION

Aircraft Type: ____________________

Rank/Designator: ____________________

Organization: ____________________

Date TACCO Designation: ____________________

Date Mission Commander (if applicable): ____________________

Deployment Locations as TACCO (and dates): ____________________

____

____

____

INSTRUCTIONS FOR THE 'SORTING' TASK

You have been given a pack of fourteen yellow cards. On each of these cards is a decision or problem that is encountered in an ASW mission. You have all probably faced these problems many times in your experience as TACCOs. Each decision is in some way different from all the others, but each decision is not totally unique; some of the decisions are more alike than others. What we would like you to do is arrange these decisions and problems into groups according to how similar they are. That is, if there are a number of cards which represent decisions or problems you feel that, based on your experience, are similar, then place all these cards together. If there is a card which you think is sufficiently unique that it isn't similar to any of the others, then place it in a group by itself. There is no limit on the number of groups you can make or on the number of cards you can place in each group. While the final definition of what constitutes similar decisions is left to you, we would like you to think of it as referring to decisions or problems which you somehow solve in the same way or which place similar demands on you as a TACCO.

INSTRUCTIONS: Record each group of decisions you have formed on a separate block below. Take one group and write the code for the decisions in it on the blank line provided. Then do the same for another group in the next block until each group has been recorded in a separate block. If you wish, you may also include a short phrase describing the similarity you saw in that group of decisions.

GROUP ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

GROUP ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

GROUP ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

GROUP ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

GROUP ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

GROUP ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

GROUP ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___ ___

INSTRUCTIONS FOR RANKING 1

We would now like you to rank these decision problems in the order in which a less-than-optimal decision would have the most detrimental effect on the mission. The decision problem for which a less-than-optimal decision would have the least detrimental impact on the mission should be ranked last, and the decision problem for which a less-than-optimal decision would have the greatest detrimental impact on the mission should be ranked first. For the mission, assume that it is an ASW mission in which the submarine is to be attacked and destroyed if possible.

INSTRUCTIONS. Enter the two-letter codes for the decisions below in the order in which you ranked them. That is, write the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. _____

2. _____

3. _____

4. _____

5. _____

6. _____

7. _____

8. _____

9. _____

10. _____

11. _____

12. _____

13. _____

14. _____

INSTRUCTIONS FOR RANKING 2

Rank the decisions according to the same criterion as in the previous case, but for the mission, assume an ASW mission in which the submarine is only to be tracked and handed-off to a relief platform.

INSTRUCTIONS. Enter the two-letter codes for the decisions below in the order in which you ranked them. That is, write the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. _____

2. _____

3. _____

4. _____

5. _____

6. _____

7. _____

8. _____

9. _____

10. _____

11. _____

12. _____

13. _____

14. _____

INSTRUCTIONS FOR RANKING 3

Rank the decisions according to their urgency. Define urgency as referring to the speed with which the decision has to be made once you know it must be made.

INSTRUCTIONS. Enter the two-letter codes for the decisions below in the order in which you ranked them. That is, write the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. _____

2. _____

3. _____

4. _____

5. _____

6. _____

7. _____

8. _____

9. _____

10. _____

11. _____

12. _____

13. _____

14. _____

INSTRUCTION FOR RANKING 4

Rank these decisions according to your workload during each of them. Consider both your cognitive, or mental workload and your physical workload in ranking the decisions. Rank the decision during which your workload is heaviest first, and the one during which your workload is least heavy last.

INSTRUCTIONS. Enter the two-letter codes for the decisions below in the order in which you ranked them. That is, write the code for the decision you ranked first next to '1.', for the decision you ranked second next to '2.' and so on.

1. _____

2. _____

3. _____

4. _____

5. _____

6. _____

7. _____

8. _____

9. _____

10. _____

11. _____

12. _____

13. _____

14. _____

APPENDIX C

RESULTS OF UNCONSTRAINED SORTINGS OF ASW DECISIONS

C. RESULTS OF UNCONSTRAINED SORTINGS OF ASW DECISIONS

This appendix presents the results of unconstrained sortings of fourteen air ASW decisions by 32 P-3C Tactical Coordinators (TACCOs) stationed at NAS, Moffett Field. The sortings were performed as part of interviews conducted at Moffett Field between 10 December 1979 and 14 December 1979. The full interview procedure is described in Section 2 of this report.

The fourteen decisions that were sorted are shown in Table C-1. The instructions for the sorting task, and a sample of the form on which the results were recorded, are given in Appendix B. Because one of the interviewees apparently misunderstood the instructions and gererated an unusable sorting, results for only 31 sortings are presented here.

Each sorting is presented as several lists of decisions. All the decisions on each list were placed into a group by the indicated individual. In the lists, each decision function is identified only by a two-letter code. The code used for each decision is also given in Table C-1. The order in which the individuals are listed below is arbitrary, but it corresponds to the order in which they are listed in Appendix D, where the ranking results are presented.

Table C-1. Fourteen ASW Decision Functions and Alphabetic Codes

CODE	DECISION FUNCTION
AP	ADJUST PATTERN TO SENSOR FAILURE
EP	EXTEND SENSOR PATTERN
AM	ANTICIPATE TARGET MOVEMENT
MP	CONSTRUCT SENSOR MONITORING PATTERN
CH	COORDINATE HAND-OFF
VC	DETERMINE SIGNAL IS A VALID CONTACT
DS	DETERMINE WEAPON AND SETTING FOR ATTACK
AC	GAIN ATTACK CRITERIA
TF	DETERMINE TARGET FIX
CP	CREATE SENSOR PATTERN
ME	MANAGE EQUIPMENT/STORES TO ACCOMODATE PRESENT AND FUTURE NEEDS
CS	CLASSIFY SIGNAL
PC	COMPENSATE FOR IN SITU ACOUSTICAL AND ATMOSPHERIC PROPAGATION CONDITIONS
LP	DETERMINE AIRCRAFT LAUNCH POSITION FOR ATTACK ON TARGET

INDIVIDUAL 1

GROUP	DECISION FUNCTIONS IN GROUP
1	PC,CP,MP,AP,ME
2	CS,VC
3	AM,EP,TF
4	AC,DS,LP
5	CH

INDIVIDUAL 2

GROUP	DECISION FUNCTIONS IN GROUP
1	CS,VC
2	PC
3	ME,MP
4	AP,CP,EP
5	TF,AC,LP,AM,DS
6	CH

INDIVIDUAL 3

GROUP	DECISION FUNCTIONS IN GROUP
1	DP,ME,AM,MP
2	VC,CS
3	AC,LP,DS,PC,EP,AP,TF
4	CH

INDIVIDUAL 4

GROUP	DECISION FUNCTIONS IN GROUP
1	CP,EP,AP
2	CH
3	ME
4	VC,PC
5	CS
6	MP,LP
7	AC,AM,DS,TF

INDIVIDUAL 5

GROUP	DECISION FUNCTIONS IN GROUP
1	AP,CP,PC,EP,MP
2	CH
3	TF,AM,AC
4	CS,VC
5	ME
6	DS
7	LP

INDIVIDUAL 6

GROUP	DECISION FUNCTIONS IN GROUP
1	ME,CP,MP,PC,AP,EP
2	CS,VC
3	TF,AM,AC,DS,LP,CH

INDIVIDUAL 7

GROUP	DECISION FUNCTIONS IN GROUP
1	TF,AM,AC,DS,LP
2	CS,VC
3	PC,CP,EP,AP,MP
4	ME
5	CH

INDIVIDUAL 8

GROUP	DECISION FUNCTIONS IN GROUP
1	CP,PC,MP,AP,EP
2	VC,CS
3	TF,AM,AC
4	DS,LP
5	CH

INDIVIDUAL 9

GROUP	DECISION FUNCTIONS IN GROUP
1	VC,CS
2	MP,CP
3	AP,EP,PC
4	AC,AM,LP,TF,DS
5	ME,CH

INDIVIDUAL 10

GROUP	DECISION FUNCTIONS IN GROUP
1	CS,VC
2	AP,EP,MP,PC,CP
3	ME
4	CH
5	DS,LP,AM,TF,AC

INDIVIDUAL 11

GROUP	DECISION FUNCTIONS IN GROUP
1	CP
2	PC,EP,ME
3	AP,MP
4	CS,VC,TF,AM
5	AC,DS,LP
6	CH

INDIVIDUAL 12

GROUP	DECISION FUNCTIONS IN GROUP
1	CP,EP
2	MP,PC,ME,AP
3	CS,VC
4	TF,AM
5	AC,DS,LP
6	CH

INDIVIDUAL 13

GROUP	DECISION FUNCTIONS IN GROUP
1	CP,PC,MP,ME
2	AP,EP,AM
3	AC,DS,LP
4	VC,CS,TF
5	CH

INDIVIDUAL 14

GROUP	DECISION FUNCTIONS IN GROUP
1	ME
2	VC,CS,CH
3	PC,CP,EP,AP,MP
4	TF,AM,AC,LP,DS

INDIVIDUAL 15

GROUP	DECISION FUNCTIONS IN GROUP
1	CH
2	CS,VC
3	AM,TF,DS,LP,AC
4	CP,MP,EP,ME,AP,PC

INDIVIDUAL 16

GROUP	DECISION FUNCTIONS IN GROUP
1	CP,MP, EP,AP,PC
2	ME
3	CS,VC
4	TF,AM, AC
5	LP,DS
6	CH

INDIVIDUAL 17

GROUP	DECISION FUNCTIONS IN GROUP
1	VC,CS
2	TF,AM
3	CP,MP,EP,AP,PC
4	CH
5	DS,AC,LP
6	ME

INDIVIDUAL 18

GROUP	DECISION FUNCTIONS IN GROUP
1	TF,AM,LP,AC
2	CP,ME,PC,MP,EP,AP
3	CS,VC
4	DS
5	CH

INDIVIDUAL 19

GROUP	DECISION FUNCTIONS IN GROUP
1	EP,MP,PC,CP,ME,AP
2	VC,CS
3	TF,AM,AC,DS,LP
4	CH

INDIVIDUAL 20

GROUP	DECISION FUNCTIONS IN GROUP
1	PC,MP,CP,AP,EP
2	ME
3	VC,CS
4	AM,TF
5	LP,AC,DS
6	CH

INDIVIDUAL 21

GROUP	DECISION FUNCTIONS IN GROUP
1	ME,PC,CP
2	AP,MP,EP
3	VC,CS
4	AM,TF,AC
5	DS,LP
6	CH

INDIVIDUAL 22

GROUP	DECISION FUNCTIONS IN GROUP
1	AM,EP
2	TF
3	ME,CH
4	VC,CS
5	PC,DP,DS
6	AC
7	LP
8	AP,MP

INDIVIDUAL 23

GROUP	DECISION FUNCTIONS IN GROUP
1	TF,AC,AM,LP,DS
2	MP,ME,AP
3	CP,EP
4	CS,VC,PC
5	CH

INDIVIDUAL 24

GROUP	DECISION FUNCTIONS IN GROUP
1	LP,DS
2	CH
3	AM,TF,AC
4	EP,CP,PC
5	VC,CS
6	AP,ME
7	MP

INDIVIDUAL 25

GROUP	DECISION FUNCTIONS IN GROUP
1	CH
2	VC,CS
3	TF,AC
4	AM,DS,LP
5	AP,EP,ME,PC,MP,CP

INDIVIDUAL 26

GROUP	DECISION FUNCTIONS IN GROUP
1	PC,CP,MP,EP,AM,TF,AC
2	ME,AP,DS,CH
3	CS,VC
4	LP

INDIVIDUAL 27

GROUP	DECISION FUNCTIONS IN GROUP
1	CP,EP,MP,PC,AP
2	ME
3	CS,VC
4	AM
5	TF
6	CH
7	AC,DS,LP

INDIVIDUAL 28

GROUP	DECISION FUNCTIONS IN GROUP
1	ME,CP,MP,PC,AP,EP
2	CS,VC
3	AC,DS,LP,AM,TF
4	CH

INDIVIDUAL 29

GROUP	DECISION FUNCTIONS IN GROUP
1	PC,CP,AP,MP,EP
2	CS,VC,TF
3	ME
4	LP,DS,AC,AM
5	CH

INDIVIDUAL 30

GROUP	DECISION FUNCTIONS IN GROUP
1	ME,CP,PC,AP,MP,EP
2	VC,CS
3	AM,TF,AC
4	DS,LP
5	CH

INDIVIDUAL 31

GROUP	DECISION FUNCTIONS IN GROUP
1	CP,PC,MP,ME,EP,AP
2	CS,VC
3	CH
4	LP,AM,TF,AC
5	DS

APPENDIX D

RESULTS OF RANKINGS OF ASW DECISIONS

D. RESULTS OF RANKINGS OF ASW DECISIONS

This appendix presents the results of rankings of fourteen Air ASW decisions (listed in Table C-1) by 32 TACCOs from NAS Moffett Field. These rankings were performed as part of the interview described in Section 2. The fourteen decisions were ranked according to four different criteria. The instructions for these rankings and the forms on which the results were recorded are given in Appendix B. The first ranking was done according to the perceived *importance* of the decision in a mission where the objective is to *attack* and destroy the hostile submarine. The second ranking was done according to the perceived *importance* of the decision function in a mission where the objective is to survey the submarine only. The third ranking was done according to the preceived *urgency* of the decisions in whatever type of mission gave them the greatest urgency. The fourth ranking was done according to the TACCO's perceived *workload* (both cognitive and physical) during each of the fourteen decision functions.

The results of these four rankings are given below. The ranking generated by each individual using each criteria is presented as a list of the two-letter codes used in the interviews to represent the decision functions. Table C-1 (in Appendix C) contains the full decision name represented by each two-letter code. The order in which the individuals are listed is arbitrary, but is the same for all four rankings, and corresponds to the order in which the unconstrained sortings are presented in Appendix C. The single individual omitted in Appendix C is individual number eight here. Thus, individual numbers one through seven refer to the same person in appendix C as in this appendix, but individual numbers eight through thirty-one in appendix C correspond to individual numbers nine through thirty-two (respectively) in this appendix.

RANKING 1

CRITERION: IMPORTANCE TO MISSION WITH ATTACK ON SUBMARINE

INDIVIDUAL NUMBER	DECISION FUNCTION GIVEN RANK OF:													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	PC	CP	ME	CS	TF	AM	AC	DS	LP	VC	AP	EP	MP	CH
2	CS	VC	TF	AC	AM	CH	PC	DS	LP	EP	CP	MP	ME	AP
3	AM	CP	MP	PC	CS	AP	TF	EP	AC	DS	LP	VC	ME	CH
4	LP	AC	CS	VC	TF	DS	CP	AM	PC	MP	ME	EP	AP	CH
5	CS	VC	CP	PC	TF	AM	AC	ME	DS	EP	MP	AP	LP	CH
6	ME	VC	CS	TF	AC	DS	LP	AM	CP	MP	PC	AP	EP	CH
7	CS	AC	DS	CP	TF	LP	PC	EP	AP	VC	MP	AM	ME	CH
8	CS	VC	AC	AM	CP	PC	TF	DS	LP	MP	AP	EP	ME	CH
9	CS	VC	TF	AM	AC	EP	AP	ME	MP	PC	DS	LP	CP	CH
10	VC	CS	TF	AC	DS	LP	AM	PC	MP	CP	EP	AP	ME	CH
11	CS	VC	TF	AC	CH	CP	EP	AM	ME	AP	PC	MP	LP	DS
12	CS	DS	LP	AC	TF	VC	AM	MP	AP	PC	EP	CP	ME	CH
13	CP	PC	EP	TF	AM	VC	CS	DS	AC	LP	AP	MP	ME	CH
14	CP	LP	AC	DS	MP	TF	PC	CS	EP	AM	AP	VC	CH	ME
15	CS	VC	TF	AM	LP	AC	ME	PC	CP	MP	DS	AP	EP	CH
16	AC	LP	PC	CP	TF	ME	EP	AM	AP	MP	DS	CS	VC	CH
17	LP	AC	CP	AM	CS	TF	DS	PC	VC	ME	AP	MP	EP	CH
18	AC	LP	DS	TF	AM	CS	VC	CP	PC	MP	EP	AP	ME	CH
19	ME	CS	VC	TF	AC	AM	LP	CP	AP	EP	MP	PC	DS	CH
20	CP	CS	VC	MP	TF	AM	AC	DS	LP	AP	PC	EP	ME	CH
21	LP	DS	AC	AM	CH	TF	EP	AP	ME	CP	MP	PC	CS	VC
22	CP	VC	CS	DS	LP	AM	TF	AC	MP	EP	PC	ME	AP	CH
23	VC	CS	AC	AM	TF	DS	EP	LP	CH	PC	CP	AP	ME	MP
24	CS	LP	DS	AC	TF	AM	CP	PC	EP	MP	ME	VC	AP	CH
25	CS	VC	AC	CH	LP	TF	AM	ME	DS	EP	MP	AP	CP	PC
26	CS	CP	TF	AC	LP	AM	DS	AP	ME	VC	EP	MP	CH	PC
27	PC	CP	MP	ME	CS	VC	TF	AC	DS	LP	AP	EP	AM	CH
28	LP	AC	DS	TF	AM	CS	VC	MP	AP	PC	CP	EP	CH	ME
29	CS	AC	DS	LP	CP	AP	EP	ME	TF	MP	VC	AM	PC	CH
30	CS	VC	CP	TF	AC	AM	ME	PC	CP	AP	DS	MP	EP	CH
31	AC	LP	DS	ME	CP	CS	TF	AM	MP	AP	EP	PC	VC	CH
32	AC	LP	TF	DS	AM	PC	CP	ME	CS	VC	MP	EP	AP	CH

RANKING 2

CRITERION: IMPORTANCE TO MISSION WITH TRACKING OF SUBMARINE BUT NO ATTACK

INDIVIDUAL NUMBER	DECISION FUNCTION GIVEN RANK OF:													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	PC	CP	ME	CS	TF	AM	CH	VC	AP	EP	MP	AC	DS	LP
2	CS	VC	TF	AM	CH	PC	ME	EP	CP	MP	AP	AC	DS	LP
3	AM	CP	MP	PC	CS	AP	TF	CH	EP	ME	VC	AC	DS	LP
4	CS	TF	AM	VC	CH	ME	CP	AP	AC	DS	LP	PC	EP	MP
5	CS	VC	CP	PC	TF	AM	CH	ME	EP	MP	AP	AC	LP	DS
6	ME	VC	CS	TF	AM	CP	MP	PC	AP	EP	CH	AC	DS	LP
7	CS	CP	TF	CH	PC	EP	AM	AP	VC	MP	AC	DS	LP	ME
8	CS	VC	AC	CH	AM	CP	PC	TF	DS	LP	MP	AP	EP	ME
9	CS	VC	TF	AM	AC	CH	EP	AP	ME	PC	MP	DS	LP	CP
10	VC	CS	TF	AM	CH	PC	MP	CP	EP	AP	ME	AC	LP	DS
11	CS	VC	CH	CP	EP	AM	ME	AP	PC	MP	TF	LP	DS	AC
12	CH	CS	VC	AM	TF	MP	PC	EP	ME	CP	LP	DS	AC	DS
13	CP	EP	PC	TF	AM	VC	CS	CH	AP	MP	ME	AC	DS	LP
14	CP	MP	PC	VC	CS	EP	AP	ME	AM	TF	CH	LP	AC	DS
15	CH	CS	VC	ME	CP	EP	PC	MP	AP	TF	AM	LP	AC	DS
16	CP	ME	EP	PC	AM	MP	AP	AC	TF	CH	VC	CS	LP	DS
17	CP	TF	AM	CH	CS	PC	AP	MP	VC	ME	EP	AC	DS	LP
18	TF	AM	CH	CS	VC	CP	PC	MP	EP	AP	ME	AC	LP	DS
19	ME	CP	AP	EP	MP	CS	VC	TF	AM	CH	LP	DS	PC	AC
20	CP	CS	VC	MP	TF	AM	AC	DS	CH	LP	AP	PC	EP	ME
21	CP	AM	CH	TF	EP	AP	ME	MP	VC	CS	PC	AC	DS	LP
22	CP	VC	CS	CH	AM	TF	MP	EP	PC	ME	AP	AC	LP	DS
23	VC	CS	AM	TF	CH	EP	PC	CP	AP	ME	MP	AC	DS	LP
24	CS	CH	AC	AM	TF	ME	AP	PC	CP	MP	EP	VC	LP	DS
25	CS	VC	CH	ME	AM	EP	AP	CP	PC	MP	TF	AC	DS	LP
26	CS	CP	TF	AC	AM	CH	ME	PC	EP	MP	VC	AP	LP	DS
27	PC	CP	MP	ME	CS	VC	AP	CH	AM	EP	TF	AC	LP	DS
28	CH	AM	TF	CS	VC	MP	AP	PC	CP	EP	ME	AC	DS	LP
29	CS	TF	AM	CH	CP	AP	EP	ME	MP	VC	PC	AC	DS	LP
30	CS	VC	CP	TF	CH	ME	PC	AM	AP	MP	EP	AC	LP	DS
31	CH	ME	CP	CS	TF	AM	MP	EP	AP	PC	VC	AC	DS	LP
32	TF	AM	ME	PC	CS	VC	CH	EP	MP	CP	AP	LP	AC	DS

RANKING 3

CRITERION: URGENCY OF THE DECISION FUNCTION WHEN IT ARISES IN A MISSION

INDIVIDUAL NUMBER	DECISION FUNCTION GIVEN RANK OF:													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	CS	TF	AM	AC	DS	LP	EP	AP	VC	CP	ME	PC	MP	CH
2	AP	LP	AM	TF	AC	PC	VC	ME	DS	CS	CH	CP	EP	MP
3	LP	DS	AP	AM	TF	EP	AC	ME	VC	CS	CP	PC	MP	CH
4	LP	AC	DS	VC	CS	TF	AM	AP	CP	PC	ME	CH	EP	MP
5	LP	AC	CH	DS	CP	AM	TF	ME	VC	CS	AP	PC	MP	EP
6	LP	AC	DS	VC	CS	TF	AM	ME	PC	MP	CP	CH	AP	EP
7	AC	DS	LP	CS	VC	AP	PC	CP	TF	CH	EP	AM	MP	ME
8	AC	LP	VC	TF	AM	CS	AP	DS	ME	PC	CP	MP	CH	EP
9	LP	DS	AC	AM	TF	CP	ME	EP	VC	CS	CH	AP	MP	PC
10	AC	DS	LP	TF	AM	PC	AP	CP	MP	EP	VC	CS	CH	ME
11	LP	DS	AM	VC	AC	CH	CS	ME	EP	AP	TF	PC	MP	CP
12	AC	LP	CS	VC	TF	AM	DS	CP	PC	EP	MP	AP	ME	CH
13	AC	LP	DS	AM	VC	CS	TF	CH	AP	ME	MP	EP	PC	CP
14	LP	AC	TF	DS	AM	AP	VC	CS	EP	ME	CH	PC	MP	CP
15	CS	VC	TF	AM	LP	AC	ME	CH	DS	PC	CP	EP	MP	AP
16	LP	AC	TF	DS	ME	PC	AM	AP	EP	MP	CP	CH	VC	CS
17	LP	DS	AC	CS	AM	TF	VC	CP	ME	EP	CH	PC	AP	MP
18	AC	LP	DS	PC	ME	TF	CP	AM	CS	VC	CH	AP	MP	EP
19	ME	DS	LP	AC	AM	TF	VC	CS	AP	MP	EP	CP	CH	PC
20	CS	VC	AM	AC	LP	PC	TF	CP	MP	ME	EP	AP	DS	CH
21	DS	LP	ME	AP	EP	AC	PC	AM	CH	TF	CS	VC	CP	MP
22	AC	DS	LP	TF	AM	VC	CS	ME	CH	EP	AP	CP	MP	PC
23	TF	AM	LP	AC	VC	CS	DS	ME	EP	AP	PC	CP	CH	MP
24	LP	AC	TF	AM	DS	AP	ME	VC	CS	CP	MP	EP	PC	CH
25	LP	DS	AC	VC	CS	CH	TF	EP	AM	AP	ME	CP	MP	PC
26	AC	LP	DS	VC	AM	CS	TF	ME	CH	PC	EP	AP	MP	CP
27	ME	DS	AC	LP	AP	TF	VC	CS	AM	EP	CH	MP	CP	PC
28	AC	AM	TF	CS	VC	LP	DS	MP	AP	PC	CP	EP	CH	ME
29	AM	TF	AC	DS	LP	CS	VC	ME	MP	EP	AP	CP	CH	PC
30	VC	CP	DS	AM	ME	PC	AP	AC	TF	CH	CS	CP	EP	MP
31	ME	PC	CP	MP	AP	EP	AM	LP	DS	CS	VC	AC	TF	CH
32	AC	LP	AP	ME	CP	AM	TF	PC	EP	CS	VC	DS	CH	MP

RANKING 4

CRITERION: WORKLOAD OF TACCO DURING DECISION FUNCTION

INDIVIDUAL NUMBER	DECISION FUNCTION GIVEN RANK OF:													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	TF	AC	LP	DS	AM	ME	CH	AP	EP	CP	MP	CS	VC	PC
2	AP	TF	LP	AM	AC	CH	VC	ME	DS	CP	EP	MP	PC	CS
3	LP	AC	DS	AP	EP	AM	TF	CP	CH	ME	MP	CS	VC	PC
4	DS	LP	AC	CH	VC	CS	TF	AM	CP	PC	ME	AP	MP	EP
5	CH	CP	ME	LP	AC	AM	DS	TF	PC	MP	AP	EP	VC	CS
6	ME	LP	DS	AC	PC	VC	CS	CP	MP	CH	AM	TF	AP	EP
7	CH	AC	DS	TF	PC	LP	AM	CP	EP	MP	AP	CS	VC	ME
8	LP	AM	AC	VC	TF	DS	CH	CS	AP	ME	PC	EP	MP	CP
9	AM	AC	TF	DS	LP	VC	CS	CP	EP	ME	PC	AP	MP	CH
10	CH	ME	LP	AC	DS	AM	TF	AP	MP	CP	EP	PC	CS	VC
11	CH	DS	LP	AC	AM	VC	AP	ME	TF	CS	EP	PC	MP	CP
12	CH	AC	TF	AM	CS	VC	PC	LP	MP	EP	AP	DS	ME	CP
13	AC	LP	DS	CH	AM	TF	CS	VC	ME	AP	MP	EP	PC	CP
14	LP	ME	CH	TF	DS	AC	MP	CP	AM	PC	EP	AP	VC	CS
15	ME	CH	TF	AM	PC	CP	MP	AC	EP	AP	CS	VC	LP	DS
16	AC	LP	PC	ME	TF	AP	DS	AM	EP	MP	CH	VC	CP	CS
17	LP	DS	AC	AM	TF	CH	ME	CS	VC	CP	PC	EP	MP	AP
18	CP	PC	ME	EP	CH	AC	TF	MP	CS	VC	AM	LP	DS	AP
19	ME	TF	AM	AC	LP	AP	EP	MP	CP	DS	PC	CS	VC	CH
20	CP	CS	VC	TF	AM	AC	AP	EP	ME	MP	PC	LP	DS	CH
21	DS	LP	ME	AP	EP	AC	PC	AM	CH	TF	CS	VC	MP	CP
22	LP	DS	AC	TF	AM	VC	CS	CH	ME	AP	EP	PC	CP	MP
23	CP	AM	TF	AC	CH	LP	DS	M,	EP	AP	PC	VC	CS	MP
24	CH	DS	LP	AC	TF	AM	CP	AP	MP	ME	EP	PC	VC	CS
25	DS	LP	AC	CH	AP	EP	VC	CS	TF	CP	MP	AM	PC	ME
26	TF	CP	AM	CH	PC	ME	CS	EP	VC	LP	MP	AC	DS	AP
27	CP	EP	AC	LP	DS	TF	ME	CH	AM	VC	CS	MP	AP	PC
28	AC	LP	TF	CH	AP	AM	CS	VC	MP	PC	CP	DS	EP	ME
29	ME	AM	CP	EP	TF	AC	CS	VC	PC	LP	DS	MP	CH	AP
30	CP	PC	ME	TF	LP	DS	AC	CH	MP	AM	AP	EP	VC	CS
31	ME	CP	AC	CH	TF	AM	PC	MP	AP	EP	LP	VC	CS	DS
32	AC	ME	CH	LP	TF	DS	AM	PC	AP	EP	MP	CP	VC	CS

APPENDIX E

ADDITIONAL COMMENTS FROM MOFFETT FIELD TACCO INTERVIEWS

E. ADDITIONAL COMMENTS FROM MOFFETT FIELD TACCO INTERVIEWS

Upon completion of the MD Scaling interviews, general comments were solicited from each group of TACCOs on the subjects of decision aiding and P-3C hardware. This appendix summarizes the comments and suggestions received from the 32 TACCOs interviewed. The comments concerning general aspects of the P-3C are reviewed first, after which the more specific comments are presented.

In considering the overall impact of automation on the TACCO, many of the interviewees expressed a belief that much of it unnecessarily increased the amount and complexity of their work. One individual commented, for example, that he felt he was "working for the computer, instead of the computer working for him." Many specific examples were given of programs possessing excessive, redundant cueing, and functions requiring excessive button-pushing. It was thought that such problems provide a roadblock to greater acceptance of automation by the operational community. The numerous nonsubstantive differences between similar programs on different platforms (e.g. baseline verus update I) were seen as another major problem with previous automation efforts. The lack of consistant design features both within and across software functions was generally criticized. The interviewees also felt that there were many programs, displays, etc. which had either outlived their usefulness or had never been useful, but which were nonetheless retained in the system. They thought those 'low-utility' features were "cluttering" the displays, consoles, and computer, and possibly deterring the development and introduction of newer, and more useful system features.

The majority of the hardware-specific comments concern the TACCO station and/or TACCO functions, as this was the primary emphasis of the interview. However, a few also concern the NAVCOM, pilot, and sensor operator stations and/or functions.

Hardware related suggestions/comments pertaining to the TACCO station were:

- Provide the ability for TACCOs to monitor both NESTOR and one other communications system, preferably ICS. When using NESTOR communications, primarily during hand-off, the TACCO is unable to monitor any other communications, including ICS. This results in the TACCO becoming temporarily removed from the tactical situation.

- Give the TACCO the ability to scuttle all types of sonobuoys when they are no longer providing target information to the ASW crew, as can currently be done with CASS sonobuoys.

- Develop sonobuoys having variable depth settings that can be changed once the sonobuoy is deployed. This capability would be similar to that available in the CASS buoys by which the hydrophone can be lowered.

- Provide an area at the TACCO station which can be used for writing. Currently, the TACCO must place writing material over the keyset in order to record information.

- Provide a means for allowing the TACCO to see sensor operators' display information, without having to leave the TACCO station.

- Incorporate a color display at the TACCO station to provide increased comprehension of data displayed.

- Relocate the TACCO's tableau so he is able to see the data entry keyset and the tableau simultaneously.

Hardware related suggestions/comments pertaining to the NAVCOM station were:

- Modify the high speed printer such that the printer side of the paper can be seen without having to move it.

- Modify the high speed printer (teletypewriter (TTY) feature) so that the NAVCOM can see what he is sending (TTY Direct Send) without having to wait for two lines of information.

- Have a clock at the NAVCOM staton which could be used without recalling tableaus to enter time information.

- Relocate the altimeter at the NAVCOM station so the NAVCOM does not have to look up to observe it.

- NAVCOM station has a bad draft due to the air conditioning.

- Install satellite navigation capability for use by the NAVCOM operator.

General hardware suggestions/comments pertaining to the overall aircraft were:

- All the seats in the aircraft get very uncomfortable. It would be desirable to have the seats recline further than currently available.

- Vibrations within the aircraft are uncomfortable.

- The noise generated by equipment, especially the cooling fans on the HF radios and the standby gyro, is excessive. Possibly install acoustic covering on the bay doors to reduce the noise level.

- Add-on equipment to the aircraft operators' stations has resulted in less than optimal human factors engineering and neccessitates excessive reaching. Possibly redesign each station.

- Investigate the use of plasma-type displays for all operators.

Hardware related suggestions/comments pertaining to the sensor operators were:

- Install displays at the operator stations which would allow the secondary operator to backup the primary operator (e.g., radar display at SS-I/II or acoustic display at SS-III).

Software related suggestions/comments pertaining to the P-3C operating programs (referring to both Baseline and Update I aircraft) were:

- Develop an extract routine which would search all stored data, extract it and format it into the RAINBOW PURPLE format. This would reduce the amount of time the TACCO spends writing during the tactical phase.

- In the baseline, develop the ability to reserve RF and sonobuoy types for future patterns, similar to the capability currently in the Update I version.

- Shorten the cueing sequence on the store selection program.

- Tableau 2 on the Baseline aircraft is ineffective and provides no useful information.

- In conjunction with weapon fly-to-points, develop and display probability-of-kill contours for the selected weapons. This could be used to allow the TACCO to release a weapon optimally if the pilot is unable to capture the fly-to-point.
- Provide the ability to transmit written information (formatted or free format) to other aircraft during swaps. Types of information desired include MDR, buoys in use, life and depth settings, layer depth, and target data.
- Have a computerized preflight of the aircraft.
- Incorporate some of the HP-67 programs into the aircraft operating programs, specifically the HOWGOZIT, PIM, LOP, NAVPREFLIGHT, and LLOYDS MIRROR programs.
- In the development of a weapon fly-to-point, incorporate the time-late factor involved with the sensor used to determine the fix.
- Eliminate all differences between similar functions of the Baseline and Update I operating programs.
- Have an alert notify the pilot that he has something on his display (e.g., fly-to-point) to which he must respond. This would reduce the ICS between the pilot and TACCO.
- On the PDIP tape, include acoustic information and ESM information on the targets-of-interest which can be displayed to the TACCO.
- Have a recommended altitude profile which is displayed to the pilot and updated according to the tactical situation.
- Provide target course readouts when amplifying the predict symbol.
- In the generation of weapon fly-to-points, utilize course information on the submarine, and generate steering commands to have the aircraft fly up the course of the submarine for the weapon release.
- Use real-time environmental information for the development of sensor patterns.
- Incorporate a time-out feature on sonobuoy symbols which would remove the symbol when its effective lifetime has been exceeded and no RF from that channel is detected.

- When selecting and setting weapons, have the computer queue two weapons in the event that a weapon station is blocked at time of release.
- Provide the capability to expand DIFAR and ACTIVE buoy simultaneously with only one cueing sequence.
- Incorporate a mission phase checklist for display to the TACCO.
- Provide the TACCO with an indication of the type of bearing information (ALI, TRACKER) being displayed.
- Display task-force-related areas of interest (submarine areas, standoff areas) which will be updated based upon Task Force PM.
- Display HARPOON kill radius that moves with aircraft.
- Incorporate multi-target Doppler tracking algorithms.
- Improve the CZ displays, possibly to show only areas of probability from intercept of multiple CZ ranges.
- Maintain past history on DIFAR bearings for display to TACCO.
- Have the auto track function displayed along with probability area contours.
- Automatically extract NAVPARAMETERS Tableau on the HSP whenever specified events occur (e.g., buoys release) or time periods expire.
- Incorporate geographical map overlays for display to TACCO and SS-III operator.

It should be noted that some of these comments were voiced by only one or two personnel. However, many of them were repeated by many individuals. The most frequently represented comments were those regarding store management/reuse RF in the Baseline P-3, the ability to have the computer generate a PURPLE message, incorporation of existing HP-67 programs into the operational programs, improved weapons fly-to-points, ability to transmit text material in a swap, and utilization of environmental information for pattern construction.

APPENDIX F

UNFOLDING ANALYSIS AND PRIORITY MAPPING

F. UNFOLDING ANALYSIS AND PRIORITY MAPPING

In a multidimensional model of a psychological domain, such as the MDS model of TACCOs perceptions of ASW decision-making constructed in the previous section, each item in the domain has a unique projection or coordinate on each of the dimensional axes. Each dimension is therefore a scale which measures some salient perceptual attribute of the domain. Together, all these scales measure all the independent features needed to represent the perceived interrelationships among the items in the domain. In the ASW decision-making case, the three dimensions (as shown in Table 3-1) provide numeric measures of all the important features by which experienced TACCOs perceive ASW decisions.

Other characteristics or features of the items scaled must therefore be combinations of the features represented by the exclusive and exhaustive dimensions in the multidimensional space. Such derivative features may have differing properties as measurement scales, and may therefore have different representations within the multidimensional space. The feature may act as a categorical scale, in which case it will be represented as a partition of the multidimensional space into unordered regions. The feature may act as an ordinal scale, in which case it will be represented as a graded or ordered partition of the multidimensional space. The feature may even act as a ratio or interval scale (similar to the dimensions themselves), in which case it will be represented as a directed vector or curve passing through the multidimensional space.

Various techniques can be used to construct representations of derivative features in an existing multidimensional model. Little can be done to represent categorical derivative features in the multidimensional model. More can be done to construct a representation of ordinal or ratio-scale derivative features, through the use of a powerful technique known as Unfolding Analysis.

This technique was first proposed by Coombs (1950) and later generalized by Bennett and Hays (1960). It is based on the concept that the general form of the representation of a derivative feature in a predefined multidimensional space can be determined by the comparison of the trial representations produced by a series of different models of increasing complexity.

Unfolding Analysis postulates that there are two basic ways in which derivative features can be expressed as a combination of the dimensions in the multidimensional space-- either as a monotonic combination of all the dimensions, or as a non-monotonic combination of the dimensions. When the relationship is monotonic, increased values on the dimensions will always yield monotonic changes in the derivative scale. When the relationship is non-monotonic, then increased values on a dimension will yield monotonic changes in the derivative scale only up to some point, beyond which the tonicity of the derivative scale will reverse. Thus, in a non-monotonic combination, there will be a point on each dimension such that the derivative scale will increase on one side of it and will decrease on the other side of it as values on the dimension increase.

While there are infinitely many monotonic and non-montonic ways of combining dimensions, Unfolding Analysis restricts itself to four specific formulae which have simple mathematical forms and direct psychological interpretations. Although the analysis can be performed on either ordinal or ratio scale features, the discussion here will be restricted to ordinal scales, because the data collected at Moffett Field used ordinal measurement scales.

In Unfolding Analysis, the four different models are sequentially considered in terms of their ability to represent a given ordinal scale in a given multidimensional space. Normally, the multidimensional space is the result of an MDS analysis and the ordinal scale is a ranking (or set of rankings) performed by one or more individuals according to some criteria. The Unfolding Analysis then can be thought of as an attempt to determine the best representation of the ranking criteria as a function of the dimensions in the MDS solution.

Once the form of the representation of the criterion has been selected, regression-like techniques can be used to precisely define an equation which models it as a function of the dimensions in the space. Carroll and Chang (1967) have developed a set of computational procedures for performing these regression analyses. Because their method was designed to relate MDS solutions to data on the *preference* or desirability of the items in the multidimensional space, they have termed it "Preference Mapping." In the analysis performed here, their computational approach is used, but instead of modeling data on preference it is used to model data on perceived priority of decision functions. Thus, this application of the model is more appropriately termed Priority Mapping, since it constructs a mathematical "map" of the TACCOs intuitive prioritization of the decision functions.

F.1 FOUR MODELS OF PRIORITY

The unfolding analysis and priority mapping procedures each employ four models of priority. These models are placed into a strict hierarchy, as each model can be shown to be a special case of the next higher model. The highest model in the hierarchy, then, subsumes all of the lower three. Because the data to be analyzed here are ordinal, the models will be explained in terms of ordinal representations.

An ordinal scale in a multidimensional space divides the space into graded regions, such that a point in any one region has a different rank than a point in any other, but has the same rank as another point in the same region. Thus the multidimensional space is broken into *isopriority regions,* which are separated by *isopriority contours*. The four models can best be described by the different kinds of isopriority contour structures they allow. The kinds of isopriority contours permitted by the four models are depicted in Figure F-1. In the following paragraphs, the differences between these four representations are discussed in detail. For simplicity, Figure F-1 and the following discussion are expressed in terms of a two-dimensional space. The generalization of the approach to three or more dimensions is straightforward and not explicitly presented.

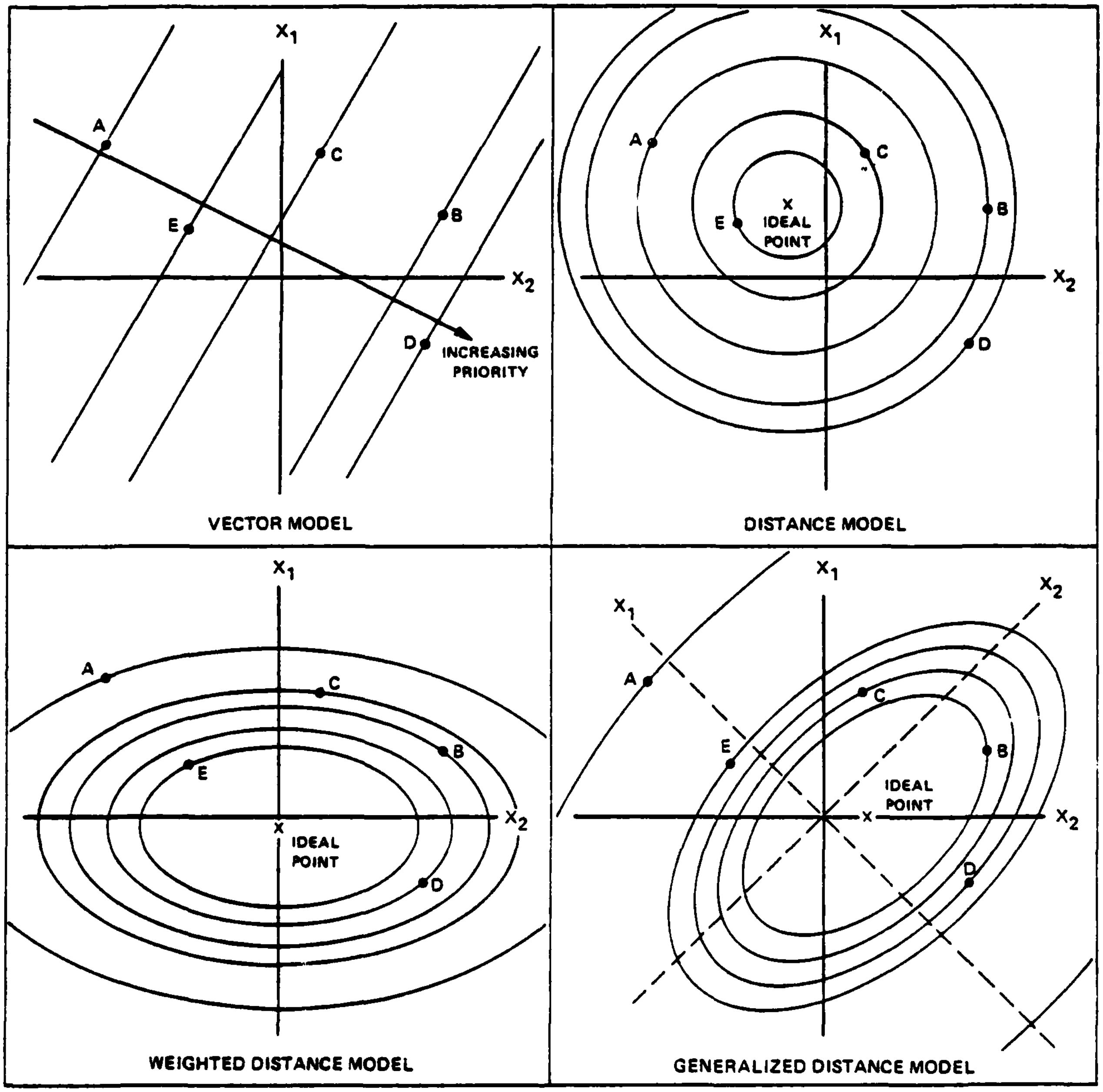

Figure F-1. Isopriority Contours in Four Models of Multidimensional Priority

F.1.1 The Vector Model

The first model, and the lowest on the hierarchy, is the only monotonic model. In fact, it is not only monotonic, it is linear. The model assumes that each dimension contributes to priority in a linear fashion, so that the prioritization of items is defined by their projections onto a linear vector in the multidimensional space. The isopriority contours in two dimensions are therefore lines which are perpendicular to this vector, as shown in the upper right portion of Figure F-1. Because this model defines priority in terms of a vector, it is termed the *vector model*. The vector priority model is quite similar to the concept of multiattribute utility. Each attribute (dimension) contributes to the overall score in a linear way, with the relative contribution of each dimension defined by a coefficient assigned to it. In the vector model (Figure F-1), the coefficient assigned to a dimension is the cosine of the priority vector with regard to that dimensional axis. The vector model can be interpreted as a "more of a good thing" model, because it assumes that whatever a dimension represents, more of it will always contribute to a higher priority. There can never be "too much" of any dimension in a vector model representation.

F.1.2 The Unweighted Distance Model

The remaining three models are non-monotonic and define priority in terms of distance in the multidimensional space. They utilize the notion that there is an "ideal point" somewhere in the multidimensional space, such that the *closer* a decision is to the ideal point the higher its priority. Alternatively, the ideal point can be an *anti-ideal point,* such that the *further* a decision is from it, the higher the priority of the decision. The simplest of the distance models is termed the *unweighted distance model* or just the distance model. It models the prioritization of the items in the space strictly according to their distance from the ideal point, as defined by the distance metric constructed for the space with the MDS analysis. Normally this metric will give the Euclidean definition of distance, and the isopriority contours will therefore appear (in two dimensions) as concentric circles around the ideal point, as shown in the upper right of Figure F-1. The vector model can be seen as a special case of the distance model in which the ideal point is located infinitely far from the origin along the priority vector. As the ideal point moves toward infinity, the concentric isopriority circles asymptote to lines which are perpendicular to the priority vector.

The distance model assumes that distance alone is the basis for priority and therefore that each dimension has a equal contribution to priority. This is because each dimension contributes equally to the distance of any one decision from any other, or from the ideal point. Because distance is a quadratic function of the dimensions of a space the distance model and all other non-monotic models in the hierarchy are based on a quadratic representation of priority. The vector model, in comparison, is based on a linear representation.

F.1.3 The Weighted Distance Model

A more general representation of priority in terms of distance allows the distance between the ideal point and a decision on certain dimensions to contribute more toward the decision's priority than the distance on other dimensions. To model this, each dimension is assigned a weight or saliency. The weights are used in computing the distance between the ideal point and each decision on each dimension, and therefore affect the decision's priority. This model, termed the ***weighted distance model,*** allows isopriority contours to assume (in two dimensions) the shape of an ***ellipse*** (or any other conic curve) parallel to the dimensional axes, as shown in the lower left of Figure F-1. The unweighted distance model is obviously a special case of the weighted model, in which all the dimensional weights are 1.0.

F.1.4 The Generalized Distance Model

Both the weighted and unweighted distance models assume that each dimension contributes independently to priority. It is quite possible, however, that there is interaction among some or even all of the dimensions in constituting the concept of priority. A model which permits such interactions among dimensions can be constructed by allowing the axes to be rotated in the multidimensional space before the distances are computed. The isopriority contours in this kind of model would still be ellipses or other conics (in two dimensions) as in the weighted distance model, but in this case they can assume any orientation in the space. This is shown in the lower right of Figure F-1. This model, termed the *generalized distance model* allows each dimension to contribute independently and in combination with each of the others to the priority of each decision function.

F.2 SELECTION OF THE OPTIMAL REPRESENTATION

In an actual application of the Priority Mapping precedure, trial representations of the (ranking) data are constructed for all four of the unfolding analysis models. Each of these representations will produce a different ranking of the stimuli, and these 'model' rankings can be statistically compared to original data to determine the appropriateness of each model. The simplest and most reasonable measure that can be used for such a comparison is the correlation between the model ranking and that of the data. The correlation, when squared, becomes the coefficient of variation statistic (r^2) which indicates the proportion of the variance in the data that is accounted for by the model. An F statistic is then computed from the value of r^2 and used to test the null hypotheses that there is no underlying correspondence between the model and the data (i.e. that the value of r^2 is strictly a chance result).

Those model representations for which the null hypothesis can *not* be rejected at a reasonable level of confidence (say 95% or 99%) can be eliminated from further consideration. If this is the case for all of the models, it must be assumed that none of them is appropriate for the data, and that Priority Mapping can not be used to prioritize the stimuli in terms of the specified multidimensional space.

A possible criterion for selecting among the remaining models (i.e. those for which the null hypotheses *could* be rejected) is the goodness of fit between each model and the data. This can be measured by the value of r^2 -- the proportion of variance accounted for. Each model in the hierarchy will normally account for more variance than any of the lower models, because each (higher) model in the hierarchy attempts to fit the date to a more complex equation than all the lower ones, and thus contains more parameters. Other things being equal, a model with more parameters will always explain more of the variance in a data set than a model with fewer parameters, so it is reasonable to expect the values of r^2 to increase as the hierarchy is traversed from bottom to top. The key question is whether or not the increase in r^2 of one model over another is significant when considered against the increase in the number of parameters.

This problem requires a statistical comparison among the rankings produced by the four models. An F statistic can be computed from the r^2 values of each pair of models to test the null hypothesis that the increase in r^2 of one model over the other is only a chance result produced by the increase in the number of parameters. A rejection of this null hypothesis for a given pair indicates the model that is higher in the hierarchy (the more powerful model) provides a significantly better representation of the data than does the model that is lower in the hierarchy. A failure to reject the null hypothesis for a given pair indicates that there is not a significant difference in the explanatory power of the two models, and that the model lower in the hierarchy should be preferred because it is simpler. By comparing all pairs of significant models in this manner, the optimal representation can be chosen.

APPENDIX G

UNFOLDING ANALYSIS AND PRIORITY MAPPING RESULTS

G. UNFOLDING ANLYSIS AND PRIORITY MAPPING RESULTS

This appendix presents the details of the Unfolding Analysis and Priority Mapping procedures as applied to the two sets of importance rankings obtained at Moffett Field. Section G.1 describes the analyses of the importance rankings in attack missions, and Section G.2 describes the analyses of the importance rankings in surveillance missions.

G.1 PRIORITIZATION OF IMPORTANCE RANKINGS FOR ATTACK MISSIONS

Using the PREFMAP program, the unfolding analysis was begun by constructing trial representations of this ranking criterion using each of the four hierarchial models discussed in Appendix F. These representations were statistically compared to the rankings made by the TACCOs interviewed at Moffett Field to determine the appropriateness of each model. The comparisons were made using the r and r^2 statistics, as described in Appendix F. The significance of the comparisons against a null hypothesis that there is no underlying correspondence between the model and the data (i.e. that the value of r^2 is strictly a chance result) was then tested using an F statistic. The values of r^2 , the F statistic, and the resulting rejection level for the null hypothesis are given in Table G-1.

Table G-1. Significance Of Results For Mission With Attack

MODEL NUMBER	MODEL FORM	$100 \cdot r^2$ (% VARIANCE ACCOUNTED FOR)	F STATISTIC	REJECTION LEVEL FOR NULL HYPOTHESIS FOR CHANCE RESULT
1	GENERALIZED	99.4	77.1	$<.01$
2	WEIGHTED DISTANCE	94.6	21.1	$<.01$
3	UNWEIGHTED DISTANCE	91.3	23.9	$<.01$
4	VECTOR	73.4	9.28	$<.01$

All four models produced a significant (i.e. non-chance) representation of the data, indicating that each model was capable of providing a reasonable representation of the TACCO rankings. The next step in the anlysis was to determine which produced the *best* representation.

As described in Appendix F, comparisons were made between all pairs of model representations using an F-statistic. Each comparison considers the increase in r^2 provided by one model over another against the greater number of parameters needed to achieve that increase in r^2. These comparisons are summarized in Table G-2.

Table G-2. Comparison Of Models For Mission With Attack

UPPER VALUE = F STATISTIC
LOWER VALUE = REJECTION LEVEL FOR NULL HYPOTHESIS OF NO DIFFERENCE

MODEL	1	2	3
2	10.8 =.025		
3	11.2 =.025	2.24* >.1	
4	30.1 <.01	9.43 <.01	18.6 <.01

MODEL

*DENOTES SIGNIFICANT DIFFERENCE

As seen in Table G-2 the generalized distance model (Model 1) is significantly more powerful than all of the other models, with a confidence of 97.5%. Therefore, it was determined to be the most appropriate of the four models for representing the rankings of the TACCOs according to this criterion.

Having identified the best form of the function representing the criterion "importance in a mission with attack" as that specified by the generalized distance model, a precise priority function was "mapped", again using the PREFMAP program. The importance of priority of a decision function j in a mission with attack ($P_{WA}(d_j)$) was found to be given by:

$$P_{WA}(d_j) = 4.87X_{j1}^2 - 1.78X_{j2}^2 + .682X_{j3}^3 - .776X_{j1}X_{j2} - 2.31X_{j1}X_{j3}$$

$$-3.71X_{j2\ j3} + .299X_{j1} + .541X_{j2} + .858X_{j3} - .301$$

where X_{j1} is the location or coordinate of d_j on dimension 1,
X_{j2} is the coordinate of d_j on dimension 2, and
X_{j3} is the coordinate of d_j on dimension 3

The values of the X_{j1}, X_{j2}, and X_{j3} were given in Table 3-1. The priority values for the fourteen decision functions generated by this function were given in Table 4-1.

G.2 PRIORITIZATION OF IMPORTANCE RANKINGS FOR SURVEILLANCE MISSIONS

An identical analysis was conducted for the TACCO rankings of decision function importance in a mission without attack -- one where the goal is only surveillance of the submarine. PREFMAP was used to construct trial representations of the aggregated TACCO rankings according to this criterion. These rankings were then compared with the TACCO rankings to determine which of the four models produced significant representations of the TACCO data. These comparisons, using the correlation between rankings (r), the proportion of variance accounted for (r^2), and the statistic test (F) for a null hypothesis of a chance result are summarized in Table G-3.

Table G-3. Significance of Results For Mission Without Attack

MODEL NUMBER	MODEL FORM	$100 \cdot r^2$ (% OF VARIANCE ACCOUNTED FOR)	F STATISTIC	REJECTION LEVEL FOR NULL HYPOTHESIS OF CHANCE RESULT
1	GENERALIZED	99.0	95.8	<.01
2	WEIGHTED DISTANCE	96.0	28.4	<.01
3	UNWEIGHTED DISTANCE	92.0	26.4	<.01
4	VECTOR	83.0	16.4	.025

As with the previous criterion (importance to a mission with attack), the null hypothesis can be rejeced for all four models, indicating that each of them provides a significant representation of the aggregated TACCO rankings.

The four models were then compared against each other to determine which of them provided the best representation of the TACCO rankings. The F statistic was used to compare each pair of models, as described in Appendix F, testing a null hypothesis that the increase in the proportion of the variance accounted for by the more powerful of the two models was merely a chance result caused by its increased number of parameters. These comparisons are shown in Table G-4. There are more nonsignificant comparisons in Table G-4 than there were in Table G-2 (the comparisons for the previous criterion). In particular, there were no significant differences among the less general models. However in this case (as in the previous one) the general distance model was found to be significantly better than any of the other models in representing the TACCO rankings according to this criterion. Therefore, it was determined to be the most appropriate of the four models for this criterion.

Having determined that the general distance model provides the best functional representation of the TACCO rankings as a combination of the three dimensions identified in the MDS analysis, PREFMAP was then used again to map the precise priority function. Using this program, the importance or priority

Table G-4. Comparison Of Models For Mission Without Attack

UPPER VALUE = F STATISTIC
LOWER VALUE = REJECTION LEVEL FOR NULL HYPOTHESIS OF NO DIFFERENCE

MODEL	1	2	3
2	10.1 / =.05		
3	12.8 / <.01	3.45* / >.1	
4	23.7 / <.01	7.60* / >.1	10.3* / >.1

*DENOTES INSIGNIFICANT DIFFERENCE

of a decision function j on a mission without attack ($P_{WOA}(d_j)$) was found to be given by:

$$P_{WOA}(d_j) = 3.59X_{j1}^2 - 3.48X_{j2}^2 + 7.85X_{j3}^2 - 6.63X_{j1}X_{j2} - 1.40X_{j2}X_{j3}$$

$$+5.70X_{j2}\ {}_{j3} - .157X_{j1} + 2.07X_{j2} + .484X_{j3} + .207$$

where X_{ji} is the coordinate of decision function j on dimension i. The values of the X_{ji} were given in Table 3-1. The priority values for the fourteen decision functions generated by this function are given in Table 4-2.

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