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Technical Memorandum

A MULTI-STAGE, MULTI-LEVEL CONCEPTUAL MODEL OF HUMAN DECISION MAKING

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FOREWORD

This paper could be extremely lengthy if it were to truly review all the research and all the author's ideas on decision making. The domain includes ideas under the headings of problem solving, decision making, option generation, creativity, learning, motivation, and many others. In truth, every response is preceded, at some level, by a decision. It is not the intent, therefore, to throughly cover the territory. An attempt will be made to point out other relevant topics where possible. Rather than an extensive review, however, the reader will be referred to other, largely original sources. This paper will attempt to integrate some of the many perspectives and show how they apply to the topic. The major goal of this paper, however, is to propose a framework for the understanding of decision making in one specific situation: the submarine approach officer deciding how to respond to a sonar contact. It is hoped that this framework will support the further experimental study of decision making within this particular decision domain.

INTRODUCTION

Human decision making is not a unitary process nor are all decision situations alike. This paper will focus on the decisions which must be made by a submarine approach officer (AO) when a contact is detected by sonar. First, a typology of decision classes will be developed. A single class of decision will then be selected for its relevance to the AO's problem. Some of the hypothetical models of the decision process which have been proposed by various researchers will be compared for applicability to this decision class. Note that, in general, different models apply to different types of decision. The models will therefore be reviewed within the appropriate decision context. A single model will then be selected which seems to best fit the requirements of this context. Neither the typology nor the hypothetical model can be claimed to be unique solutions to the problem of classifying, analyzing, or modeling these problems and the human cognitive and observable behaviors within them. They do represent a way of understanding the decision context and the human behaviors within the specified domain. For definitions of context-specific terms, the reader is referred to the glossary found in the appendix.

A brief word is in order about the decision problem that faces the AO aboard a submarine. The AO is the officer in charge of all activity from the time of detection of a target until the end of the encounter. He must decide when and how to maneuver to determine the target's range, speed, course, and bearing relative to own ship and how to respond to the target (by tracking only, shooting, or breaking contact). This officer may be the commanding officer (CO) or one of the senior officers. Only the CO may have extensive experience at command and the authority to take certain actions.

The principal threat is that the target will counterdetect own ship before own ship responds to the presence of the target. The principal problem is that sonar (the only available sensor underwater) information is highly ambiguous. There are many sources of distortion, both random and systematic. Even the ocean itself causes distortion. Under some ocean conditions, a maneuver can cause loss of contact with the target. Furthermore, sonar frequently provides only bearing information; not range, course, or speed. Humans are accustomed to navigate with more complete and accurate visual information that provides relatively unambiguous direction, relative distance, and identification information. Surface ships have both vision and radar to aid navigation, but a submerged submarine has only the relatively ambiguous sonar data. To alleviate these problems the AO is provided with several estimates of the other parameters computed by a variety of algorithms, but these vary in accuracy and may conflict. Which is "best" depends on a number of environmental, target, and own ship conditions and on how one defines "best."

In summary, the AO's decision problem is characterized by ambiguity and information overload. Many years of experience are required to successfully integrate and filter all the information to make good decisions under conditions of time stress, fatigue, and the ever-present threat of counterdetection. It is this situation and the varieties of possible expertise that frame the following discussion. The overall purpose of this analysis is twofold. First is the need to understand the command decision process well enough to design aids to support this process. Second is the need to understand how individual differences in general and novice/expert differences specifically impact that process. These understandings are required to support research currently underway to investigate the feasibility of a decision aid that would adapt to differences in user (AO) expertise.

DECISION TYPOLOGY

A decision occurs in a number of steps in which 1) the need for action arises, 2) information is gathered about the current state of the world and possible response consequences, 3) some action (including no action) is taken, and 4) a consequence of that action occurs. The "decision" itself is an unobservable cognitive process that occurs between the second and third steps. With any (decision) action, some situation (S) exists which elicits a response (R). This response changes the original situation in some way. The change is thus the consequence (or outcome, O) of the response. Note that this S-R-O schema is a traditional way for psychology to examine many classes of events, not just decisions. It has the advantage of focusing on the relationships among the full set of observable elements, but sometimes has the disadvantage of limiting the view of the theorist to these observables.

Fortunately, decision theorists have generally not fallen into this trap. They have been prolific at creating theories that account for how the unobservable cognitive activities of man affect observable behavior. They have, however, focused on information and expectancies decision-makers (think they) have about the R-O and largely ignored the initial situational elements of the S-R-O event. This may be because decision science has evolved from the management science perspective in which most of the uncertainty is associated with the response and its consequence.

CLASSIFICATION BY OUTCOME

The most common classification scheme in the current literature is the risky/riskless dichotomy (Kahneman and Tversky, 1984). In risky choices decisions must be made "without advance knowledge of their consequences" (Kahneman and Tversky, 1984). They are therefore somewhat like gambles where the range of actions, possible outcomes, and even the probabilities of various outcomes may be known, but the exact outcome cannot be known until after the action has been taken. Each response can lead to one of several outcomes with a probability distribution associated with each possible consequence. Thus the decision maker must take both the preferred outcome and its likelihood of occurrence into account when deciding on an action.

The second decision situation, called riskless, involves trades, chosen from among known alternatives, in exchange for goods, money, or services. In this case the consequence for any given decision is known in advance. Uncertainty is largely associated with the values and priorities of the decision maker in deciding among known choices. It is thus at least partially a question of motivational factors (see below). The decision process is characterized as rather like a cost-benefit analysis. The various outcomes and costs may be compared on the basis of their attributes. A decision can then be made with the reasonable expectation that "If I choose A, I will expend X and acquire A."

Characterized within this risky/riskless dichotomy, the AO's decision task is a risky one. One cannot know if a given maneuver will improve own ship's position or cause it to lose contact due, for example, to the perversities of ocean currents. In another sense, the AO's decisions do resemble trades as they must balance the benefit (improving information) with the cost (increasing the risk of counterdetection). Thus, research on both risky and riskless decisions are relevant.

Other classification schemes have also been proposed (summarized in Nickerson and Feehrer, 1975). For example, Edwards (1967) has proposed the distinction between static, one-time decisions and dynamic, progressively interacting decisions in which each decision becomes the baseline for the next. Certainly, the AO's task is dynamic in this sense, but the early decisions are best described as a series of sub-goal actions designed to implement an overall plan. Howard (1968) has proposed three orthogonal dimensions: degree of uncertainty (riskiness), degree of complexity (number of variables), and degree of time dependency. These three dimensions lead to a complex, multivariate classification system in which the AO's task falls in the area of high complexity, high risk, and highly time dependent. Neither Edwards' (1967) nor Howard's (1968) classifications have received the attention (theoretical or experimental) of the risky/riskless dichotomy.

CLASSIFICATION BY SITUATION

All the classification schemes focus on the outcome/consequence end of the process. Problem specification (obtaining information about the current state of the world) may have similar characteristics. The decision maker can only respond to the situation information that is perceived. This may or may not be an accurate representation of the true state of the world. At best, it is still only a cognitive representation and not that state itself. Furthermore, certain characteristics of the information can complicate interpretation. For example, situation information may be certain or uncertain; it may arrive all at one time or be developed over time; it may vary in complexity and clarity. These dimensions (and others) may interact to complicate both the scientist's and decision-maker's understanding of the problem.

Einhorn and Hogarth (1985a) note that situation information may be complete, reliable, and valid or may lack any of these components. It may be incomplete. It may be mixed with noise so as to be unreliable, or it may be completely erroneous. In many cases this uncertainty associated with the situation may be more of a problem than the uncertainty associated with the outcome. In these cases, situation analysis may be the critical step in the decision-making process. For example, when choosing a route to work, information about traffic, road construction, accidents, weather, etc., could almost completely determine which option is chosen. Situation information, however, may be difficult to access, not timely, incomplete, unreliable, or wrong. Despite this situation ambiguity, choosing a route is based on knowledge about current conditions and on past experiences with various information sources and various routes under various conditions. Parallel kinds of problems also arise for the submarine AO.

CLASSIFICATION BY S-R-O SET

Coombs, Dawes, and Tversky (1970) classify problems (not just decision situations) into three types: pure transmission situations in which there is no uncertainty; equivocation problems in which there is uncertainty associated with the outcome; and ambiguity problems in which there is uncertainty associated with the situation. (See figure 1.) The pure transmission problem is similar to a riskless situation. The

		SITUATION	
		UNCERTAIN	CERTAIN
OUTCOME	UNCERTAIN	DOUBLY UNCERTAIN	EQUIVOCATION
	CERTAIN	AMBIGUITY	PURE TRANSMISSION

FIGURE 1. SITUATION AND OUTCOME UNCERTAINTY

principal variable is the motivational state of the decision maker since there is a one-to-one correspondence between available responses and outcomes as signaled by the situation. Equivocation problems are those associated with risky decisions. The outcome associated with a given response is uncertain. Ambiguity problems are those associated with situation assessment. The situation information gives no clear indication of the available responses or their possible outcomes. This may be due to situation noise or to the partial lack of any information or to a purposive attempt to mislead the decision maker. The fourth box in the set defines what can be called the doubly uncertain decision situation. This is the situation in which both the precise consequences of a given response and the state of the world itself are uncertain.

TYPOLOGY APPLICATION

Although each of the classes may contribute to the understanding of the AO's decision task, the doubly uncertain-decision-type best describes the AO's task. Situation uncertainty is due to such factors as the nature of sonar signals, the variety of ocean conditions possible, and the variety of algorithms that are used to interpret the sonar signal. Once the situation has been assessed, response options are fairly limited. The consequence of any one response, however, is uncertain within the bounds described by the probabilities of counterdetection by the target, of loss of the target's signal, and of a hit when a weapon was fired. Thus, the doubly uncertain situation has been selected as most descriptive of the AO's decision task.

MODELS OF DECISION MAKING

BACKGROUND

Before beginning the detailed discussion of some of the many models of human decision making it is important to specify some basic understandings. The first of these understandings is the assumption that all behavior, including cognitive behavior, is aroused, sustained and shaped by motivational forces (Lopes, 1986a; Thorngate, 1980). These motivational forces include certain biological, psychological, and social needs that can be either internal, as the need ("drive" in psychological terms) for food, or external, as the need (called "incentive") for brand name clothing.

The source of motivation can also be a combination of these as when it is learned that money (a generalized incentive) can lead to the satisfaction of both internally and externally stimulated requirements. The objects of these needs are called goals and they activate and direct activity. Learning how to meet these needs, expectancies are developed about the relationships between events (objects) in the natural world, personal behavior, and goal events (objects). These learned S-R-O expectancies help guide and direct activity, both overt and cognitive. Thus, one may not notice the color and model of the car ahead -- unless one expects to follow a "green Dodge" to get to someone's house for dinner. There are too many stimuli to which one could respond for one to attend to them all. Furthermore, the human-information processing capacity is too limited to respond to all the available information. Motivation helps determine which stimuli are important to achieve specific goals, whether that goal is dinner or survival. Motivation also shapes one's response to the stimuli. The same set of stimuli can lead one to shoot, follow, or avoid some target depending upon the goal and expected outcome.

Motivational considerations are relevant to this discussion in two ways. First, because there are some quintessential goals, such as survival, some stimuli will always attract attention. Such stimuli are salient, not because they are relevant to current goals, but because they have strong predetermined (either learned or biological) associations with issues of survival. For example, within the submarine world, certain classes of sonar signals may be closely linked (in the AO's mind) with enemy targets and therefore invoke an immediate reaction whenever they occur. The response to these stimuli is strongly determined by the current mission, current rules of engagement, and the state of own ship, as well as the drive to survive and the reward (incentive) that follows "good performance."

The second way that motivation is relevant is that people learn not only certain ways of responding, but also certain ways of understanding the relationships between the situations, their own responses, and the outcomes of those responses. Thus, they may learn that they are efficacious in certain classes of situation or at performing certain classes of responses, but not others. These self-efficacy expectations (Bandura, 1977, 1980; Kirschenbaum, 1986) shape the choices of responses one makes to a given class of situation. One person may expect to succeed with physical responses but not with verbal ones while another person, in the same situation, may expect to succeed by "out thinking" or "out talking" and not by "out fighting" an opponent.

The second preliminary topic is an overview of classes of models. Models of decision making may take several forms. They may be normative, predicting optimal behavior, or descriptive, explaining actual human behavior. They may focus on a limited section of the overall decision process or attempt to describe the entire process. Most are limited in scope to one decision class. They can focus on risky or riskless outcomes, situation assessment, or the doubly uncertain situation. Although the doubly uncertain situation is most relevant to the domain under consideration, models of each decision class have something to add to the overall understanding of decision making. Several representative theories in each category will be reviewed. For a more complete review the reader is referred to Slovic, Fishhoff, and Lichtenstein (1977), Einhorn and Hogarth (1981), and Pitz and Sachs (1984). Figure 2 summarizes the classes of decision models, types of decisions, and the principal focus of several of the theories discussed herein. Bill-Wray and Kirschenbaum (1986) provide a bibliography which contains additional references that may be of interest to the reader.

As most of the recent work has been done on risky and riskless outcomes, decision making models that account for these classes of decisions will be examined first. Second, situation

	OUTCOME UNCERTAINTY	SITUATION UNCERTAINTY	DOUBLY UNCERTAIN
NORMATIVE THEORY	SEU MAU	------	SHOR
DESCRIPTIVE THEORY	PROSPECT THEORY BOUNDED RATIONALITY	AMBIGUITY, SURPRISE, & MULTIPLE SOURCES (EINHORN & HOGARTH)	SHOR SHORE
PROCESS TRACING	SVENSON (1979)	HYPOTHESIS TESTING	SHORE
	-- NICKERSON AND FEEHRER (1975) --		

FIGURE 2. THEORY BY DECISION CLASS MATRIX

assessment models will be considered. Decision models that apply to the doubly uncertain type of decision class will be encountered last. Process or stage models will be considered in this last section as they are relevant only to the entire start-to-finish decision.

Research on decision making has involved three principal research strategies. Many studies use carefully designed, contrived scenarios and ask the subjects what they would do in these situations. In these studies the decision is the dependent variable. The purpose of such studies is usually to examine the anomalies and heuristics of human decision performance. A second strategy is to simulate the use of certain decision rules to either compare the results of the rules to each other or to actual human performance. As above, the decision is the dependent variable. This strategy is frequently used to examine the implications of various theories without the irregularities and uncontrolled variables inevitable in research with human subjects.

Some situations lend themselves to a process tracing research strategy. This can be in the form of verbal protocol analysis (Ericsson and Simon, 1984) or some other method of process tracing, behavioral observation, or computer tracing as with an eye monitor or MouseLab (Johnson, Payne, Schkade, and Bettman, 1986). As with the first type of study, process tracing research usually places the subject in a well defined, structured scenario. The dependent variables are the pattern by which the information is searched, the stated search "rules," and the final decision. Einhorn, Kleinmuntz, and Kleinmuntz (1980) argue persuasively for such a multi-method approach to both generate and evaluate decision theories.

MODELS AND RESEARCH

Risky and Riskless Outcomes

Decision making under (outcome) uncertainty has been modeled rather exactly by optimization techniques such as subjective expected utility (SEU) theory (Bernoulli, 1738/1954 and Edwards, 1954) that has its roots in Bayes' theorem. SEU theory is based on the assumption that the optimal decision maker behaves so as to maximize the expected utility (worth) of the outcome given its subjective probability of occurring. The "best" decision can thus be predicted by assessing the utilities (U_i) of each possible outcome from any action and the probabilities (P_i) of each outcome occurring and then computing the SEU ($\Sigma P_i U_i$) of each alternative action. The most common decision strategy is to choose the action that maximizes the SEU. Extensive research has shown that humans do not behave in this optimizing manner. For example, they are notoriously poor at assessing probabilities as compared to Bayes' Theorem (see review in Beach and Beach, 1982). Other human departures from optimal behavior have been described as a number of biases or heuristics (Kahneman and Tversky, 1984). The most well-formulated descriptive theory of risky choice behavior is Kahneman and Tversky's (1979) Prospect Theory that specifies a number of reference effects, such as representativeness and availability, and a number of certainty effects, such as overconfidence and anchoring, that distort behavior in predictable ways. Recent research (Thorngate, 1980; Payne, et al., 1986) has indicated that even so called "biases" in decision making, such as ignoring prior probabilities, do not reduce human decision making very much below optimal. With such biases the optimal decision is still made about 80 percent of the time. Improvement would require more effort than the benefit derived. People are very adaptive in their use of decision making strategies. Payne, Bettman, and Johnson (1986), in a process tracing study, showed that, with changes in time pressure and in the nature of alternatives, strategies tend to match those that were "best." Best was defined by a computer simulation of similar conditions.

It is likely that AO's are subject to these biases, but, as indicated above, the use of these heuristics under time and situational constraints may not negatively impact good decision making (Thorngate, 1980; Payne, Bettman, and Johnson, 1986). Prospect Theory has not resolved many of the paradoxes that exist in decision making data (Hogarth, 1986). Futhermore, there are no complementary data on how decision situations are posed or interpreted outside the confines of artificially structured laboratory problems (Fishhoff, Goitein, and Shapira, 1982). The results found by Tversky and Kahneman (1973, 1971) and other decision researchers may be an artifact of the unrealistic way that problems are posed (Lopes, 1986b). This is an especially important issue in the context of AO decision making and a major criticism of much decision making research.

Behavior in the riskless kind of choice is formally described by the normative multi-attribute utility (MAU) theory (Pitz, Heerboth, and Sachs, 1980) in which optimal choice behavior requires a kind of cognitive cost-benefit analysis. Within this formulation, utility (U_i) is equal to the sums of the attributes of the choices (a_i), weighted by the importance of each attribute (w_i) such that $U_i=\Sigma w_i a_i$. As the probability of outcome O given response R is unity, the decision maker's task is to respond so as to maximize U.

MAU theory assumes (1) that humans are able to process information on all attributes of all choices, (2) that people can identify and weight their preferences, and (3) that such comparisons will not violate rules of additivity and transitivity. Research (Einhorn and Hogarth, 1985b) indicates that these assumptions may be unsupportable. Actual behavior is limited by the inability to retain all the necessary information in memory for complete comparisons of all the attributes of all the choices (even in the two-choice case). People must make use of such techniques as "satisficing" (Simon, 1979), attribute ranking, cut-off points, and elimination-by-aspect (Tversky, 1972) to reduce the task to a manageable level. Simon (1979) calls this use of data reduction heuristics "bounded rationality." There is a substantial body of data to indicate that decision makers do employ these strategies. For example, Svenson (1979) reviewed a number of process tracing studies of riskless decisions. The studies all indicated that data reduction heuristics are used by individuals when the available data set is large or complex or when the subject is under time pressure. Also, there was a strong individual differences component in the decisions made and how rules were used. In all these data, however, there was no clear correlation between situational variables and the data reduction heuristics.

In summary, there is clearly a relationship between decision processes employed in risky and riskless situations. The response choices in risky decisions have attributes such as cost, degree of risk, and anticipated reward or punishment value from the possible outcomes. The risk in riskless decisions is that anticipated outcomes will not be as expected, or that another better or less costly alternative will become available, or that the decision maker's values will change. Behavior in any decision situation appears to be guided by one's understanding of the possible outcomes, assessment of the costs or risks, preferences, and assessment of ability to perform the required response. These assessments and understandings are limited by available information and human capability.

Situation Uncertainty

In many of the problems used to research risky and riskless decisions no information is given about the situation that led to these choices. Why is the decision required? Are the given options the full set or is no action or some other response a choice? What is the "game" (cards or horse racing or business mergers)? Is it a game of chance or can skill (be seen to) influence the outcome? Are other people (assistants or opponents) included and what is known about them? How does one know the probabilities and payoffs? What are the (expected) capabilities of the person who must make the response? All these and other issues may change the choice of a response. The theories that attempt to describe and predict how people choose among alternative responses do not deal adequately with these and other issues of situation assessment in either the certain or uncertain case. Even within the context of situation assessment very little has been written on ambiguous input information (for an exception see Einhorn and Hogarth, 1985b).

Psychology has proceeded as if stimulus information generally has a one-to-one correspondence with some feature of the real world. Where this one-to-one correspondence is clearly untrue (e.g., illusions) the distortion has been attributed to a failure of human perception, not some transmission failure within the world itself. Only in the area of language is the uncertain nature of the transmission recognized (Campbell, 1982). In many ways the signal detected by sonar is subject to language-like distortions. The identical received signal may result from RED or READ; from 90^{o} right or 90^{o} left; from 2000 yards to 20,000 yards. Corbin (1980), in one of the few discussions of situation ambiguity in the decision literature, states:

> Unless some ambiguity cutoff is exceeded, the potential decision is not attended to, and the cognitive processes we talk about in decision making will not proceed. Assuming that the cutoff is exceeded, the potential decision will be delayed at least until uncertainty is reduced to an acceptable level. (p. 62)

The AO, however, cannot afford to fail to attend to information or fail to make a decision simply because of uncertain information. He must decide despite ambiguity. Thus, situation assessment is central to his problem.

A series of papers by Einhorn and Hogarth (1978, 1985a, 1985b, 1986) proposes a related set of descriptive mechanisms for dealing with various aspects of situation assessment: ambiguity, surprise, and multiple causation. These mechanisms depend heavily on the anchoring-and-adjustment strategy and each appears to do a reasonable job of accounting for some of the anomalies associated with human situation assessment.

The ambiguity model (Einhorn and Hogarth, 1985b) is of particular relevance here. It postulates that decision makers assign some subjective starting anchor point to their judgment of the situation. Adjustments are made as a function of the perceived amount of ambiguity in the information and the individual's attitude toward ambiguity. The adjustment can be conceptualized as a kind of weighted average. The authors define ambiguity as the unavailability of some information about the probability of a specific R-O association obtainable from the initial situation. Thus ambiguity could result from unreliable, incomplete, or conflicting situational information. In the case of the AO, all these conditions could exist. Einhorn and Hogarth (1985b) have tested this model using a variety of scenarios. In addition to some support for their model, they found interesting patterns of individual differences in decision making. They also found individuals whose behavior could not be accommodated within the parameters of their model.

In the AO's decision environment, information is not static. Data are dynamic, arriving over time. That dynamic change itself imparts additional information. Einhorn and Hogarth (1985a) have hypothesized a contrast/surprise model for updating beliefs about the state of the world. This model predicts a strong recency effect for conflicting evidence. In contrast, the discounting version of an anchoring-and-adjusting model (Tversky and

Kahneman, 1974) predicts a primacy effect for strongly held opinions. Bayesian models predict no order effects. Evidence for how beliefs are updated is inconsistent (see Einhorn and Hogarth, 1985a; Tversky and Kahneman, 1974; and Hastie and Park, 1986). The one conclusion that can be drawn is that the current hypothesis differentially affects the processing of confirming and disconfirming information. This result is consistent with attentional and memory research that indicates a similar phenomenon for attending to and remembering data.

In addition to the dynamic characteristic of the information available to the AO, the sonar data are analyzed by several processes and thus parameter estimates come from several sources. Einhorn and Hogarth (1985b) suggest that this multi-source, dynamic, ambiguous information can be conceptualized as an evidence matrix. There are no comprehensive theories of how individuals cope with such a matrix of changing and often conflicting information. What research evidence we have comes from studies of problem solving (Anzai and Simon, 1979; Gick and Holyoak, 1980) and will be discussed below.

Signal detection theory (Greeno and Swets, 1966) is another relevant perspective in the situation assessment context. It accounts for the effects of motivational factors associated with stimulus detection. These motivational factors can either decrease or increase the likelihood of observing, and thus processing, a given bit of information or of falsely identifying information as noise. Thus motivation (e.g., incentive, expectancy or a priori mind set) can influence the perception and identification of information. This theme shall be revisited in a later section.

In summary, situation assessment is the process of observing incoming data and interpreting these data to understand and perhaps construct a mental model of the state of the world. Some of the problems encountered in constructing a hypothesized model are the ambiguity, dynamism, quantity, conflict, and incompleteness in the stimulus information. This may be compounded by motivational factors and human capacity limitations. Thus the individual's mental model can only be a selective, incomplete, and partially accurate representation at best. It is this mental model, however, from which R-O expectancies are derived and, therefore, which guides response selection.

Doubly Uncertain Decision Class

In the AO's decision task, both situation ambiguity and outcome uncertainty exist. As noted, sonar information may be ambiguous due to several factors including (but not limited to) the ocean environment, the particular sensor used, the variation in the way data are analyzed, and the limited location parameters (bearings-only) available from passive sonar information. For the AO as well, there are trade-offs and risks to consider. For example, waiting (no response) may increase the certainty of a hit, but it may also increase the risk of counterdetection. Conversely, a maneuver may increase the risk of losing contact with the target, although it is usually required for a range solution. Safety, certainty, and solution accuracy are attributes of the choices, each with given probability distributions. Uncertainty in the outcome of any response includes the risk of counterdetection, loss of target, and failure to hit the target (if firing). Much of this uncertainty is due to the inability to locate the contact exactly from the situational information. This is the essence of the doubly uncertain situation. Because the doubly uncertain situation is a combination of both the previous types of decision situations, much of the research discussed above is relevant here.

The doubly uncertain decision class lends itself to stage or process models because the entire S-R-O set is considered. Most of these models are not specifically designed to account for any one type of decision but will be considered here for ease of comparison. Fishhoff (1983) has summarized decision processes as occurring in four stages: identification of all relevant options, identification of the possible outcomes from each, assessment of the probabilities of each outcome occurring given that response, and identification of the best option. These stages are both general and arbitrary. Other models, as summarized in Nickerson and Feehrer (1975), break the stages at other points, specify up to 13 separate stages, or hypothesize a hierarchical set of super- and sub-stages. Nickerson and Feehrer (1975) conclude that these too are arbitrary but that each has its applications. Their own assessment sees decision-making as a series of eight problem-solving tasks: (1) information gathering, (2) data evaluation, (3) problem structuring, (4) hypothesis generation, (5) hypothesis evaluation, (6) preference selection, (7) action selection, and (8) decision evaluation. Within each stage they analyze the applicable descriptive and normative processes that might take place.

The stages of Nickerson and Feehrer (1975) partially map onto the more parsimonious and well formulated Stimulus-Hypothesis-Option-Response (SHOR) model of Wohl, Entin, and Eterno (1983). Nickerson and Feehrer's (1975) model includes problem structuring and decision evaluation stages not specifically included in the SHOR model but do not include an option generation stage. The SHOR model has the advantage for this application of having been specifically developed to describe the military command and control problem. As noted by Hogarth (1986) there has generally been a large task-contingency effect in the results of decision-making research. Thus, one should not expect any of the several theories developed for business decision-making to adequately describe the submarine situation. SHOR uses both a conceptual process and mathematical approach to model decision making. These are integrated to produce a single normative-descriptive model that has some of the advantages and disadvantages of each.

The SHOR model hypothesizes that four stages characterize the decision-making process: stimulus recognition (S), hypothesis generation and evaluation (H), option generation and evaluation (O), and response (R). The mathematical version of this model employs a combination of linear and Bayesian methods and a Kalman filter for situation assessment. As with other mathematical models, there is no implication that the human cognitive process uses similar computations. One might propose, as alternatives, an anchoring and adjustment heuristic or a Piagetian-like assimilation and accommodation process.

While the model is compelling, it can be improved by the addition of an explicit evaluation (E) phase, similar to that of Nickerson and Feehrer (1975), in which the consequences of any response action taken are analyzed. This modification allows for feedback which can change future behavior in the same class of situation. Without feedback, as without the study of history, we are destined to repeat our errors. The modified model will henceforth be called the SHORE model. This modification is implied in Wohl, Entin, and Eterno's (1983) model and simply specified here for clarity. A second modification of the SHOR model is proposed for the decision task under consideration. This is the grouping of the S and H stages under the superstage of situation analysis and the O and R stages under the superstage of response formulation. These two superstages follow a similar distinction made by Einhorn, Kleinmuntz, and Kleinmuntz (1980) between judgment and choice. The E stage occurs after the response is made and thus affects only future occurrences of the same class of event. Observational evidence for these superstages will be discussed below. The conceptual SHORE model, as outlined above, will be the basis for the remainder of this analysis.

In summary, decisions have been typed into three classes: one which focuses on outcome uncertainty, a second which is defined by situation uncertainty, and a third which is characterized by both situation and outcome uncertainty. This last class was found to best describe the AO's decision task. Several models were explored that account for the effects of situation and/or outcome uncertainty. From these the modified SHORE model has been selected for further analysis. This selection was made both because SHORE is able to account for the effects of both situation and outcome uncertainty and because it is a concise and yet flexible framework for exploring the process that the military decision maker undergoes. The remainder of this memorandum will further specify how the process may function at each stage and relate some of the relevant variables and concepts.

SHORE

As noted, the Stimulus and Hypothesis stages of the SHORE process make up the situation assessment component of the decision process. They will therefore be considered together. Much of the research appropriate to this process has been previously discussed under the heading of situation uncertainty; however, several specific lines of research will be reviewed below. We will then consider the response formulation component of the process, which is composed of the Option and Response stages. Many of the issues relevant to response formulation have been discussed under the heading of risky and riskless outcomes. Others, such as option generation, will be analyzed below. The process and effects of the Evaluation stage will be investigated.

SITUATION ANALYSIS

The SHORE model has its roots in stimulus-response (S-R) psychology. This means that analysis is focused on the relationship between stimulus and associated response. The stimulus may be thought of as containing information about the appropriate response acquired from past experience with the same class of stimuli. The need for a decision arises in response to some stimulus, for example, a sonar contact. The first task of the decision maker is to detect and recognize the stimulus event. In a submarine, information is sent to the combat control system only when the sonar operator has determined that a contact exists. The AO is stationed in the combat control center where this information is received. This initial signal detection is highly salient if there are few contacts in the system. It does not, however, provide enough information to allow for reliable hypothesis generation. If there are many contacts in the system a new target could be overlooked entirely.

Evaluation of stimulus information takes place gradually, over time. Bearing data are averaged automatically by the system to reduce the effects of random error. Only the averaged data are displayed to the crewmen who operate the combat control system. The AO receives information both directly from a sonar display and from officers who assist in the analysis of incoming data. Data points are analyzed by a number of methods including several different paper plots, a Kalman filtering algorithm, and others. The AO's task is to integrate and filter this information and decide on a course of action. Thus, for the AO the S stage of decision making consists largely of continually sampling already processed data and selecting the most reliable and relevant elements to incorporate into a hypothesis. The evidence matrix proposed by Einhorn and Hogarth (1985b) is an economical way of conceptualizing the possible variables.

Once the initial stimulus is detected, incoming information must be analyzed for its informational content and matched to previously experienced similar or prototypic situations to generate a hypothesis of the state of the real world. The experienced AO is trying to "guess" where the contact is located relative to own ship and what kind of threat is represented by the contact. Several models of this process have been developed within the context of pattern recognition theory (Uhr, 1966) and concept formation research (Trabasso and Bower, 1968; Glass, Holyoak, and Santa, 1979). Some of the features of these theories include template matching, feature matching, prototyping, recall from both semantic and episotic memory, selective attention, and context effects. Each theory of human recognition seems to account for some, but not all of the data in this complex area. Most likely, there are several mechanisms that apply separately or in parallel in different cases.

Most researchers report only one primary hypothesis is considered at a time (Trabasso and Bower, 1968; Anzai and Simon, 1979). Other, alternative hypotheses may be readily available if the primary hypothesis is disproven, but these alternatives are not generally reported in verbal protocols (our only source of relevant data). Einhorn and Hogarth (1985a) suggest that a decision maker imagines several alternative causes for the events observed and responds according to the most reasonable of these hypothesized causes. Note that the most frequently observed information search and selection strategies appear to be those designed to confirm an existing hypothesis rather than test it against other possible hypotheses (Skov and Sherman, 1986). Additional research will be required to resolve this issue in the context of the AO decision maker. As new information is received, this hypothesis (or these hypotheses) may be updated or entirely discarded. As a working hypothesis is evaluated and updated, information selection and filtering can become critical.

There are usually a variety of other data available to the decision maker that may or may not be relevant. This part of the process may be viewed as an information selection problem.

Difficulty occurs when there is excessive noise, when there is more information than the individual can process, or when there are other demands on the limited human information-processing capabilities. When there is excessive noise or information, the problem is one of determining which is the most reliable or relevant information. Frequently, however, the information which captures attention in such a situation is determined by relevance to any existing hypothesis or opinion and/or by the salience (size, color, brightness, loudness, etc.) of the stimulus. Research has contributed greatly to understanding the characteristics of a stimulus that elicits attention (see Norman, 1969).

In the AO's decision task, stimulus detection and recognition is an ongoing process as the situation develops over a period of time. Thus, the AO must be able to recognize new information as salient because it can confirm or disconfirm a hypothesis, add needed detail, or indicate a change in the situation such as a target maneuver. There is almost no information in the literature on how an experienced AO actually uses incoming data to generate and test hypotheses about the state of the world. In some knowledge acquisition studies (Silva and Regan, 1986), it has been observed that certain classes of data seem of primary importance and that there are qualitative differences due to experience.

These studies have also led to the observation that S and H seem to be interactive, parallel processes. The AO may initially propose a very tentative hypothesis of the state of the world and predict from that the next data point. One observed source of the hypothesis was generation by comparison to similar situations encountered in the past. This episotic recall by an experienced AO appeared to be a richer, more detailed, and more complete source of situation hypothesis than the rule-based semantic recall of inexperienced (but very knowledgeable) officers. The initial hypothesis may serve like an anchor point and adjustment may then occur in response to additional data. As with other anchor-and-adjustment models, more weight appeared to be given to the anchor over time. This looping and parallel updating of S and H appeared to continue until some threshold was reached.

That threshold might be established by a time constraint or a satisficing point.

In observations conducted by NUSC (Silva and Regan, 1986), it appeared that important novice/expert differences occurred in several areas. These included perception of the data as relevant, speed and accuracy to the initial hypothesis generation, weight given to updated information when it conflicted with the stated current hypothesis, and satisficing threshold. Another significant difference appeared to be the source of knowledge called upon to generate situation hypotheses. The highly trained but less experienced subjects appeared more likely to cite formal rules while the experienced CO referred to the similarity of previous experiences. The form of the situation assessment appeared to be general across levels of experience. These informal observations need to be confirmed by rigorous, controlled experiments.

RESPONSE FORMULATION

Once the decision maker is reasonably satisfied with a working mental model of the situation, how to respond must be decided. As Einhorn, Kleinmuntz, and Kleinmuntz (1980) noted, in some cases situation assessment is sufficient to suggest that only a single response option is appropriate. In other cases there is a known, limited set of options, and selection is the primary task. Some situations, however, require both option generation and selection. For the submarine AO there may be a single prescribed response, two or more incompatible prescribed responses, or no applicable guidance. Therefore, it is necessary to review the research on option generation and then address response selection.

There are several lines of research relevant to option generation. The first of these is memory and learning research. As with hypothesis generation, option generation may be strongly influenced by recall of either learned rules or similar experiences. The selection of options generated by recall of similar past experiences will be influenced by recall of the outcome that followed the response (Fox, 1980; Gick and Holyoak, 1980). (See the following discussion of the effects of the evaluation of such feedback.) It may be hypothesized that when the outcome of a past response was satisfactory, the option generation process will usually be limited to that one option. When the outcome was not satisfactory, however, other response options must be considered.

Reasoning by analogy is one possible source for these "new" response options. In a problem-solving situation Gick and Holyoak (1980) found that if subjects could recall past successful solutions for some other domain, they used these to generate analogous solutions. Anzai and Simon (1979) observed that the subject learned from experience about not only specific responses but also about response strategies such as sub-goal analysis that are composed of several moves. In the AO's task, a similar response strategy analysis is relevant because the period from initial contact until resolution frequently requires a number of sub-goal responses.

Option evaluation may take the form of mental "what-if" outcome testing. In a multi-response situation the validity of such sub-goal expectancies can be verified by testing each expected outcome (sub-goal) against the actual outcome from the individual responses. For example, if the AO expects to follow a target, a maneuver may be ordered. Incoming data after the maneuver should conform to the expected information. If there is a serious mismatch, the entire response option and perhaps the situation hypothesis must be reconsidered. When post-response information confirms expected outcomes, the entire response set is likely to be used. When it does not confirm the expected outcome, the situation hypothesis may need to be revised. Notice that this is another example of recursive looping within the SHORE paradigm.

Motivational factors play a part in option evaluation. The decision maker's goal definitely influences the direction of the response. For example, during peace time an AO is less likely to worry about the threat implied by counterdetection if engaged in an information gathering mission than if engaged in a mock battle exercise. Another motivational factor is the decision maker's evaluation of his or her own ability to execute a particular response. If, for example, the crew is inexperienced or the ship is disabled, an AO might take a more conservative action, even in response to a perceived threat.

Self-efficacy expectations are closely linked to the causal attributions developed when evaluating past successes and failures in the same class of situation. Attribution theory (Heider, 1958; Weiner, 1972) has analyzed these causal ascriptions in a number of situations and has found several dimensions along which causal ascriptions seem to vary. Some of the more relevant are ability, locus of control, and stability of causal judgments. Thus, one might ascribe a successful encounter to one's own skill at out maneuvering the target, to some event outside personal control such as target maneuver, to chance, or to some complex interaction of these factors. The formation of these causal ascriptions is learned and requires feedback from the event. Some of the relevant factors are reviewed in Kirschenbaum (1986). It is sufficient to say that the AO's understanding of the causal factors of past success and failure will influence future responses in events perceived as similar. For further information on such causal ascriptions see Heider (1958), Weiner (1972), Bandura (1977, 1980), and Kirschenbaum (1986).

In summary, response formulation is the process of generating response options from past experiences, learned rules, or analogies, and testing them against recalled previous outcomes and "what-if" mental simulations. The decision maker's evaluation of the situation, desired outcome, and self-efficacy expectations influence the choice of responses. When the response is multistep, feedback from the earlier steps can influence the shape of later responses in the set and may even cause a reevaluation of the situation hypothesis.

EVALUATION

The human being has sometimes been described as a naive scientist (Heider, 1958). There is clearly survival value in trying to understand the causal relationships in our environment. Sometimes, when those relationships are not readily apparent, "reasons" are even invented (gods, myths, and science). It is not surprising, therefore, that there is a tendency to evaluate an event, post hoc, and try to determine the reasons for success or failure.

Feedback from previous events that are perceived as similar can be recalled. This feedback creates the expectancy that, if the situation is correctly assessed as of the same class, the same response should produce the same outcome. Therefore, if the desired outcome is the same, response selection is obvious. A variation in this much too simple analysis occurs when the relationship between the response and outcome is probabilistic rather than deterministic. This is sometimes called the partial reinforcement situation. Partial reinforcement causes the acquisition time of a response to be lengthened as well as the extinction time. Thus it takes many more experiences with probabilistic feedback to learn the relationships between stimulus, response, and outcome.

Humans appear to be particularly poor at nonlinear probability learning. Klayman (1984) argues that most research on human probability learning is not representative of real situations. He found that although humans do not seem to be able to quantify and aggregate specific probability relationships, they do seem to be proficient at identifying relevant cues and eliminating irrelevant ones. Thus, much probability learning may be of the situation-outcome type rather than of the response-outcome type. This means that situational cues, not specific responses, are associated with the probabilistic outcomes. This would explain why cue learning is better than response learning in these situations.

In human learning, it appears that responding is related to the individual's hypothesis about the situation (Nelson, 1976). Not only are estimates of the probability of reinforcement likely to be inaccurate, but humans tend to provide explanations to themselves for why a given outcome followed a given response. Thus memory is skewed by causal hypotheses. Option generation and selection, therefore, may be influenced either positively or negatively by the (perhaps erroneous) recalled previous S-R-O event.

CONCLUSIONS

Many types of decision and many decision-making theories have been discussed. The research has been briefly reviewed, but more questions than answers have been encountered. Several questions seem of particular importance for the context under consideration. The most general of these is the need to be able to fully describe the AO's decision process. The SHORE paradigm has been suggested as a conceptual model of this process but controlled observations are required to confirm the usefulness of this model. Within the confines of the SHORE model specific questions have been raised about the number of hypotheses generated and evaluated at one time, the effects of confirming and disconfirming information, patterns of information search, termination of the hypothesis updating search, option generation sources, and many other issues. Some of these will be investigated experimentally. Others will have to remain hypotheses or unresolved questions. The most important of the questions raised, for the purposes of guiding near-term research, is which of these decision-making processes are different across AOs and which seem to be stable across people.

Many decision theories describe biases and heuristics in human decision-making performance that lead to suboptimal behavior. Optimal is defined against some, frequently Bayesian, arbitrary standard that assumes the availability of not only all relevant information but also unlimited time, memory, and resources. Normally the human does not operate under these ideal conditions. It is argued that under realistic conditions the human decision maker who is experienced in his or her field performs in a manner very close to ideal. Research using simulations to evaluate a number of hypothesized decision strategies supports this conclusion. The human decision maker has developed and uses strategies and heuristics that have been reinforced by success in the past and are thus likely to be repeated. There is an excess of research designed to evaluate hypothesized biases in contrived or simulated situations and a dearth of research that observes, records, and explains the actual decision process. This latter is the goal of subsequent research.

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APPENDIX
GLOSSARY OF TERMS

Ambiguity: Uncertainty about the situation. Uncertainty associated with the stimuli received by the individual and how well they represent the "true" state of the world.

Decision making: The processes by which an organism chooses among alternate responses. This may require the ability to model the state of the real world, generate response options, and recall past experience with similar situation-response-consequence sets to evaluate the options.

Individual differences: Unique ways in which individuals of the same species vary. Such differences may be on any dimension: physical, psychological, intellectual, etc.

Information: That property of a stimulus which reduces uncertainty about the "true" state of affairs.

Information processing: The conscious process of fitting sensory and recalled material together so that they produce a reasonable mental model (see mental model).

Feedback: The informational content of a response outcome. Thus feedback is only that portion of the consequence of a response of which the individual is aware. Responses can have consequences which are not apparent to the person making the response and thus are not feedback. Note that feedback is therefore a stimulus (see stimulus).

Generalization: A learned tendency to respond in the same way to stimuli which are similar in some way, but not identical.

Learning: A process causing a relatively permanent change in performance potential due to experience. It does not include change caused by development, growth, and/or maturation.

Long-term memory: (LTM) The relatively permanent storage of information, experience, or knowledge.

Mental model: Functional, evolving ways people have of understanding some domain of knowledge about the natural world. They are usually not technically accurate or detailed. They may take the form of mental "images," verbal relationships, or sets of situation-response-outcome understandings and are derived from experience with the domain.

Motivation: A process by which behavior is aroused, sustained, and directed toward (or away from) a given goal or incentive. Motivation can be a bottom-up or top-down process and is frequently directed by a combination of both.

Order effects: These occur when the order of stimulus presentation changes the response probabilities. For example, when trying to recall the items on a list one is more likely to be successful with the first and last items regardless of the contents of those positions in the list (see primacy effect and recency effect).

Outcome: The consequence of a response, usually resulting in some change in the situation.

Primacy effect: This occurs when information has greater weight if it was encountered early in the situation, rather than later. An example of this is the strength of first impressions.

Problem space: The cognitive representation of the task. This is different from a mental model of the world because it is essentially task or context dependent. Thus it may be a subset of the more general mental model.

Recency effect: This is the opposite of a primacy effect and occurs when the most recent information is given more weight. Recency may be a short-lived effect due to short-term memory or a temporary short-term salience (importance).

Redundancy: Any restatement of known information. Usually the purpose is to increase the likelihood of a message being transmitted accurately.

Response: Any observable behavior made by an organism. This can include verbal, emotional, and motor behavior. Some theorists only include behavior in response to environmental stimuli while others include internally generated (non-observable) stimuli.

Riskless decisions: Those decisions made with the full knowledge of the outcome resulting from each possible choice. They are therefore like trades or exchanges. The decision maker's task is to determine his or her own preferences and values.

Risky decisions: Those decisions made without prior knowledge of their exact consequences. The set of possible consequences may be known. Thus, risky decisions are like gambles. In riskless decisions one knows that if a specific decision is made a given outcome will follow.

Satisficing: The process of evaluating data only until a satisfactory but not ideal decision is reached.

SHOR model: A model of decision-making developed by J. Wohl. It is an extension of the basic stimulus-response association hypothesis of behavioral psychology. The SHOR model also hypothesizes the functioning of several cognitive processes. These are (1) hypothesis generation/evaluation about the real state of the world given the current stimulus inputs and (2) option generation/evaluation for response to that hypothesized situation.

Short-term memory: (STM) The retention in consciousness of material either encountered in the sensory world or recalled from long-term storage. Short-term memory is of limited capacity and can only be retained through active use (rehearsal, etc.). The limit is sometimes given as 7 ± 2 chunks.

S-R-O: A unit, composed of stimulus-response-outcome, which is likely to be recalled together because of its contingent or contigiuous association.

S-R psychology: That perspective which hypothesizes that a bond (association) is formed between any stimulus and response occurring together such that when the stimulus occurs in the future the associated response is more likely to also occur.

Stimulus: Any form of energy which the organism is capable of detecting with its sensory mechanisms.

Situation: The total stimulus set which makes up the decision environment.

A MULTI-STAGE, MULTI-LEVEL CONCEPTUAL MODEL OF HUMAN DECISION MAKING

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