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RESEARCH ON COGNITIVE COLLABORATION BETWEEN PERSONS AND COMPUTERS

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Abstract

The introduction of decision aids and knowledge-based expert systems incurs resistance when non-congenial styles of problem solving are imposed on users. Ongoing research addresses the design of computer-based display and analysis systems which cater flexibly to personal styles while providing non-obtrusive safeguards against potential errors and biases. Capabilities which permit monitoring of the user's task by the computer and of the computer by the user have been explored.

The Problem

High-level users of computer-based information systems typically find that either too little or too much help is offered.[1][2] On the one hand, sophisticated systems are available for data retrieval, analysis, and display, yet they provide little guidance in selecting the information that ought to be retrieved or the type of analysis which the user ought to apply. On the other hand, decision aids and knowledge-based expert systems typically impose an analytical structure and mode of interaction which may prove inappropriate or uncongenial to the user's own preferred style of problem solving. Users, in short, are caught between systems that automate routine functions and systems which cannot help but dominate any dialogue with the decision maker.

It might be thought that as computer-based systems more completely automate intellectual tasks, the issue of user preferences will become moot. Yet the most critical characteristic of these new applications is that they are neither fully objective nor demonstrably optimal. Knowledge-based expert systems incorporate the assumptions and modes of reasoning employed by human specialists. Decision-analytic aids provide logical constraints for inputs from human experts or decision makers regarding subjective probabilities, preferences, and problem structure. Both kinds of systems are appropriately regarded only as fallible advisors. Complete automation could be inappropriate if users possess substantive expertise or analytic insights not incorporated in the computer.

What is required, both to encourage user acceptance and to enhance aid performance, is a repertoire of techniques for blending the expertise of the user and computer. Such techniques must be fine-grained and flexible enough to capture shifting availabilities of human and computer resources, relative levels of expertise, and user preferences.

Unfortunately, in the design of systems that foster cognitive collaboration, two basic objectives tend to conflict: On the one hand, we want to exploit user inputs where (and only where) they can enhance the overall credibility of aid outputs. On the other hand, users have their own preferences and styles of problem solving that may not correspond to optimal patterns of allocating cognitive effort. By imposing a rigid structure on person-machine interaction (however "optimal" it may be from the point of view of relative expertise), the net outcome may be less effective problem-solving--including perhaps a failure to use the system altogether.

To deal with these conflicting objectives, our research has focused on three broad capabilities in cognitive system design:

- flexible blending of computer and human contributions, under the personal control of the user;
- monitoring by the computer of selected human-performed tasks; and
- monitoring by the human of selected computer-performed tasks.

The first principle maximizes the tailoring of person-computer interaction to the particular style of a user. The second and third principles provide a prescriptive counterbalance: they are designed to compensate for deviations from optimality that may emerge from the first principle, and to do so in the most non-obtrusive way possible.

In the following sections, we briefly summarize some of the research we have done under these three headings. The focus is on the psychological underpinnings and implications of the work, rather than on the details of the decision aids that have been developed. This work has been supported by the Engineering Psychology Group of the Office of Naval Research under two on-going contracts.*

Aids for Personalized Decision Making

Under the Defense Department's Small-Business Advanced Technology (DESAT) program, DSC has explored the design of a computer-based display and analysis system which is customized to the personal cognitive styles of users.[3] The design process has drawn on relevant work in the cognitive psychology of judgment and choice, in computer science, and in the prescriptive theory of decision making. A prototype system, developed for attack submarine antisubmarine warfare (ASW), is based in part on our own study of individual differences in decision-making styles among submarine officers.

The Decision Setting and the Decision Process

The dilemmas faced by the command staff of a hunter-killer submarine in approaching and attacking an (as yet) unalerted hostile submarine are characteristic of situations involving stealth in warfare: How long should I attempt to remain undetected and to improve my position, before I tip my hand by launching a weapon? In planning an attack, the Commander faces a number of choices (among weapons, targets, approach maneuvers, and times of fire) and is flooded with an increasingly unmanageable quantity of data (about the target, own ship, and environment). To capitalize on the element of surprise, a price must be paid in the quality of the data, the complexity of options, and the strenuousness of the choice process. In all of these areas, there is substantial leeway for differences in individual cognitive styles of coping.

Situation Assessment. Assessment tasks must depend almost exclusively on passive sensors (which do not alert the enemy); as a result, data are often fragmentary, noisy, and inconsistent. Little or no guidance is provided in reconciling multiple conflicting estimates of the same variable (e.g., target range), organizing data acquisition, assessing the quality of estimates, or drawing inferences about critical opportunities and dangers (e.g., probability of kill, probability of counterdetection).

Work in cognitive psychology suggests a number of ways in which people may simplify the cognitive demands of these tasks at the risk of suboptimal performance. Where multiple estimates are available for a single variable (e.g., target range), people tend to ignore evidence that contradicts a favored, or earlier, datum and to double count redundant evidence.[4] Patterns of information search tend to avoid stringent tests of favored hypotheses.[5][6][7] Assessments of degree of certainty tend to be overconfident.[8] When inference proceeds in stages (e.g., deriving probability of kill from information about range, which is derived from bearings data), people often act as if conclusions at earlier stages were known to be true, rather than merely inferred.[9] Similarly, the probability of a detailed scenario is often judged higher than the probabilities for component events.[10]

Option Generation. Interdependent elements of a tactic should be considered together: for example, use of certain types of weapons may be precluded by the risk of counterdetection by a third party threat, unless appropriate maneuvers, firing position, and time of fire are selected. The consequences of immediate decisions for later choices may also be critical - e.g., the ability to proceed against or evade a second threat after the initial attack, or the ability to respond if unexpectedly counterdetected.

Research suggests that the process of formulating options is often truncated in a variety of ways. People prefer to treat the elements of complex options as if they were independent choices. There is a tendency to formulate options that span only a short time-frame, and to overlook, as a result, the cumulative risk of pursuing a given course of action over a long period of time.[11] Individuals differ in the degree to which future acts are considered in current planning [12] and in the sheer number of options they consider.[13] Customary ways of viewing a problem tend to hinder the generation of novel and creative solutions.[14]

Choice. The aim of avoiding counterdetection frequently clashes with other goals. A premature attack may both alert the enemy and miss; yet continued approach increases the risk that own ship will be detected before attack or that the target will successfully evade. Perhaps because the information load tends to be large, simple heuristic decision rules are often invoked: e.g., for time-of-fire, "avoid counterdetection"; or "fire as soon as within maximum weapon range and in possession of a range solution."

There is a growing literature in cognitive psychology suggesting that rules like these may be adopted to reduce the cognitive effort that would be involved in a thorough consideration of each option.[15][16] With one such rule, Elimination-by-Aspects [17], all options falling below a cutoff on an attribute are eliminated, and attributes are considered in turn until only one option remains. In "satisficing" [18][19], the decision maker considers a sequence of options but stops as soon as he finds one that clears a cutoff or set of cutoffs on selected attributes. In each of these examples, an option might be eliminated even though it scores very high on some dimensions. In the submarine context, such rules exclude a balancing of tradeoffs - such as accepting a small risk of detection in order to accomplish a mission objective. Satisficing can cause superior options (e.g., a later time of fire) to be overlooked.

It has been suggested that experts differ from novices in their capability to individually recognize a very large number of different problem situations. [20] Klein [21] argues that experts tend to reason holistically, by analogy with previous similar experiences, rather than by analysis and computation. To the extend that this is true, we might expect that for experienced commanders all stages of decision making--situation assessment, option generation, and choice--would be considerably streamlined. At the least, we would expect decision makers to differ in the degree to which they arrive at highly integrative conclusions without the necessity of a large number of explicit intervening steps.

Individual Differences in Decision-Making Style

Early in the design process of the prototype aid, data regarding individual patterns in the use of information was gathered in a procedure involving four former submarine command personnel. They received a questionnaire describing a realistic multiple threat ASW approach and attack scenario. The questions were designed to focus not only on observable patterns of information use, but also on the less conspicuous decision-making processes within which that information plays a role. At each of a number of break points in the scenarios, the officers were asked to specify: the information currently available on board the submarine which they would seek, the source from which they would seek it, the combat decisions that depended on the information, the way the information would affect those decisions, and the objectives of the decision.

Analysis of this data suggested that there were important differences in styles of data gathering, option formulation, and choice to which an aid might cater.

Situation Assessment (A): Amount of Information. The total number of items utilized varied considerably, from 42 information requests by one officer to 18 by another.

Situation Assessment (B): Information Search Pattern. Requests for data fell into two quite distinct patterns. Two of the officers tended to organize data acquisition by source, asking for a "dump" of current estimates from sonar, plot, or fire control, then going on to another source. The other two officers organized data acquisition by item, asking for a given estimate, like target range, from a variety of sources or else selectively requesting different items from different sources.

Option Generation: Time-Span. The officers differed in the time horizon of the options they considered, e.g., focusing exclusively on the immediate actions required to regain a lost contact versus evaluating in advance approach tactics contingent upon recovery of the contact.

Choice (A): Level of Integration. There were differences among officers and for all individual officers across situations in the scope of the objectives which they brought to bear on the evaluation of options. Objectives might be specified quite broadly as preserving own ship, or more narrowly as avoiding counterdetection or watching for clues regarding counterdetection status. Similarly, the goal might be killing the target, achieving a suitable firing position, or opening torpedo tube doors.

Choice (B): Number of Evaluative Dimensions. One officer combined concerns for own ship survival and killing the target in all decisions (each concern might be at various levels of integration). Two of the officers appeared to shift back and forth in their focus between these concerns. The fourth officer went all out for target kill, never once explicitly mentioning an objective related to own ship survival (at any level of integration).

Choice (C): Use of Cutoff Criteria. Three of the four officers evaluated actions explicitly in terms of cutoffs. All three used the achievement of maximum weapon range as a criterion for attack; one used arrival at counterdetection range as a criterion for withdrawal.

A Prototype Personalized System

A prototype personalized aid has been designed and partially implemented for approach and attack planning by the command staff of a nuclear attack submarine. However, only the data base of the aid is affected by the nature of the specific application. Its functional logic, and the methods used to achieve both personalization and prescriptive impact, are quite general. The implementation of a demonstration prototype system in a specific context, however, permits a realistic test of the feasibility of the concepts, with potential users.

Figure 1 outlines the general logic of the cognitive interface. The prototype aid design consists of a data base, a flexible general-purpose Planning Module, and four relatively specialized routines for customizing the aid. The system utilizes principles of spatial data management which combine an undemanding style of interaction with a high degree of user control over display contents. All user inputs are via a single simple locator device (a joystick plus button) with control properties that shift appropriately with the display region where the cursor is located.

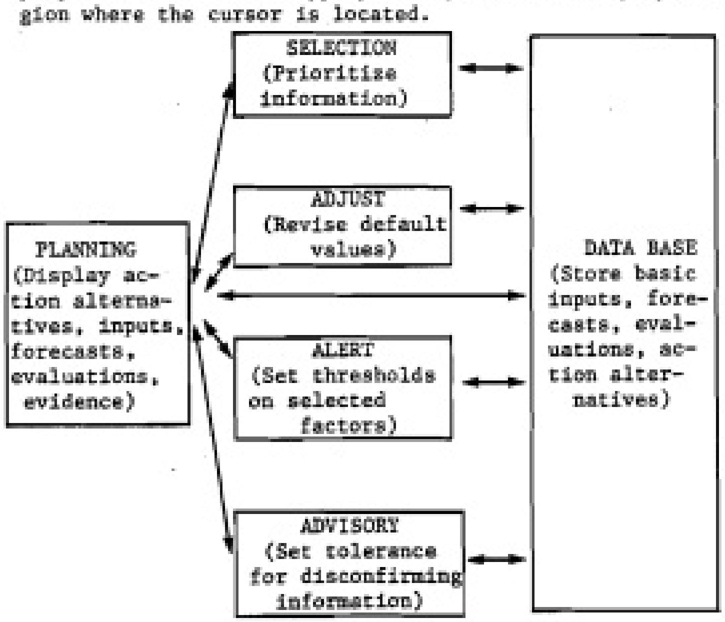

Figure 1. Structure of Prototype Aid

The display area of the Planning Module (Figure 2) is divided into a set of windows which permit simultaneous viewing of substantive results (evaluations of alternative tactics) and a variety of menus by means of which the user can specify the tactics to be evaluated, the criteria to be employed in the evaluation, and sources of validation for displayed results. A final menu enables the user to select other specialized modules (Select, Adjust, Alert, Advisory). The Planning Module facilitates a variety of personal preferences in the approach to situation assessment, formulation of options, and choice.

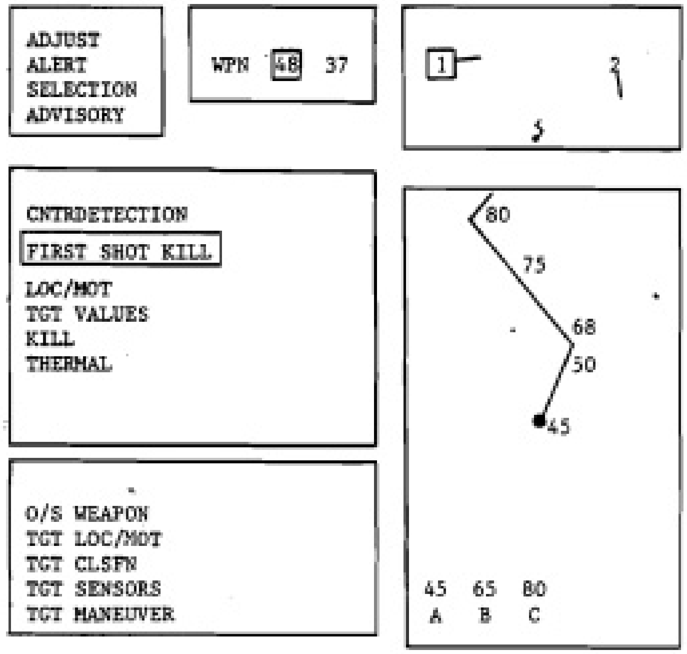

Figure 2. Planning Module Display

Situation Assessment. The data base consists of basic inputs (in the submarine testbed these concern own ship, contacts, and the environment) together with a set of prescriptive models which aggregate those inputs into high-level inferences and forecasts of critical events (e.g., counterdetection and first-shot kill) and evaluations in terms of ultimate combat objectives. The Planning Module enables users to sample information at any preferred level of aggregation in the data base. When higher-level inferences are displayed, the Planning Module clearly distinguishes conclusions from evidence, and indicates the sources from which each inference is derived. The user may elect to examine in more detail any of the evidence utilized in deriving a particular conclusion.

The Selection Module allows the user to view a map of the total data base and to personally select the portion which will be immediately accessible through the Planning Module.

The Adjust Module enables the user to insert subjective judgments in place of default values at any level in the data base. The Planning Module will then display the implications of the hypothetical or revised values for any higher-level inference. (Default values, however, continue to be stored and displayed.) The Adjust Module thus accommodates individual differences in beliefs and preferences and - from a prescriptive point of view - adds a potentially valuable source of information (the user) to the data base. We return to this feature in the last section.

The Alert Module performs situation monitoring for the user. It enables him to set a cutoff or threshold for any variable in the data base (at any level of aggregation) when cutoffs are crossed.

Option Generation. The Planning Module facilitates the formulation and evaluation of complete tactical options (weapons, targets, approach maneuvers, and times of fire). It enables the user to vary the number of alternatives examined and the time into the future over which an option extends. A version of the aid currently under development gives the user a choice between entering his own options directly for evaluation or specifying personalized parameters to constrain automatic option generation.

Choice. In the Planning Module, the user can evaluate options by reference to objectives at any of a variety of levels of integrative scope (e.g., how quickly will the option get me to point x? How will it help improve probability of kill? What is its overall merit, combining probability of kill and probability of own ship survival?).

The Alert Module facilitates individual heuristic strategies (such as Elimination-by-Aspects and satisficing) which evaluate actions by reference to cutoffs as opposed to tradeoffs. After the user sets a threshold on a variable, the Planning Module forecasts whether or not the threshold is expected to be crossed for any action alternative which he wishes to evaluate, and if so, when. Different heuristic strategies for choice imply differences in the way information is searched: e.g., by action (run through all relevant evaluative variables for a given tactic, as in prescriptive theory or satisficing) or by criterion (examine all options for a given evaluative variable, as in Elimination-by-Aspects). In the Planning Module both of these search modes are specifically facilitated.

Prescriptive Prompting

An important factor in designing a personalized and prescriptive aid is the impact of individual preferences on outcomes. Simplifying for illustrative purposes, alternative strategies for performing the same task may fall into one of two classes in this respect:

- Strategy A is generally expected to be more accurate or yield more preferred outcomes than strategy B, but requires more training, more time, and/or draws away more attention from other tasks.

An example, in the area of choice, might be evaluating each option by reference to all the relevant dimensions (A) versus eliminating some options by reference to only a few (B). (Or, in inference tasks, ignoring important sources of uncertainty.) In these cases, differences among people in preference between A and B might reflect differences in their underlying ability to perform A, in their training or knowledge, in their handling of workload, degree of motivation, or their evaluation of the cost of errors.

- For some people, strategy A is expected to be more effective (better in accuracy, payoffs, speed, effort, etc.) than strategy B, while for other people, strategy B is more effective than A.

Payne [15] speculates that search organized by options versus search organized by attributes may reflect individual differences in the way knowledge is internally represented. People who differ in their degree of experience or areas of expertise may prefer and benefit from different ways of structuring a problem.

These distinctions have implications for the appropriateness of prescriptive advice in a personalized decision aid. In the second case discussed above, the user usually does best with the strategy which he prefers; accordingly, an interactive system should simply facilitate selection by the user of the information processing rule or structure to be employed.

In the first case, the computer's role may, at the request of the user, be somewhat more active. It involves an apparent conflict between the user-preferred and the normative strategy - though the use of the former may in fact be well justified by savings in time and effort. In such cases, the computer can assist by applying a prescriptive model to the problem, in parallel with the user's own effort which it monitors. The aid may then advise the user when discrepancies seem significant. The prescriptive model applied by the aid, of course, has no automatic claim to truth; it takes the role, rather, of a "cooperative adversary" or "devil's advocate." It enables the user to concentrate his own attention selectively, in areas that he regards as critical, while notifying him when other issues seem worthy of attention. Advisory prompts thus complement the freedom of individual choice granted by personalizing features; they encourage flexibility by offering some insurance against possible pitfalls.

Two important features of advisory prompts as we seen them are worth stressing:

- The objective is not simply to alert the user whenever there is some difference, however small, between his judgment and the output of a prescriptive model. The difference must be large enough to matter, in the actions to be selected and in their expected outcomes.[22]

- The user himself determines the size of the discrepancy that would justify a prescriptive prompt. The frequency of prompting will thus depend on his own informal assessment of the value of his time and effort relative to the cost of errors. The Adjust Module of the personalized aid enables the user to input that judgment.

Prompts may be introduced to assist users in tasks of situation assessment, option generation, and choice. Our current research involves the conceptual design, implementation, and testing of a variety of such prompts.

Situation Assessment. The user might be notified when two information sources, both of which are regarded as credible, have contradicted one another. He might then choose to implement prescriptive procedures for appropriately readjusting one or both credibility assessments downward. A prescriptive prompt might notify him on future occasions when either of the (partially) discredited sources is involved in an important conclusion.

Advisory prompts might signal when favored information search patterns seem inefficient, e.g., seeking additional confirming evidence for an already well-supported hypothesis.

Prescriptive prompts might warn users, when they estimate or subjectively adjust higher-level inferred variables, that a number of stages of uncertainty must be kept in mind. The same type of caution might be appropriate when the likelihood of a compound, or conjunctive, event is being assessed.

Option Generation. Short range planning might be more appropriate in some situations (e.g., where feedback is continuous and mistakes can be easily and quickly corrected), while long range planning would be more suitable in others (e.g., where a risk appears small unless it is considered cumulatively over the long run). Prompts might recommend that the user consider a shift in time horizon under appropriate circumstances.

A variety of prompts might be utilized to stimulate "creativity," or the generation of novel options. The system might encourage the user to adopt, hypothetically, a new "schema" of the situation by questioning his basic assumptions about the threat, own ship, and environment - especially where the system data base actually has information that deviates from "normal" conditions. Alternatively, the system might encourage the user to better delineate the space of options by generating options tailored to single objectives, especially objectives not so far considered by the user.

Choice. Advisory prompts might signal a user who is employing cutoffs when tradeoffs bear looking into; in particular, where tradeoffs involve evaluative dimensions he has not as yet examined. More generally, the Planning Module might monitor the user's selection of information and specification of options, and derive hypotheses regarding the user's decision process and conclusions. The user would be advised when information about tactical options which he has not requested may have implications for choice that clash with the system-inferred user model.

User Override

In a personalized decision aid, ultimate control over task assignments belongs to the user. We have just seen how this flexibility might be counterbalanced by the aid's capability to monitor the user. In a complementary fashion, the user might quite gladly hand over certain tasks to the aid, retaining, however, the capability of monitoring its performance and interjecting his own judgments where he deems it appropriate.

In a second project for ONR, DSC has developed decision aids which can incorporate both objective data and subjective judgment.[23][24][25] A special focus of this work has been the analysis of passive sonar data to estimate the range of a target on a nuclear attack submarine. This task, logically, should be included within the situation assessment feature of the attack planning aid described in previous sections. In particular, work on this aid has shed some light on how the Adjust Module might be utilized to facilitate user inputs into an otherwise automatic process.

Problem Setting

Numerous techniques are available for estimating target range - based on different aspects of the data (e.g., bearing, intensity, angle between direct and reflected sound paths) and using different analytical tools and assumptions. Typically, since their sources of error are both pronounced and different, they produce quite diverse estimates. Confronted with a divergent set of estimates, the commander is likely either to suspend judgment about range altogether or to focus on only one or two favored techniques, at the expense of others that might either corroborate or contradict them. Attack may be needlessly delayed while a good solution is improved, or be launched prematurely based on overconfidence in a bad one.

Pooling Aid

A range pooling decision aid has been developed, utilizing a Bayesian framework to assist the command staff in balancing and integrating the diverse sets of relevant information. The aid displays evidence (i.e., particular ranging techniques with assessments of their quality) as well as conclusions (a single best guess as to target range together with an interval of uncertainty). This aid has been implemented for testing purposes at the Naval Underwater Systems Center (NUSC-Newport).

For present purposes, two critical features of the aid should be noted:

- It can operate in a completely automatic mode.

Default estimates of pooling parameters, i.e., weights describing the precision of the solutions and their correlations, are based on at-sea exercise data. Ultimately, default parameters will be contingent on a variety of environmental and threat characteristics.

- The user can interpose his own assessments in addition to or in place of default estimates at any point in the range pooling process.

Preliminary Testing of Interactive Modes

The pooling aid has been tested in three modes:

(1) totally automatic (default weights),

(2) totally subjective (weights supplied by user), and

(3) user override (default pooled solutions adjusted by user).

Prerecorded data from at-sea exercises were used to simulate conditions (2) and (3). Recorded command staff estimates ("system solutions") were used to derive subjective weights by multiple regression of command staff estimates on the particular ranging techniques. Command staff adjustment of default pooled solutions was simulated by pooling command staff estimates and default pooled estimates.

Figure 3 summarizes the results of this test for two different samples of Rangex data:

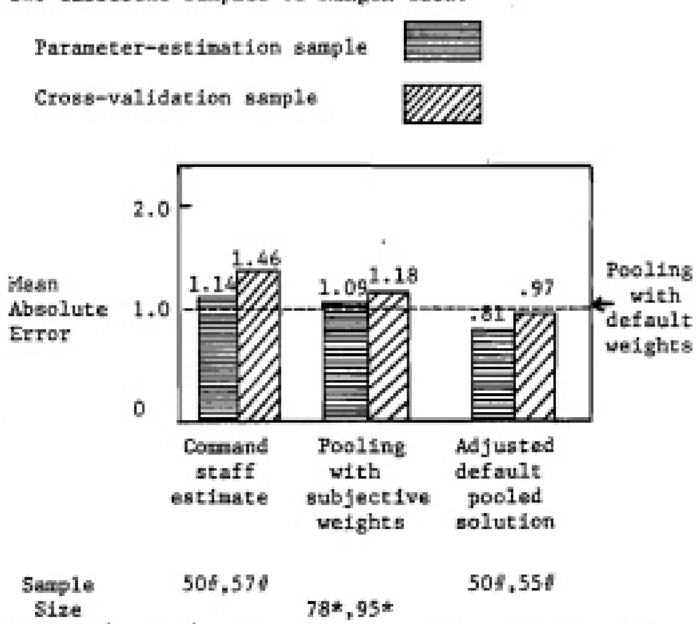

Figure 3. Ratio of Mean Absolute Error (MAE) for Various Interaction Modes to MAE for Default Pooled Solution. # = Rangex 1-78 data; * = Rangex 1-78 and 1-79 data

Subjective Pooling. Pooling with subjective weights was superior in accuracy both to the command staff estimate and to the specific ranging techniques. Although command staff estimates were superior to particular ranging techniques, the superiority of pooling with command staff weights to the command staff itself suggests that the information actually available to the command staff was not being optimally utilized by them.[26] These results would occur, for example, if the command staff were probabilistically selecting among estimates, with probabilities dependent on their relative accuracy, rather than pooling.

Automatic Pooling. Pooling with default weights was more accurate than pooling with subjective weights. This is not surprising since default weights were optimized for the type of data involved in the test. It is at least possible that subjective weights would outperform default weights in situations which differ sharply from exercise conditions.

User Override. The most accurate result was obtained in the third condition, where objective (default) data and subjective inputs were combined. This strongly suggests that, despite ineffective utilization, command personnel have access to relevant information not incorporated in the pooling aid.

This information can be tapped without burdening personnel with the task of formally pooling estimates. Leaving that job to the decision aid, appropriate staff might nonetheless monitor its performance and make adjustments when they observe significant discrepancies from their own intuitive solutions. The Alerting Module can assist in this monitoring, by alerting staff when default pooled range estimates or intervals of uncertainty fall outside a user-specified "plausible" region. Quite apart from any enhancement of user acceptance, our data suggest that incorporation of judgments in addition to objective data can improve the quantitative accuracy of aid outputs.

Other Applications

The requirement of stealth in warfare often imposes a severe constraint on communication among friendly units. Coordination can be achieved by prespecifying courses of action, but at the expense of flexibility. The combination of automatic aid functioning and user override capability offers a different approach. It may be applied to option generation (for example, user override of default option generation settings) and choice (for example, user override of default evaluations of outcomes, such as the relative worth of different types of targets). In either of these cases, default settings might be based on doctrine or mission directives; the provision of override will then set a balance between central guidance and flexible response to unique circumstances.

Conclusion

Both the attack planning aid and the range pooling aid have met with some success in initial demonstrations with representative potential users. Nonetheless, many if not most of the basic ideas presented in this report remain untested. Careful work remains to be done in delimiting the cognitive structures and modes of processing to which aids should cater, in defining and testing non-obtrusive prescriptive prompts, in identifying non-burdensome methods for incorporating judgment, and in developing guidelines to determine when and for whom methods of the sort described here are appropriate. The hoped for benefits include both increased user acceptance and improved system performance.

Note

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