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Effectiveness and Cost Benefits of Computer-Based Decision Aids for Equipment Maintenance

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PREFACE

This study was conducted for Office of the Deputy Under Secretary of Defense (Science and Technology) under the "Cognitive Readiness" task. Technical cognizance for this task was assigned to Dr. Robert Foster, Director, BioSystems.

Dr. Harold F. O'Neil Jr. and Dr. Eva Baker reviewed a draft of this document. We gratefully acknowledge their helpful comments.

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EXECUTIVE SUMMARY

Most "real-world" problem solving is multivariate, complex, and steeped in uncertainty. It encompasses a full range of activity—from vehicle maintenance to tactical deployments. It is an integral and inevitable component of the human competence needed to ensure workforce readiness and viability in the global marketplace. It is an equally integral and inevitable component of military readiness.

Given the complexity of real-world problem solving and the range (both descriptive and prescriptive) of its theoretic underpinnings and procedures, it seems reasonable to seek assistance from technology. The value of doing so is presaged by early studies of clinical and statistical decision-making. These studies found statistical, algorithmic procedures to be superior to the clinical judgments of human beings, even though the statistical procedures were derived solely from the practice of human decision-makers.

This study reviewed the effectiveness and cost benefits of technology used to aid performance of maintenance operations. Performance data have been reported for three military performance-aiding systems:

1. **Computer-Based Maintenance Aids System (CMAS).** CMAS was developed by the Air Force Armstrong Laboratory Human Resources Directorate, Brooks Air Force Base (AFB), Texas.
2. **Portable Electronic Aid for Maintenance (PEAM).** PEAM was developed by the U.S Army Research Institute for Behavioral and Social Sciences (ARI) and the Navy Personnel Research and Development Center (NPRDC).
3. **Integrated Maintenance Information System (IMIS).** IMIS was developed by the Air Force Armstrong Laboratory Human Resources Directorate, Brooks AFB, Texas.

CMAS was a logical extension of efforts to develop maintenance performance aids that could be traced at least to the 1960s, beginning with paper-based performance aids and later with those same performance aids installed on computer systems. Evaluation studies compared technicians using paper-based technical manuals (TMs) with those using CMAS. These evaluations found that technicians using CMAS took less than half the time to find system faults, were able to check more test points, made fewer (i.e., no) false replacements, and solved more problems.

PEAM followed the Defense Advanced Research Projects Agency's (DARPA) development of the Voice Interactive Maintenance Aiding Device (VIMAD) in the late 1970s. VIMAD was the first voice-controlled, wearable computer intended as a maintenance performance aid. PEAM was also portable (briefcase-size) and used voice interaction to allow hands-free access to text and graphics maintenance information needed by technicians. Evaluations, which for a variety of reasons did not use voice interaction, found that maintenance technicians using PEAM exhibited substantial reductions (factors of 5 and 6) of errors in troubleshooting tasks and reductions (factor of 2) in errors solving nontroubleshooting problems.

IMIS is a more recently evaluated computer-based performance-aiding system. Its evaluation concerned fault-isolation problems in three F-16 avionics subsystems: the fire control radar (FCR), the heads-up display (HUD), and the Inertial Navigation System (INS). Technicians involved in the evaluation study used paper-based task orders (TOs) (Air Force TMs) for half of the problems and IMIS for the other half. These evaluations found that technicians using IMIS found more correct solutions in less time, used fewer parts to do so, and took less time to order parts. Analysis of costs found a net savings of about $20 million per year in maintaining these three avionics subsystems for the full Air Force fleet of F-16s.

These findings suggest that

- A strong cost-effectiveness case can be made for using these computer-based performance-aiding devices.
- The development and implementation of these devices should consider the full range of options available for ensuring competent human performance.
- Both descriptive and prescriptive approaches should be employed in the design of these devices.
- These devices should capitalize on modeling capabilities developed for intelligent tutoring systems
- The absence of these devices from routine use, despite their demonstrated value, suggests that more effort is needed to ensure that the state of practice in maintenance operations advances along with the state of the art.

EFFECTIVENESS AND COST BENEFITS OF COMPUTER-BASED PERFORMANCE AIDS FOR EQUIPMENT MAINTENANCE

A. INTRODUCTION

Decision-making and problem solving by technicians are central components of maintenance operations. Problem solving is required when an individual or a group of individuals must achieve a goal but are uncertain how to do so (Baker and Mayer, 1999; Mayer and Wittrock, 1996). Problem solvers require ingenuity and creativity to manipulate and transform the knowledge and skills they possess into paths of action leading to the goal. Most "real-world" problem solving is a multivariate and complex activity steeped in uncertainty. It involves a full spectrum of activity—ranging from vehicle maintenance to tactical deployments.

Decision-making is an integral aspect of human problem solving. It is a critical skill needed to ensure workforce readiness and viability in the global marketplace (O'Neil, 1999). It is made difficult by the frequency with which decision makers are confronted with too much data, too many options, and unknown levels of risk. Decision-making has been the object of systematic study by past and present psychologists for many years (James, 1890/1950; Edwards and Fasolo, 2001).

Given the complexity of real-world decision-making and problem solving and the descriptive and prescriptive range of their theoretic underpinnings, seeking assistance from technology in both activities seems reasonable. The value of technology applications in this area is presaged by early studies of clinical and statistical decision-making (Meehl, 1954). These studies were originally intended to show what human (clinical) judgment would add to purely statistical predictions of outcomes, such as patient response to treatment or academic success. As described by Dawes (1971), the statistical prediction "floor" turned out to be a ceiling. In all 20 cases reviewed by Meehl, statistical predictions based on straightforward linear models turned out to be superior to the clinical judgments of human beings.

Meehl's results might be taken to suggest that we should seek to replace human decision-making with computer-based algorithmic procedures that capture human processes but apply them consistently. However, this approach may go too far for at least three reasons:

1. Many decisions must be made in a dynamic environment. By the time an algorithmic procedure can capture the environment and the decision process, the need for the decision may have long passed.
2. As described by Hastie (2001), incorporating all the elements that should be included in a decision may be impossible. Elements involving intuition, social roles, identification of alternatives, payoff-probability interactions, utilities, uncertainties, and so forth are often too elusive to be captured in anything like the algorithms needed for technological applications.
3. Most humans want to maintain control over their lives. They do not want their lives to be run by machines.

On the other hand, most people are willing to accept (even pay for) assistance and advice in making complicated decisions. The extent to which they are willing to do this depends on the decision to be made and the individual who must make it. Areas in which a great many possibilities can be collected, stored, and accessed by computer and then organized and presented to human decision-makers seem ripe for technology assistance. The value of using computer-based technology to aid human decision-making, problem solving, and generally to augment human cognition is a topic of this document. An example of such augmentation used in life or death decisions is the clinical oncology decision aid.

Example: Clinical Oncology Decision Aid

A combined theoretical approach was used to develop the National Cancer Institute's (NCI) Clinical Trial Decision Aid (Whiteis, McGovern, and Johnston, 2001). The decision aid uses standard personal digital assistant (PDA) technology and evolving heuristics for inclusion and exclusion to assist oncologists in determining a patient's eligibility to participate in melanoma and colorectal cancer clinical trials.

Before developing this decision aid, Mozelak, Glassman, and Johnston (2001) performed a clinical oncology needs assessment that included interviews, focus groups, and surveys. They found that 14 percent of all cancer patients are eligible for enrollment in cancer clinical trials but only 2 percent are actually enrolled. They also found hundreds of public and private clinical trials are being performed nationally. New clinical trials are added and existing trials are dropped with equal frequency. Each clinical trial has its own criteria for including and excluding patients, and each is subject to continuing modification by regulatory bodies and current research results. The situation makes enrollment heuristics hard to acquire and apply.

Physicians indicated that using the Internet or journals to track clinical trials in their field was an unmanageable solution that proved to be time consuming and confusing because of rapid changes in trial availability. They also indicated that each trial had its own selection criteria, which left them to focus on one or two individual trials, neglect other trials, and seek patients who fit the criteria for the specific trials they selected. Mozelak, Glassman, and Johnston (2001) concluded that significant problems exist in enrolling cancer patients for clinical trials because of the need to manage increasing volumes of data and track the rapidly evolving inclusion and exclusion heuristics for each trial.

By searching clinical trial inclusion and exclusion criteria, Mozelak, Glassman, and Johnston (2001) determined that algorithmic heuristics could fit each of the clinical trials. Physicians could adjust the values of seven clinical variables, thereby reducing the number of available clinical trial choices from more than 400 matched trials per patient to an average of 3 matched trials per patient. While the selection rules were not a perfect fit, these rules reduced to a manageable number the trials for which any patient might hypothetically qualify. In turn, the process increased the probability that individual patients might qualify for a clinical trial because the physician no longer needed to screen them for a limited number of trials but could identify for each patient all the trials that were appropriate and applicable.

A prototype decision aid was developed on a handheld PalmOS™ device that downloads NCI melanoma and colorectal cancer clinical trial information each time a physician connects the handheld device to the Internet. By combining formally developed heuristics with a large source of data, the device can locate hundreds of clinical trials along with their descriptions, locations, points of contact, and inclusion and exclusion criteria. The device is currently being tested against other clinical datasets to verify its inclusion and exclusion heuristics.

Recently, 80 percent of one sample of oncologists reported using PDA-based decision aids for this purpose [Mozelak, Glassman, and Johnston (2001)]. Many other applications are likely to be developed, raising issues concerning their cost and effectiveness. Their value is indicated by the military's assessments of problem-solving and decision-aiding devices.

B. MILITARY APPLICATIONS OF TECHNOLOGY-BASED PERFORMANCE AIDS

University research is primarily concerned with developing technical opportunities, not assessing cost and effectiveness tradeoffs. This orientation leads to an interest in effectiveness (i.e., Does it work?) but not necessarily to cost-effectiveness (i.e., Should anyone buy it?). Consideration of the effectiveness and the costs of a proposed innovation is essential for its transition from the research laboratory to routine use. The primary concern of business is not to advance the state of the art, but to seek proprietary advantage. This situation leaves the task of enhancing the state of the art and practice in performance aiding to the government—particularly, the military. The task requires impartial assessments of costs and effectiveness and open dissemination of the findings.

Three system developments are notable in this regard:

1. **Computer-Based Maintenance Aids System (CMAS).** CMAS was developed by the Air Force Armstrong Laboratory Human Resources Directorate, Brooks Air Force Base, Texas.
2. **Portable Electronic Aid for Maintenance (PEAM).** PEAM was developed by the U.S Army Research Institute for Behavioral and Social Sciences (ARI) and the Navy Personnel Research and Development Center (NPRDC).
3. **Integrated Maintenance Information System (IMIS).** IMIS was developed by the Air Force Armstrong Laboratory Human Resources Directorate, Brooks Air Force Base, Texas.

1. CMAS

CMAS was a logical extension of efforts to develop maintenance performance aids that could be traced at least to the 1960s, beginning with an Air Force Project called Presentation of Information for Maintenance and Operations (PIMO) (Serendipity, 1969). PIMO used paper-based, task-specific job guides as performance aids for maintenance and was followed by other paper-based performance aids such as XYZYX Corporation's Job Performance Aids on cards (Inaba, 1988).

Paper-based performance aids were shown to be better than conventional technical manuals in improving technician performance (e.g., Foley and Camm, 1972; Booher, 1978), but they shared and continue to share the usual drawbacks of paper-based technical manuals. For example, they are expensive and inefficient to update; it is difficult to design their presentations to match the differing needs of novice, journeymen, and experienced technicians; they often make necessary information difficult to find and access; and they are heavy and cumbersome to store and use.

Computer technology early entered the scene with recipe conversion aids presented by the Programmed Logic for Automatic Teaching Operations (PLATO) instructional system. Hurlock and Slough (1976) reported data showing that the capability was effective. However, given the state of computer technology at the time, PLATO was too expensive and too cumbersome for routine use. In 1977, the Air Force's CMAS project extended this capability (Clay, 1986). CMAS began the development of concepts for presenting maintenance-aiding information by computer and initiated a chain of developmental efforts continuing into today's Interactive Electronic Technical Manuals (IETMs) and the "mentoring" (decision-aiding) capabilities now incorporated in the Advanced Distributed Learning Initiative (Dodds, 2000, 2001).

Nugent et al. (1987) compared the troubleshooting performance of 36 technicians using technical manuals (TMs) with technicians using electronic presentation of an augmented CMAS database to detect and isolate single component failures in a radio receiver-transmitter. Four problems were presented: two had to be solved using performance aiding presented by TMs and two had to be solved using the electronically presented performance aiding. Table 1 shows the results reported by Nugent et al. As the table suggests, technicians using CMAS took less than half the time to find system faults, were able to check more test points, made no false replacements, and solved more problems. All these results are statistically significant.

Table 1. Troubleshooting Performance of 36 Technicians in Locating Two Faults Using Technical Manuals (TMs) and Two Faults Using CMAS

Avg. Minutes to Locate Fault		Avg. Number of Test Points Checked		Avg. Number of False Replacements		Avg. Number of Problems Solved	
TMs	CMAS	TMs	CMAS	TMs	CMAS	TMs	CMAS
56.5	24.4	3.6	5.6	1.2	0.0	1.7	2.0

2. PEAM

PEAM followed the Defense Advanced Research Projects Agency's (DARPA) development of the Voice Interactive Maintenance Aiding Device (VIMAD) in the late 1970s. VIMAD was the first voice-controlled, wearable computer intended as a maintenance performance aid. PEAM also was portable (briefcase-size) and used voice interaction to allow hands-free access to textual and graphics maintenance information needed by technicians. For a variety of reasons, these evaluations did not use voice interaction.

Evaluation of PEAM was a joint Service effort summarized by Wisher and Kincaid (1989). It involved Army and Navy technicians. The Army used PEAM and, alternatively, a laptop computer to provide PEAM-based maintenance performance aiding for M1 tank turrets. The Army used a between-subjects evaluation, with 9 technicians assigned to the PEAM group and 5 technicians assigned to a paper-based TM group. Both groups of technicians solved 6 troubleshooting tasks and 28 nontroubleshooting tasks (3 adjust and align tasks, 2 service maintenance tasks, 11 unit removal tasks, and 12 install/replace tasks). Table 2 presents the evaluation results.

Table 2. Maintenance Performance of Army and Navy Technicians Using Technical Manuals (TMs) and PEAM

	Avg. Errors per TS Task		Avg. Errors per NTS Task		Avg. Minutes per TS Task		Avg. Minutes per NTS Task	
	TMs	PEAM	TMs	PEAM	TMs	PEAM	TMs	PEAM
Army	3.4	0.7	1.1	0.4	37.0	41.6	12.0	16.1
Navy	5.7	0.9	N/A	N/A	43.9	33.1	N/A	N/A

Note for Table 2: *TS = troubleshooting; NTS = nontroubleshooting.*

To present the PEAM material, the Navy used a workstation-size computer to provide PEAM-based maintenance performance aiding for the North Atlantic Treaty Organization (NATO) SEASPARROW missile. It used a within-subjects design with 28 technicians required to solve two fault-isolation (troubleshooting only) problems: one set of technicians used TMs and the other set of technicians used PEAM simulation.

Table 2 shows, for PEAM groups, substantial reductions (factors of 5 and 6) of errors in troubleshooting tasks for the Army and Navy technicians and lesser, but still substantial, reductions (factor of 2) of errors among the Army technicians solving nontroubleshooting problems. All these results are statistically significant (and practically significant for military operations).

Results concerning the time to perform tasks were mixed, most probably [as Wisher and Kincaid (1989) suggest] because of the long time (in excess of 15 sec) that it took for graphics to appear on the Army PEAM systems. Consequently, the Army technicians using PEAM took longer to perform troubleshooting and nontroubleshooting tasks, although neither of these differences was statistically significant. On the other hand, the

Navy technicians, who used a more powerful computer for PEAM, finished their trouble-shooting tasks more quickly. This difference is statistically significant.

3. IMIS

Assessments of IMIS provide perhaps the best and most complete current evidence on the value of technology-based performance aiding. Tomasetti et al. (1993) documented a thorough cost analysis of IMIS, Thomas (1995) reported results from an empirical investigation of IMIS effectiveness, and Teitelbaum and Orlansky (1996) summarized results from both studies, combined them into a more complete cost-effectiveness assessment, and discussed the implications of these findings.

Thomas (1995) compared the performance of 12 avionics specialists and 12 Airplane General (APG) technicians on 12 fault-isolation problems concerning three F-16 avionics subsystems: the fire control radar (FCR), the heads-up display (HUD), and the Inertial Navigation System (INS). Within each of the two groups of subjects, six of the fault-isolation problems were performed using paper-based TOs (Air Force TMs), and six were performed using IMIS. Training for APG technicians includes all aspects of aircraft maintenance, only a small portion of which concerns avionics. In contrast, the avionics specialists, who must meet higher selection standards, receive 16 weeks of specialized training focused on avionics maintenance.

Results of this study, which are shown in Table 3, can be summarized as follows:

- **Avionics specialists using TOs compared with those using IMIS.** The avionics specialists using IMIS found more correct solutions in less time, used fewer parts to do so, and took less time to order these parts. All these results were statistically significant.

  The number of parts required deserves brief comment. Savings in spare parts inventory and transportation were by far the largest factors in the Tomasetti et al. (1993) cost analysis. The number of parts required also exerted considerable leverage on the overall cost savings reported by Teitelbaum and Orlansky (1996).

  The results concerning time to order parts are to be expected because IMIS automates most of this process. These results are included here because they are large and because the time required by technicians to complete the paperwork in the absence of IMIS could be spent elsewhere (i.e., substantial productivity gains and cost savings could be realized if IMIS, or a similar capability, performs these paperwork chores).

Table 3. Maintenance Performance of 12 Air Force Avionics Specialists and 12 General (APG) Technicians Using Task Orders (TOs) and IMIS

	Correct Solutions (%)		Time To Solution (Min)		Average Number of Parts Used		Time To Order Parts (Min)	
	TOs	IMIS	TOs	IMIS	TOs	IMIS	TOs	IMIS
Avionics Specialists	81.9	100.0	149.3	123.6	8.7	6.4	19.4	1.2
APG Technicians	69.4	98.6	175.8	124.0	8.3	5.3	25.3	1.5

- **APG technicians using TOs compared with those using IMIS.** Thomas found similar results in these comparisons. The APG technicians using IMIS found more correct solutions in less time, used fewer parts to do so, and took less time to order them. As with the avionics specialists, all these results were statistically significant.
- **APG technicians using IMIS compared with avionics specialists using TOs.** The APG technicians using IMIS found more correct solutions in less time, used fewer parts to do so, and took less time to order these parts than the avionics specialists using paper-based TOs. All these results were statistically significant. This result suggests that replacing some of the extra training required by specialists with the on-the-job, just-in-time performance aids (e.g., IMIS) supplied to nonspecialists is feasible and desirable.
- **APG technicians using IMIS compared with avionics specialists using IMIS.** In these comparisons, the APG technicians performed almost as well as the Avionics specialists overall and even slightly better in the number of parts used. None of these comparisons were statistically significant, and none appear to be practically significant. These results again suggest the feasibility of replacing some number of specialists (and their greater training costs and requirements) with general technicians who are provided with on-the-job, just-in-time performance aids. These results also suggest the desirability of doing so, because, in this case, the training costs of the specialists are greater than those of the nonspecialists even though the resulting performance on the job, where it counts, is the same in both cases.

The promise suggested by these results could vanish if the costs to provide the IMIS performance aid exceed the costs they otherwise save. However, what if the costs and benefits analysis by Tomasetti et al. (1993) were combined with the empirical results reported by Thomas (1995)? By using these two sources of data, Teitelbaum and Orlansky (1996) were able to estimate reductions in depot-level maintenance, organizational-level maintenance, and maintenance and transportation of inventories of spare parts. They estimated annual savings from the use of IMIS to be about $38 million for the full Air Force fleet of about 1,700 F-16s.

Teitelbaum and Orlansky also considered the costs to develop and maintain IMIS. Assuming an 8-year useful life for IMIS, they arrived at a figure of about $18 million per year to maintain IMIS (including its databases) and to amortize its development costs. The result is a benefit of about $20 million per year in net savings.

This figure of $20 million is conservative. It does not include

- Savings in selection and training that would result from a reduction in Air Force requirements to recruit and train specialized personnel (e.g., the avionics specialists in Thomas' study)
- Savings in training that would accrue from using IMIS as a performance aid and as a training device
- Savings in the costs to print, distribute, and update paper TMs
- Savings (of about 50 percent) in time to debrief pilots about maintenance problems.

Most importantly, these benefits do not include those arising from increased sortie rates and unit operational readiness and effectiveness that would result from the substantially improved problem-solving competencies of maintenance personnel. The monetary value of these benefits is difficult, perhaps even impossible, to assess.

C. DISCUSSION AND CONCLUSIONS

At least six observations can be made concerning the findings reported in this document.

1. Observation 1: Performance aids enhance performance and lower costs.

The Oncology Aid, CMAS, PEAM, and IMIS assist decision-making and problem solving. Capabilities such as job performance aids, electronic performance support systems, technology-based "mentoring," and those capabilities more typically described as individual and group performance aids are intended to match user intentions and relevant data with the decision heuristics that address a full range of problem solving. As suggested by results presented in this document, this range includes the maintenance of devices and systems. Performance aiding in maintenance operations has yielded useful evidence on effectiveness and cost returns. This evidence indicates the general value of technology-based performance aiding.

2. Observation 2: Design guidelines are needed.

The results discussed in this document suggest that a strong cost-effectiveness case can be made for the development and implementation of technology-based performance aids across a variety of applications. More data of this sort are needed for a conclusive case, but, as current findings suggest, so far, so good. What is not clearly evident is how these technology-based capabilities should be designed. Current functional designs are based on best guesses. We still have much to learn about what functionalities should be included to ensure that these technology-based capabilities serve as effective partners in human decision-making and problem solving. To accomplish this end, we need to know more about both the functionalities we are able create and the human problem-solving processes we want to assist.

3. Observation 3: Performance aids are part of a system.

A decision, for instance, to supply IMIS to all Air Force APG technicians may be a good idea, but it should not be extended to a wholesale replacement of all avionics specialists and avionics specialist training. This decision should consider the full perspective of all efforts undertaken to ensure that human performance is provided when and where it is needed.

More generally, aids for performance aiding and problem solving need to be treated as components of an integrated system intended to ensure the availability of human competence. The object is not just effective decisions or problem solving alone, but also an effective military organization. Resources to accomplish this end involve developing selection standards for the people who are to solve the problems; structuring the tasks, jobs, and careers to which they are assigned; providing training and education; and, of course, carefully designing the performance aids they will use and ensuring the effective implementation of these performance aids. All these components interact. An investment (or lack thereof) in one area affects all other components and the functioning of the organization as a whole. Determining these allocations should be treated as part of the full system of human competence needed by the organizational entity—be it a military unit, company, university, or government agency.

4. Observation 4: Performance aids should accommodate natural and formal heuristics.

As Edwards and Fasolo (2001) discuss, the design of performance aids has necessary roles for descriptive and prescriptive approaches. Prescriptive theories help by explaining—often in quite formal terms that are amenable to algorithmic procedures—how decisions should be made, based on well-defined criteria and optimized choice of alternatives. Techniques like utility theory (von Neumann and Morgenstern, 1947) rational choice theory (Simon, 1955), and prospect theory (Kahneman and Tversky, 1979) are all applicable. Edwards and Fasolo summarized current prescriptive techniques by organizing them under three widely used, general approaches (multiattribute utility measurement, Bayesian probability rules, and maximization of subjectively expected utility), all of which can play a role in good decision-making.

In contrast, descriptive approaches attempt to explain how people actually make decisions in "real life." These approaches often use case studies to understand and explain decisions by describing the actors, the context of the decisions, and the intended outcomes for case. Examples of this second category include an analysis of decision-making in the Cuban missile crises (Allison, 1971) and an analysis of the surprise attack at Pearl Harbor (Wohlstetter, 1962). Such descriptive approaches were used extensively in the design of the Oncology Aid.

A synthesis of descriptive and prescriptive approaches can be provided by naturalistic decision-making (NDM) (e.g., Orasanu and Connolly, 1993; Klein, 2000). NDM combines elements of formal models with reason-based analysis, elicitation, and direct observation. Zsambok (1997) describes NDM as the "way people use their expertise to make decisions in field settings" (p. 4). It attempts to capture and describe decision-making by observing and interviewing individuals (as in descriptive approaches) and abstracting from these cases more formal models (as in prescriptive approaches), such as Klein's Recognition-Primed Decision Model (Klein, Calderwood, and Clinton-Cirocco, 1985), which categorizes decision-making stages and strategies. A systematic effort to apply NDM to the maintenance-aiding applications discussed in this document may be an important next step in the development of these applications.

Performance aids need to address real-world decision processes and the requirements of field applications while incorporating prescriptive theories and/or optimal heuristics derived from value-based models. Both descriptive and prescriptive approaches can and should be used in designing and developing performance aids. As the examples discussed in this document suggest, computer technology may not be necessary to support such applications, but it is difficult to imagine any practical alternative to it.

5. Observation 5: Performance aids need "intelligence."

If we seek technologies that participate as partners in human problem solving, the technologies need to understand the human side of the issue. To some extent, they need to be "intelligent." For instance, the primary need for maintenance technicians (and other problem solvers) is not a capability that starts at the beginning of a procedure and leads them through to the end, valuable as that may be. More typically, maintenance technicians begin troubleshooting a specific procedure, encounter anomalies, and need help. They need a device that has the capability to engage in a decision-aiding, mixed-initiative dialogue with either the technician or the performance aid capable of taking the initiative to ask questions, seek clarification, access databases, and suggest measurements and hypotheses. Much is made of dialogue management in tutorial instruction (e.g., Graesser, Person, and Magliano, 1995). A capability for dialogue management in problem solving, in general, and maintenance aiding, specifically, is needed and should be developed. This need suggests that the decision-aiding communities and the intelligent-tutoring communities should collaborate.

Other "intelligence" is required in technology-based problem solving and performance aiding. As described by Fletcher (2002), among many others, this intelligence is needed for comprehensive coverage of the decision space so that the suggested actions are relevant and applicable. Intelligence is also needed to represent the user so that advice is given in a form that the user—at whatever level of knowledge, intent, or ability—is capable of understanding and using. Finally, heuristics are needed to infer solutions to the problem presented. These capabilities are to one degree or another present in intelligent tutoring systems and performance aids. It is not a great distance from the avionics training capabilities impressively demonstrated by an intelligent tutoring system such as Sherlock (Gott, Kane, and Lesgold, 1995) to avionics performance aiding. Again, the communities concerned with these developments would benefit from increased coordination and communication.

6. Observation 6: Where are the performance aids?

In contrast to the favorable findings reported in this document and the promise of even more capabilities as technology-based performance aids are developed, only one of the devices—the Oncology Decision Aid—is currently in use. CMAS, PEAM, IMIS, and

Sherlock are absent from daily maintenance practice in the military. The research and development (R&D) community has assumed a responsibility to advance the state of the art and has been successful in fulfilling it. The complementary responsibility to advance the state of practice in performance aiding and problem solving through technology transfer and engineering in the field does not appear to be receiving the attention it needs.

D. FINAL WORD

This brief summary presages an evolving and perhaps inevitable future in which hand-held, or more likely wearable, personal technology-based learning and problem-solving assistants will be as common as wristwatches. They will be widely used to augment human cognition and enhance human competency. As evidenced by the findings reported in this document, we can build technology-based tools that make us "smart" (Norman, 1993). We will communicate with them in natural language, and they, in turn, will communicate with the global grid to provide advice and information. How well they articulate this advice and information back to the individuals who use them will depend, to some extent, on how well they understand each individual's needs, intentions, and capabilities. As suggested in this document and elsewhere, capabilities for individualizing presentations and communications are evolving in several domains [e.g., human computer interaction, modeling and simulation (M&S), and intelligent tutoring].

How well these technology-based learning and problem-solving assistants enhance human problem solving will also depend on how well those who design and build them understand the processes human beings use to solve problems. What is the optimal, most effective division of labor between humans and machines? Meehl's (1954) ancient finding still stands: procedures that capture our decision processes, but avoid human distractions and foibles, may make better decisions than we do. We must learn how best to develop and use this capability. We need to progress from art to engineering. The results presented here suggest that efforts to do so will be worthwhile.

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GLOSSARY

AFB	Air Force Base
APG	Airplane General (technicians)
ARI	U.S Army Research Institute for Behavioral and Social Sciences
CMAS	Computer-Based Maintenance Aids System
DARPA	Defense Advanced Research Projects Agency
DTIC	Defense Technical Information Center
FCR	fire control radar
HUD	heads-up display
IEEE	Institute of Electrical and Electronics Engineers
IETM	Interactive Electronic Technical Manual
INS	Inertial Navigation System
M&S	modeling and simulation
NATO	North Atlantic Treaty Organization
NCI	National Cancer Institute
NDM	naturalistic decision-making
NPRDC	Navy Personnel Research and Development Center
NTIS	National Technical Information Service
PDA	personal digital assistant
PIMO	Presentation of Information for Maintenance and Operation
PLATO	Programmed Logic for Automatic Teaching Operations
POC	point of contact
R&D	research and development
TM	Technical Manual
TO	task order
TR	Technical Report
VIMAD	Voice Interactive Maintenance Aiding Device

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14. ABSTRACT

Data are summarized from assessments of three computer-based aids—Computer-Based Maintenance Aids System (CMAS), Portable Electronic Aid for Maintenance (PEAM), and Integrated Maintenance Information System (IMIS)—intended to support problem solving in maintenance operations. All three were shown to increase accuracy and to reduce errors and time required for maintenance operations. Cost benefits were reported for IMIS, which produced net savings of about $20 M per year in maintaining three F-16 avionics subsystems. The findings suggest that (a) a strong cost-effectiveness case can be made for the computer-based aids, (b) their development and implementation should consider the full range of options available for ensuring competent human performance, (c) both descriptive and prescriptive approaches should be employed in their design, (d) they should incorporate capabilities developed for intelligent tutoring systems, and (e) their absence from routine use despite their demonstrated value suggests that more effort is needed to ensure that the state-of-practice advances in maintenance operations along with the state of the art.

15. SUBJECT TERMS: avionics, Computer-Based Maintenance Aids System (CMAS), cost and effectiveness, decision aiding, equipment maintenance, Integrated Maintenance Information System (IMIS), maintenance technicians, performance aiding, Portable Electronic Aid for Maintenance (PEAM)

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