Information Processing Analysis of Human Land Mine Detection Skill

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ABSTRACT

This paper describes findings from a study conducted to analyze the behavior, knowledge, and thinking that support the highest levels of human land mine detection skill. A recent assessment of land mine detection capability concluded that "human operators perform better with any detector system than the corresponding fully automated system."[1] This assessment, plus evidence linking individual differences in detection ability to experience, suggests that methods, data, and theory developed in studying human expertise can be applied to the problems of land mine detection and discrimination. Studies of experts across a variety of skill domains have demonstrated that analyses of experts' skills can yield findings useful for designing efficient and effective training programs and supporting technology development. This initial field study was performed to (a) identify the upper levels of human mine detection capability using currently-fielded hand-held equipment and (b) model the knowledge, thinking, and techniques employed by proficient human operators. Two experienced operators showed sufficiently impressive detection performance to qualify as experts. Data also show that a skilled PSS-12 operator can detect low-metal mines with considerable accuracy. A first-approximation information-processing model of expert operator skill is presented that is based on observation of the operators' activities as they searched for mine targets.

Keywords: cognition, expert, human operator, information processing, land mine detection, skill, training

1. INTRODUCTION

Land mines pose a significant and growing threat both to the capabilities of US military ground forces and to the lives, limbs, and economic welfare of civilians in lands in which armed conflicts occur. From a military perspective, land mines have accounted for an increasing proportion of the casualties sustained in wars and operations other than war in which the US has engaged since World War II.[2] Technological advances have decreased mine size and costs, thus promoting widespread proliferation, and have also made mines harder to find and neutralize. Currently mines provide inferior forces with the capability to neutralize US military superiority in mobility and firepower.[2,3] Moreover, once deployed, mines' lethal longevity threatens the lives and welfare of native peoples decades after conflicts that prompted their use have ended. An estimated 26,000 civilian deaths annually are attributed to mines.[4] An estimated 100,000,000+ mines remain emplaced in more than 62 countries.[3,4]

The scope, complexity, and difficulty of the mine problem creates a threat comparable to that posed by nuclear, biological, and chemical warfare.[2] As a consequence, multiple coordinated countermine initiatives are underway that operate on several time scales. The recent infusion of support for basic research on concepts and approaches that have potential to support future solutions is a long-term strategy. The near-term strategy involves development of a variety of new technologies for mine detection and neutralization tailored to fit the different requirements of combat countermine and humanitarian demining missions. In the area of advanced detection technology, new airborne systems, multi-sensor hand-held systems (HSTAMIDS), and ground-based autonomous vehicle systems are being developed.[5] Until these approaches are tested and fielded, however, more immediate countermine initiatives must address the problem. Programs to disseminate information about the severity and nature of mine threats are in place and efforts are directed toward maximizing the effectiveness of existing countermine technologies.[3]

Currently, the most sophisticated hand-held land mine detection system used by US forces is the AN/19, PSS-12 metal detector in the hands of a well-trained human operator. Although the limitations of this technology are understood, especially the problem of detecting mines with minimal or no metal content,[3,6] until the more sophisticated HSTAMIDS systems are fielded, the hand-held PSS-12 represents the detection tool, whose effectiveness must be maximized. Given the

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limited development potential of the hardware component of this system, a near-term strategy for improving mine detection capability is to focus on improving the capabilities of the human component of the system.

Training is the principal mechanism for modifying the human component of the system. However, while calls for developing new countermine machinery have been addressed, calls for a similar effort to "re-engineer" training[2,5,7] have only recently received attention. This project is part of this initiative.

The goal of this project is to investigate the peak capabilities of a human operating a PSS-12 and to identify the nature of the expert skills and abilities that produce maximal mine detection capability. Definition of these skills and their component elements offers essential basic principles and data for engineering new and more effective countermine training programs.

This paper outlines the aims and approach of this project, findings from an empirical study on mine-detection expertise, and an information-processing model of the skilled land mine detection that describes the behavior, knowledge, and thought processes employed by skilled PSS-12 operators to achieve the observed levels of mine detection performance.

1.1 Approach

HSTAMIDS are systems with two basic components: a sensor device, in this case a PSS-12, and a human operator. The PSS-12 extends the sensory capabilities of the operator, providing information which he interprets to infer the presence and location of buried land mines. Maximizing the capabilities of the system involves maximizing the capabilities of the two components and their interface. To do so, the same engineering principles should be applied uniformly to the entire design, although the basic principles, theories, and methods applied to the design of the key components are, of course, quite different.

Recent studies in Cognitive Science show that it is possible to "engineer" human expertise far more effectively and efficiently than could have been believed 25 years ago. Theory, empirical principles, and methods characterizing the knowledge and cognitive processes that produce highly skilled performance and the ways knowledge, processing, and performance change as complex skills are learned represent the basis science for engineering expertise[8-14] and designing instructional programs.[15,16] The critical resource is an information-processing model of the knowledge and mental processes that an expert performer in a particular domain uses to achieve exemplary performance. Development of such a model in the domain of land mine detection holds potential to guide the development of new training programs. Such a model could also inform the design of robotic land mine detection systems and information displays for future hand-held and remotely-operated, man-in-the-loop detection systems.

Development of such a model requires the availability of an expert PSS-12 operator for study. Although analysis of expertise performance is usually carried out prior to an information processing analysis of that performance, limited availability of appropriate field testing facilities dictated pursuit of the two project goals simultaneously: In this study data were collected to identify the most capable and experienced land mine detection personnel available based on measures of performance, and to obtain insights into how they achieve the levels of performance they demonstrate.

2. METHOD

2.1 Operators

Two operators were recruited who had extensive field experience in land mine detection and neutralization using the PSS-12 and its predecessor, the PSS-11. Both operators were paid their standard hourly rate for participation in this study.

RR first received military training in countermine and explosive ordnance disposal in 1967. He has participated in mine unexploded ordnance (UXO) clearance operations in Vietnam, Cambodia, Somalia, Mozambique, El Salvador, and Kuwait, working as a team leader and deminer. In Kuwait alone, RR is credited with the detection and neutralization of over 10,000 land mines. He has logged approximately 26 months clearing mines and unexploded ordnance. RR has served as a trainer and as a consultant to Mines, Countermines, and Demolition at Ft. Belvoir and the Engineering School at Ft. Leonard Wood. His last experience in detecting and clearing live mines and UXO was in late 1996.

The second operator, WS, had trained under RR and worked as a member and later as a leader in RR‘s demining team in Kuwait following Operation Desert Storm. He accumulated approximately 8 months of experience, where he was personally credited with the detection and neutralization of approximately 2,200 mines. His last experience in using a PSS-12 for this purpose was in Kuwait in mid-1993.

2.2 Equipment

The detection equipment used was the PSS-12 (designated AN-19 by its manufacturer, Schiebel Corporation). This device is a hand-held, pulsed induction metal detector. The sensor head of this device consists of transit and receiver circuitry arranged in two concentric circles approximately 35 mm apart. The outer coil is .270 m in diameter. The sensor head is attached to a lightweight, telescopic shaft that the operator grips to sweep the sensor head over the ground. Signals from the sensor are carried via shielded cable to an electronics unit worn by the operator on a shoulder strap. The system's electronic circuitry and battery compartment are housed in this unit where a power switch, controls for sensitivity and volume, and a failure warning light are located also. The PSS-12 outputs an auditory signal to the operator when conducting material enters its sensor field. In standard configuration, signals are output via an earphone that can be worn over the ear, or attached to the operator's clothing. The unit employed also had an external speaker, which both operators had the option of using. This unit was the personal property of RR. Although RR was familiar with the unit, having familiarized himself with its performance, he had no experience with the unit in areas where live ordnance was present. WS had no previous experience with this particular unit.

A metallic trowel was also carried by each operator. This tool was used to check the PSS-12's sensitivity at short intervals throughout its use. RR also used the trowel to mark locations on the surface of test lanes.

Targets used were a mix of 71 anti-tank (AT) and anti-personnel (AP) mines, whose size and metal content varied. All were actual mines carrying their normal explosive charges (except for the PMA3 and the booster for the M14) rendered safe for test purposes by installation of inert detonators. Table 1 lists the distribution of targets on different test lanes. Not included in the table are plastic mine surrogates of varying size that were buried in each lane and three PMA3s buried in lane 3B, whose metal components had been removed.

Table 1

Target Frequency by Mine Type and Lane

			Lane			
Mine Type	**Class**	**Metal Content**	**3B**	**2B**	**5B**	**4B**
M14	AP	LM(S)	2	2	4	4
TS50	AP	LM(L)	3	2	4	3
PMA3	AP	LM(L)	0	2	2	1
VS50	AP	M	3	2	3	3
PMD6	AP	M	3	3	3	3
VAL69	AP	M	2	2	2	2
VS1.6	AT	LM	0	0	1	1
M19	AT	LM	1	1	1	1
M15	AT	M	2	0	2	1

A miniature video camera and recorder with two-channel audio recording capabilities and a pair of microphones were used to capture the operator's view of the detector head against the ground surface, the PSS-12's output, and the operator's verbalizations during search.

2.3 Setting and Test Conditions

Tests was performed on four specially prepared mine test lanes located on Range 71A at Fort A. P. Hill, Virginia. Each lane was 3 meters wide. Lengths varied, with two lanes 41.5 meters long (4B, 5B) and two others 44 m (3B) and 45 m (2B). The soil in two lanes was a sandy/clay mixture (3B, 5B) and the two others (2B, 4B) were covered with crushed stone. According to available archival information, mine locations were randomly distributed within lanes. AP mines were buried at depths of 1 or 2 inches and AT mines were buried at depths of either 2 or 6 inches. At the time of testing all mines had been in place for at least 5.5 months. The lane surfaces were well weathered and showed no surface anomalies that could allow identification of mine location by visual inspection (acknowledged by each operator in post-trial interviews).

In addition to the mines in the test lanes, an example of each type of target mine was buried in soil of the type found in the sand/clay and gravel lanes in marked calibration areas that were continuations of two of the test lanes. The identity of each exemplar was provided and the exact position of each was marked on the ground surface. AP mines were buried at 1" depth and AT mines were buried at 2" in the calibration area at the end of gravel-covered lane 4B. AP mines were buried at 2" depth and AT mines were buried at 6" in the calibration area at the end of lane 5B, composed of sandy clay.

Weather conditions throughout the four days of testing in December 1998 were uniformly sunny and very dry with high temperatures in the 70s F.

2.4 Test Design

Each operator was tested on the entirety of each of four lanes. Each lane was searched once by each operator. The ordering of lanes for testing was determined randomly, subject to the constraint that operators alternate search between sandy/clay and gravel lanes. The ordering that resulted was sand/clay (3B), gravel (2B), sand/clay (4B), and gravel (5B). The order of lane search was identical for the two operators. Note that this confounded lane with testing order.

2.5 Procedures

Prior to testing, each operator was given an overview of testing procedures, target materials, and the test schedule. Then, instructions for testing were presented. Each operator was told that the goals of testing, in order of priority, were to (1) maximize target detections, (2) minimize false alarms, and (3) search as quickly as possible without compromising (1) and (2). Mine declarations were to be indicated by the operator by placing a poker chip on the ground as close as possible to where the center of a mine was inferred to be. After placing each chip, operators were asked to report a confidence rating for each declaration using a 5-point rating scale.

Operators then received instructions for providing verbal reports of their thought processes while they were searching[17] and approximately 10 minutes of practice. They then proceeded to the calibration lane whose surface corresponded to the lane about to be searched. Operators were given up to 10 minutes to familiarize themselves with equipment and set equipment sensitivity using the calibration targets. Operators were reminded of performance goals and their priorities before starting search of each lane.

Prior to operator testing on each lane, the lane was divided in half lengthwise and the boundaries of the search area were clearly marked. The entire length of the right hand side of each lane was searched first, followed by search of the remaining half in the same direction. Operators were tested individually.

Testing was “blind,” following standard Army test procedures; that is, no feedback on the accuracy of mine declarations was provided to operators. Probing or digging for mines was also prohibited.

Operators were free to interrupt search at any time to either recalibrate their equipment in the calibration lanes or take rest breaks, water, or food. Following each trial, operators were debriefed and given the opportunity for rest and refreshment. At the conclusion of each test session, each operator received a more extensive debriefing.

2.6 Measures and Scoring

Scoring of declarations was performed by an Army survey team supporting this effort. Declarations within a halo of .1016 m measured from the outer perimeter of each target were scored as hits. Performance measures calculated from these data included probability of detection (PD) and false alarm rates (FAR).[18, 19] Excluded from scoring of PD were the plastic surrogates and the PMA3s in lane 3B that had no metallic content, and hence, should not be detectable using the PSS-12. Rate of advance (ROA) was calculated based on actual search time in lanes, excluding calibration and break times, and is expressed as sec/m.[2] Due to failure of recording equipment on RR’s first test trial, an observer recorded trial start and stop times, declaration locations, confidence ratings, and verbalizations in writing on specially prepared coding sheets while advancing alongside the operator outside of the nearest lane boundary. Target locations were unknown to the observer.

3. RESULTS

The military performance standard for a portable, soldier-operated metallic mine detecting device as specified in the 1990 Operational Requirements Document[20] sets PD at greater than 0.92 and an advance rate of approximately 18 sec/m.[2] Generally, humanitarian demining places a premium on PD, accepting a slower pace.

Aggregating over lanes and trials, WS achieved the military accuracy standard with an overall PD of 0.93[2] (0.83, 0.97). The PD observed for RR was 0.80 (0.68, 0.87). In contrast, overall PD for soldiers tested using the PSS-12 on the same lanes and targets in an independent study[21] was 0.71 (0.67, 0.77).[3] Median FARs for RR and WS were 0.21 and 0.55. The FARs for specific lanes varied considerably.[4] Densities of false alarms within 5 m segments differ by as much as a factor of 5, with the exception of lane 2B, where the distribution of FAs is relatively uniform for both operators across segments. The pattern of variation in FAR densities is quite similar for both operators across all lanes ($\rho_s = .76$, $p < .01$). FARs for soldiers were not available for comparison. Overall ROAs for RR and WS were 33.3 and 54.6 respectively. High variability in ROAs for individual lanes/trials was seen again. Comparison of the relation of the PDs of each operator to his respective FARs and ROAs shows individual differences suggestive of a PD/FA tradeoff. WS achieves higher PDs than RR, but the greater accuracy comes at the expense of more FAs and a slower ROA.

Table 2 shows performance measures for both operators as a function of trial/lane. Striking monotonic trends are seen on all measures for WS. For each measure, PD, FAR, and ROA, a linear function characterizes the relation between practice, measured in trials, and each performance measure, when log tranforms are applied. Such functions reflect the general empirical principle governing the relation between practice and skill learning.[22] In short, WS' performance improves with each trial.

Table 2

Operator Performance as a Function of Trial Order

	RR			WS		
Trial	**PD**	**FAR**	**ROA**	**PD**	**FAR**	**ROA**
1	0.68	0.38	60.0	0.84	1.42	119.1
2	0.86	0.08	25.9	0.93	0.99	58.6
3	0.82	0.23	40.0	0.95	0.86	50.6
4	0.84	0.15	26.5	1.00	0.63	37.1

Note: False Alarm Rate (FAR) is expressed as FA/m^2 ; Rate of Advance (ROA) is expressed as sec/m^2.

RR's performance across trials shows a different, but nonetheless consistent pattern across the three measures. Generally, his performance improves substantially (20-30%) from his first to second trials on sandy/clay lanes. On the gravel lanes, he shows negligible change on PD and ROA and slight degradation on FAR, although the reliability of a difference of the observed magnitude is certainly suspect.

For both operators, FAR and ROA show a curvilinear relation that is well fit when a quadratic transformation is applied to ROA. Thus, false alarms cost in terms of search time, but the cost in time per false alarm is not uniform. Rather, the cost per FA increases as false alarm frequency increases.

The ability to detect mines with low metallic content with a PSS-12 is particularly important. Figure 1 addresses this issue, showing PD for RR, WS, and soldiers as a function of mine categories created by aggregating as a function of mine

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[2] The upper and lower limits of the 95% confidence intervals associated with each PD are included in parentheses.

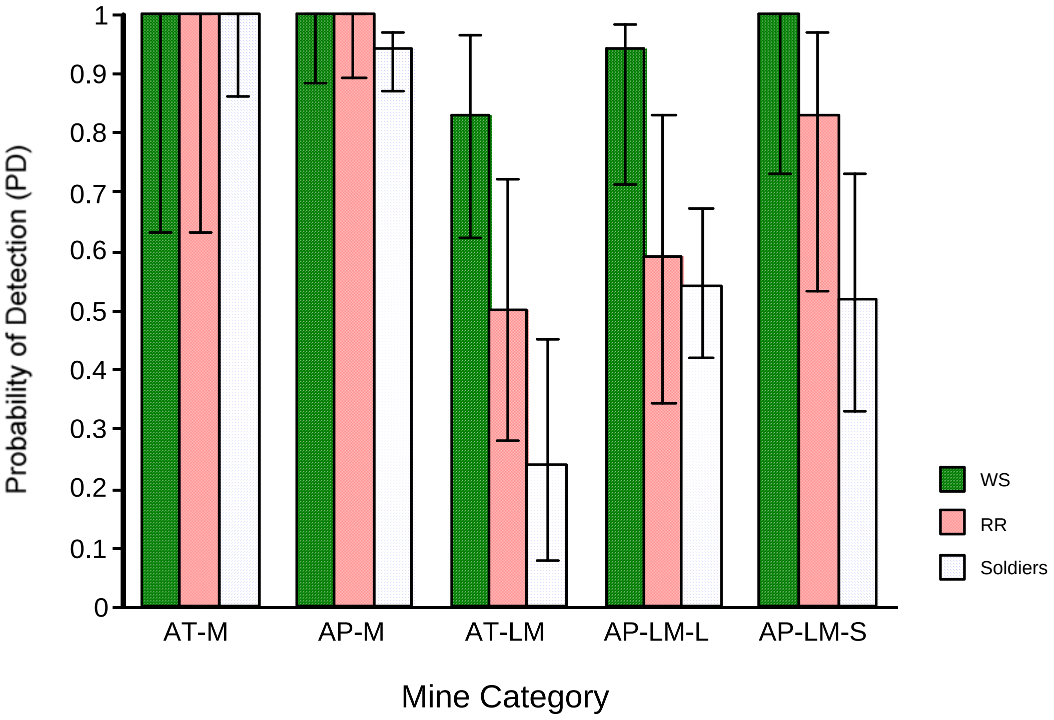
[3] Differences in test procedures between studies dictate caution in interpreting soldiers' performance relative to that of WS and RR. The soldiers were tested in the summer in hot and humid weather, they used different PSS-12s, and all soldiers were not tested on all lanes. At the same time, the soldier data set is the only one known obtained on the same mines in the same location with the PSS-12.

[4] The high variability of FARs within lanes for each operator violates assumptions related to the use of confidence intervals, thus 95% confidence intervals are not reported.

type (AT, AP), metallic content (M, LM), and size (for LM mines only). The effects of metallic content on PD are striking. WS, RR, and the soldiers show effectively asymptotic performance for metal AT and AP mines. PD on notoriously difficult-to-find LM targets differentiates the operators and the soldiers. The pattern of detection performance is consistent with findings in the literature on human expertise showing that differences as a function of experience are best highlighted by harder tasks.[12] WS' PD exceeds that of the soldiers by roughly a factor of three on all of the low-metal mine categories. RR's detection performance falls between that of WS and the soldiers.

The primary goal of testing was to evaluate the mine detection capabilities of RR and WS to determine if they qualified as experts. Their performance was assessed on the basis of the measures PD, ROA, and FAR. In absolute terms, both WS and RR performed well on arguably the most important performance measure, PD. Apart from their performance on the first trial (Lane 3B), on which the performance of both was poorest, WS' PD exceeds the high military standard and RR's falls just short of it. WS's PD for the low metal mines is particularly impressive. It shows how well a skilled operator can detect these notoriously hard-to-find mines. Both operators, however, show rates of advance that fail to meet the military standard. Their observed ROAs can be attributed to the considerable time expended evaluating candidate targets that proved to be FAs. Both operators show improvement on these latter measures over trials, however.

Figure 1



4. DISCUSSION

Before assessing WS' and RR's status as expert mine detectors on the basis of the data, several pieces of evidence should be considered that suggest that their observed performance may underestimate their detection and discrimination capabilities. First, minimal opportunity was available to practice detection prior to testing. The literature on the retention and recovery of well-established complex skills shows that performance decays with lack of practice, but is restored to original levels with "refresher" training.[23-25] WS' improvement on all measures with each test trial is consistent with these data. In addition, his decelerating rate of improvement matches the form of the relearning functions consistently observed in laboratory studies of skill retention and recovery. RR shows evidence for relearning on a more modest scale. This is consistent with the fact that he has had more recent detection experience than WS and also more experience with the equipment used for testing. In contrast, WS had to refamiliarize himself with the task as well as learn the idiosyncrasies of the particular detector used.[7] Post-trial comments by each operator also suggested that refresher training was occurring during testing. The general implication is that additional pre-test practice would have yielded higher levels of performance for each operator.

Significant differences between testing conditions and the standard operating procedures that both operators employed in demining operations further suggests that the results may underestimate their detection and discrimination capabilities. Generally, human expertise is domain-specific,[8,12] reflecting precise adaptation to particular task environments.[25] When experts are exposed to task environments in which they have not developed their skills, performance levels typically decline.

In their live demining operations, both operators' standard operating procedures (SOPs) involved identifying the source of *every* reliable alerting signal produced by the detector. The rationale for developing such discipline in live minefields should be obvious, especially when no life-threatening enemy forces are present to shift the speed/accuracy criterion more toward speed. The implication is that the deeply ingrained habits both operators developed in live minefields may have produced negative transfer and required unlearning under the present testing circumstances.

The prohibition against digging/probing may also have had a deleterious effect upon the operators' performance, because their SOPs incorporated digging to identify the objects producing alerting signals. The identification of signal sources constitutes feedback on the accuracy of each potential declaration. Feedback is critical for learning (or refreshing) perceptual categories which serve as the basis for the perceptual discriminations that the current task requires; each PSS-12 signal must be categorized as either indicating the presence of a mine target or not.

The "blind" testing requirement imposed by the test facilities denies the feedback which the operators had come to expect and indeed need in order to discriminate as accurately as possible between mines and either buried clutter or conductive soil. Two consequences follow. First, operators' performance should suffer relative to the (unobserved) level exhibited in the environment to which operators have adapted. Second, their adaptation to the test environment is impeded seriously by the absence of feedback critical for relearning perceptual categories or adjusting them to the immediate context.

The latter holds important implications for interpreting the observed FARs and ROAs. The absence of immediate feedback on the accuracy of declarations denied the operators access to information needed to improve both FARs and ROAs. The two are linked because ROAs can be expected to slow as FARs rise. This is because investigating the signals producing false alarms is time-consuming. Investigation times were high where the density of false alarms was high. In such areas, the operators had to differentiate signals coming from nearby sources as well as signals that overlapped spatially. Thus, categorization of each signal source in such circumstances took longer than when a signal was relatively isolated spatially. The problem of mutually interfering signal sources will be elaborated upon in the following section.

To return to the immediate issue, the first goal of this study was to identify operators who qualify as experts at mine detection with a PSS-12. The detection performance that RR and WS exhibited justifies designation of them as experts, at least tentatively. Further investigation aimed at addressing the reliability of their observed performance is planned. For the present, this designation justifies investigation of the knowledge, thought processes, and techniques these operators employ. Such an investigation is described in the next section.

5. AN INFORMATION PROCESSING MODEL OF MINE DETECTION SKILL

Qualitative regularities in the verbal reports and behaviors of the two operators during test trials as well as in post-trial comments provided the basis for a first approximation information-processing model of skilled mine detection with the AN/PSS-12. This model is regarded as tentative and subject to further empirical validation and development, especially due to concerns about the completeness of the qualitative data record. Despite these concerns, the model serves as a useful framework for organizing observed phenomena, generating testable hypotheses for subsequent investigation, and identifying interesting issues.

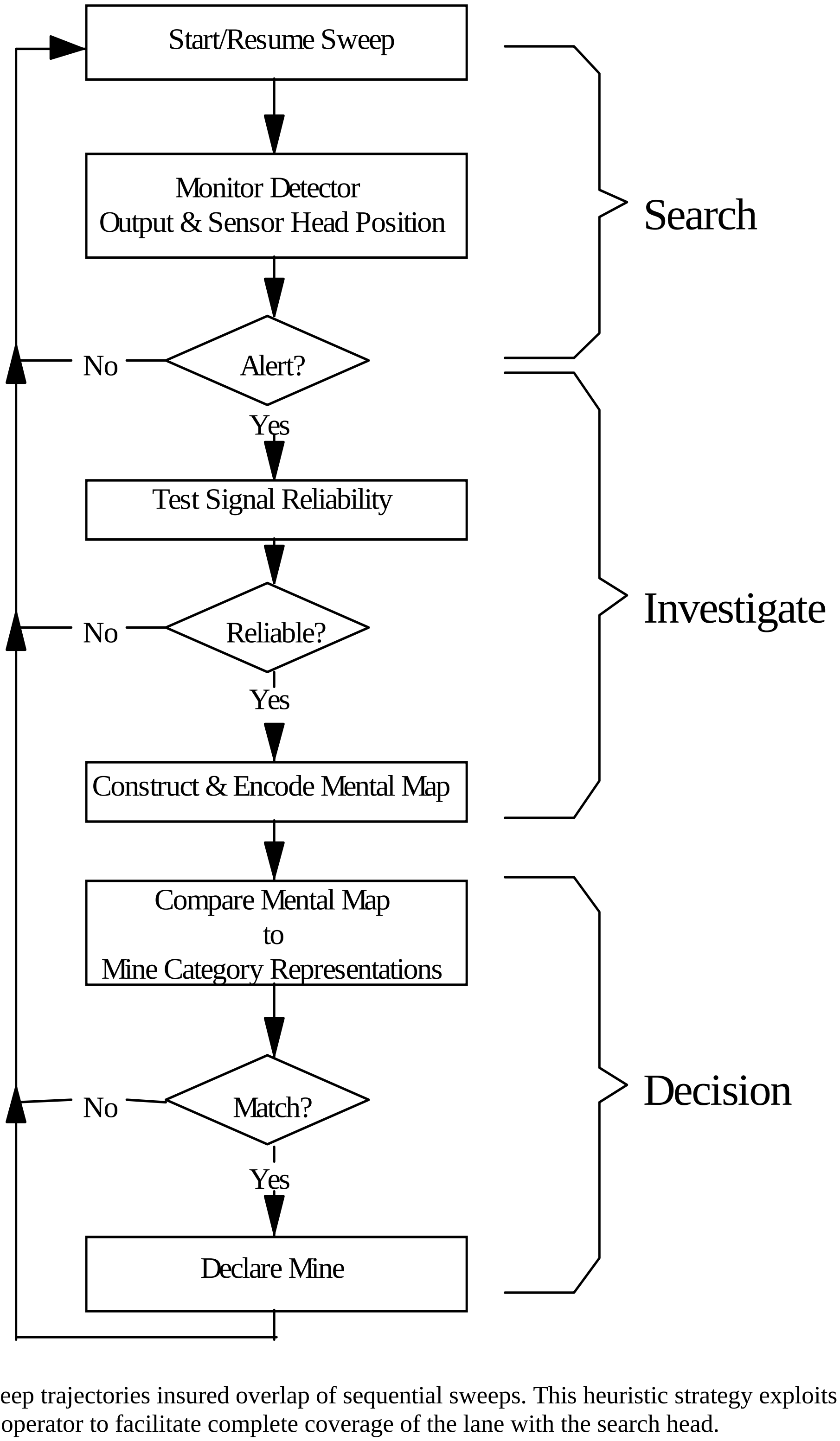
The basic unit of analysis for this model was created by parsing the continuous streams of behavior and verbal reports produced by each operator on a test trial into sequences of discrete events. Each event starts either with initiation of search at the beginning of a test trial or else with resumption of search after the operator has decided either to make a mine declaration or else that the information available does not warrant a declaration.

Internally, these events have a hierarchical structure, characteristic of skilled human problem-solving,[27,28] that is decomposable at several levels of abstraction. The components at each level can be identified as sequentially-related units of mental activity and overt behavior carried out to achieve specific operator goals. The overarching goal of the operator for each event is finding the next mine in a designated area. Phrases like "OK, let's get the next one" often uttered after a declaration signified such intent. “Getting the next one” invariably involved execution of three macroscopic steps carried out to satisfy three different subordinate goals: search, investigation, and decision. Figure 2 illustrates the macrostructure of the search/detection process used to attain these goals.

5.1 Search for Alerting Signals

The first goal involves determining whether a target is present in the area immediately in front of the operator. The area is defined by the diameter of the PSS-12 search head and the arc of its sweep. The activities involved include simultaneously sweeping the detector head over a designated path at an appropriate speed, continuously listening for an alerting signal, and attending visually to the changing location of the search head over the ground surface. If the equipment emits an alerting signal, the sweep is truncated and attention shifts to a new goal -- investigation of the signal. If no alerting signal is received from the detector, the operator advances one-half step -- approximately the diameter of the search head -- and makes a new sweep in the opposite direction, back across the lane. Both operators explained that the disciplined use of half-

Figure 2



step advances and consistent sweep trajectories insured overlap of sequential sweeps. This heuristic strategy exploits the biomechanical properties of the operator to facilitate complete coverage of the lane with the search head.

Two aspects of sweep procedures used by RR and WS are noteworthy. First, counter to doctrine for PSS-12 operation,[29] both operators loosened the mechanism that fixes the position of the search head relative to the shaft and then carried out their sweeps with the search head riding over the ground surface in direct contact with the surface. Both independently explained that this procedure enhanced the sensitivity of the detector. Each operator later informally demonstrated this to be the case in the calibration lanes. Generally, stronger, more distinct output signals resulted from having the search head in contact with the ground than when it was swept the doctrinal 5 cm above the surface.

The second interesting feature of their sweep behavior was the high frequency with which both would test and sometimes adjust the sensitivity of their detectors. Although each occasion was not systematically recorded, neither operator appeared to advance more the three meters without such a test. Such tests appeared far more frequently in areas of lanes where detector output was constant. Because the test procedures assume a detector calibrated against representative sample targets, both operators carried out adjustments to detector sensitivity in the calibration lanes prior to sweeping each lane as well as after breaks. Both interrupted their sweeps of lane 3B to recalibrate after encountering nearly constant output from their equipment in its initial 10 meters. This was the first lane tested and the lane where continuous output signals were most prevalent over areas several meters square. WS interrupted search on one other occasion on the same lane, where similar conditions appeared for another 5 meter stretch. He did so again after searching the first 3 meters of the next lane, whose surface was gravel and where he encountered only relatively clear signal onsets and offsets.

The characteristics of alerting signals produced during search showed striking variability. In some instances, the detector would output a full, continuous tone with a very clear onset. In other instances, a weak, intermittent signal, described as a “growl” by RR, was heard. In contrast to such simple “off-on” signals, alerting signals of a very different quality were observed as well. These occurred in areas of lanes 3B and 5B where the detector produced continuous output as it was swept over large regions of the ground surface. In these cases, the alerting signal was a modulation in the frequency of the detector’s auditory output. Complicating the detection of an alerting signal was variation in background output. Clearly, the auditory discriminations operators make before shifting to an “investigation” mode vary considerably with context. The operators’ post-trial comments indicated that making such discriminations was extremely difficult, especially in the “noisy” portions of lanes 3B and 5B.

Both operators reported experience with the problem of detection in the presence of continuous output, noting two circumstances under which such conditions occur. One is in the presence of conductive soil. The other occurs when a mine with relatively high metallic content (e.g., M15 or VAL 69) is “protected” by or “coupled” with a near-by low-metal AP mine. The larger metallic mines elicit an omnidirectional detector signal at distances as much as a meter from the mine’s physical perimeter. This area is labeled the mine’s “shadow.” A common counter-countermine strategy involves placing a smaller AP mine within the shadow on the assumption that the shadow would function as camouflage. Both operators reported considerable experience with such situations in their demining efforts in Kuwait. Both demonstrated the ability to literally extract task-relevant auditory signals from noise to find mines in this test.

5.2 Investigation of Alerting Signals

Detection of an alerting signal triggers further investigation of the signal that occurs in two phases. The first involves establishing the reliability of the alerting signal. The second investigation phase is “mental mapping.”

The transition between search and investigation is marked behaviorally by cessation of the continuous cross-lane sweeping and progressive forward advance seen prior to receipt of an alerting signal. Upon hearing such a signal, the operator proceeds to investigate the signal’s reliability, repeating part of the sweep that produced the signal in the area in which it occurred. If the alerting signal was replicated, the operator often performed another sweep or two to fix the location of the alert. RR sometimes marked the ground at his location with his trowel. Both he and WS also used landmarks indicated by the use of phrases like "OK, just to the left of the light pebble." Such markers support memory for signal location.

If the alert cannot be replicated in the sweep path in which it was remembered to have occurred, search is extended over a wider area. First, a partial sweep is made slightly ahead and behind the remembered path of the original sweep. An additional activity that often follows when alerts cannot be reliably regenerated involves checking the detector for sensitivity drift and repeating sweeps of the suspected target area following adjustments to the detector’s sensitivity. When multiple efforts to regularly reproduce the alert fail, operators then advance their search.

When alerting signals are reproduced satisfactorily, investigation proceeds with systematic exploration of the area where the alerting signal was detected. This activity is characterized as a mapping process because the detector is employed to determine the boundaries and shape of an area adjacent to the location of the initial alerting signal. The sweep procedure used to establish the location of the alerting signal is now repeated by moving the detector in several new trajectories. The first typically takes the detector head along the arc of the sweep that first produced the alert across its location, continuing until output changes. After the operator notes the location where the change occurs, a short sweep is made in the opposite direction, with a signal onset expected at the same point. This process is then repeated along a path that bisects the arc created by the two boundary points, first locating the point closest to the operator where an output indicates the presence of conductive material, and then at the farthest point along this line. If four such points are successfully identified, the area bounding the box created by an imaginary connection of these points receives further investigation.

Up to this point, the mapping process conforms to the military procedures. Regularly, however, both operators continued to seek points adjacent to the "box." The technique employed involved fixing the position of the detector head on the shaft and then carrying out further search with the plane of the circular sensor head at roughly a 30 deg angle to the ground. Operating the detector in this orientation, each operator would proceed to establish additional boundary points. Both operators reported that using the detector in this unconventional manner yields more precise boundary information. An internal, imaginary linkage of the pattern of boundary points then yields a 2-dimensional representation, i.e., a mental map.

RR's technique to derive shape uses back-and-forth sweeps that follow lines extending outward from the center of the imaginary enclosure, at least for cases where boundary points are spatially dispersed. WS' trajectories usually traced contours continuously defined by established points to establish a perimeter. These behaviors suggest that both operators use the PSS-12 on some occasions as an edge-detector for progressively synthesizing a spatial pattern. This map is then maintained in memory for the next processing step: deciding whether the signal source signifies a mine.

5.3 Decision

The decision stage involves internal comparison of the mental map derived from the preceding investigation phase with a pattern or set of patterns stored in an experienced operator's memory. The patterns constitute the operator's knowledge of the patterns of information generated by mines, accumulated through extensive experience of finding them with a metal detector. An internal assessment of the degree to which the current perceptual map matches knowledge representations of mines determines whether or not a mine declaration is made.

The lack of complete and detailed verbal reports seriously limits inferences about the subprocesses involved in this step. However, several observations support the notion that a pattern comparison process contributes to the declaration decision. These observations also offer insight into the nature of the patterns that are compared.

Both operators' investigations of alerting signals involved spatially dispersed exploration of the area of the signal directed toward identifying boundaries. WS' boundary "tracing" efforts imply an effort to establish continuous contours that define a spatial pattern. In a post-test debriefing, he showed how the mines in the calibration lanes produced varying spatial signatures, noting that "this was what he was looking for." During his search efforts he frequently made comments like "That looks like an M14" or "That looks like a VAL" or "Big ring-off...longer than it is wide...rectangular...kinda like a PMD6." Comments produced by RR, particularly in instances when he attributed a signal to clutter, frequently suggested evaluations of the shape of signal patterns. A prototypical example accompanied his decision not to make a declaration in response to a particular signal: "That's too long and skinny...probably a piece of barb wire." Certainly, the available evidence cannot support strong inferences about the representations and processes either operator employs in the model's decision stage. The data do, however, justify hypothesizing that comparisons of patterns represented in memory play a role in declaration decisions, and that these patterns, at least for some mine types, may have a spatial character. Future plans include testing these hypotheses because they hold potentially important theoretical and practical implications.

Understanding these implications involves first understanding some of the model's theoretical assumptions. One is that the accuracy of a declaration decision is dependent upon the accuracy of the postulated comparison of two patterns, one derived from recent sensory experience and the other the product of related previous experiences accumulated in an individual's archive of knowledge. It follows that the accuracy of the comparison is crucially dependent upon the quality of the patterns being matched. Inaccuracies or incompleteness in either should have a negative effect.

Rapid and highly selective retrieval of complex patterns stored in a knowledge base support one of the empirical hallmarks of human expertise:[30] the ability to quickly and accurately recognize domain-relevant perceptual inputs.[26] It is well established that experts have high quality, well-integrated, and easily accessible "standard" patterns against which perceptual input can be compared to properly categorize it. Less-skilled individuals typically have fewer patterns available and process available patterns with far less facility, having difficulty maintaining patterns in memory for input to specific processing operations. Novices lack such knowledge.

Applying these theoretical principles to mine detection, it follows the reintroduction of WS and RR to the task of mine detection with a PSS-12 in the calibration areas should make an important contribution to their performance. This exposure served to retrieve and sensitize mine signatures durably stored in their memories, thus facilitating their decision processes by restoring accessibility to critical knowledge. The testable implication is that less-experienced individuals, who either lack such patterns or lack the ability to actively maintain such patterns for comparisons with perceptual input, would detect a higher proportion of mines if their search activities were supported by access to nearby calibration mines that match the type being sought than if such support were unavailable. Reference to calibration mines would be expected to support temporary retention of "standard" patterns and thus to enable more accurate declaration decisions.

The representational modality of the patterns involved in the comparison process also holds implications for the potential mine detection capabilities of different individuals. A wealth of psychological measurement studies show that individuals differ in spatial ability. In the context of human information processing, differences in spatial ability are correlated with differential abilities of individuals to maintain and process internal representations of a spatial character (versus representations of an acoustic character, such as those underlying recognition and discrimination of spoken words). If memory for and processing of "mental maps" play a general role in skilled land mine detection with a metal detector, two practical implications for training mine detection follow. Individuals with higher spatial ability would be expected to learn more quickly and perform better than individuals with lower spatial ability. This hypothesis implies that high spatial ability should be used as a selection criterion for PSS-12 operators. Second, because such individuals may be unavailable, technologies that support operators' maintenance and processing of spatial representations should be developed to help individuals with substandard spatial abilities compensate. The technology reported by Dr. Herman in this volume is an excellent example of a potential compensatory tool.

6. CONCLUDING REMARKS & FUTURE DIRECTIONS

Use of the term “concluding” in the heading for this section seems inappropriate. Both the performance data presented and the model sketched above raise far more questions than they answer. This is to be expected with initial explorations of any new area. The knowledge gained, though, however limited, stakes out empirical ground on which to build (or from which to move). It also provides a vantage point for selecting directions for future investigations, suggesting where to go and where not to go. Plans for forthcoming investigation are sketched below.

First, high priority is placed on replicating this test to assess the stability of the performance achieved by RR and WS and to answer the question “Is this as good as it gets?” This latter question focuses on PD for low-metal mines, false alarm rates, and search speed. Arguments that RR’s and WS’ performance data may underestimate their competence predict that a shorter interval between detection efforts and the knowledge gained by both about the particular detector employed and Range 71A’s test lanes should enhance performance in a test scheduled for later this spring. Experimention on the effects of feedback availability during training upon detection and especially discrimination capabilities also receives a high priority.

To better understand the cognitive substrate of expert performance, an accurate, complete, fine-grained record of the three streams of information is needed to elaborate the model presented here in the desired detail and test it. These data can be collected fairly unobtrusively as operators carry out lane sweeps. Therefore, plans are to collect a continuous, time-synchronized record of the PSS-12’s audio output, the position of the sensor head relative to the location of mine targets, and the operator’s verbal reports as he “thinks aloud” during sweep of each lane. Sufficient detail means that these data streams must be analyzed on a hit-by-hit, false alarm-by-false alarm, and miss-by-miss basis to make sound inferences about the perceptual information, the category representations, representational modalities, and cognitive strategies that these operators bring to bear in interpreting alerting signals, constructing perceptual patterns, and making declaration decisions. Aided by a thorough geological assay of the contents and soil properties of the test lanes used in this study, information-processing analysis at this level can also provide insight into how operators adapt to the highly variable micro-contexts observed in this investigation.

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