III

TRAINING OR FACILITATING SKILLED PERFORMANCE

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Chapter 9

Spatial Thinking and the Design of Landmine Detection Training

James J. Staszewski
Carnegie Mellon University

COGNITIVE ENGINEERING AND LANDMINE DETECTION TRAINING

This chapter describes the successful linkage of basic research on visual imagery and spatial thinking to the activities of soldiers tasked to neutralize highly feared (Hackworth & England, 2002) and common weapons of both war and terrorism. More specifically, the chapter's purpose is to describe contributions of fundamental science on visuo-spatial cognition to two applied projects whose impact illustrates the practical value of cognitive science. Both projects employed cognitive engineering to create training programs for operators of equipment that the U.S. military uses to detect landmines.

The projects shared a common approach to training development: Equipment-specific models of expert operators' skills provided content for designing the training programs. The analyses supporting model construction suggested that significant components of the experts' skills involved spatial information processing. Visual information-processing studies, particularly research on visual imagery and mental synthesis, guided the analyses and the translation of findings into strategies for training. Translating the expert models' contents into training activities required more than just an understanding of the mechanisms that produced the expert operators' performance. Here, studies of categorization of spatial displays and individual differences in spatial ability guided not only the design of training activities, but also the development and use of training aids.

Both projects achieved their objectives and, more importantly, have improved U.S. soldiers' mine detection capability. Field test results for the training program developed for standard detection equipment used by the U.S. Army in countermine operations—the AN/PSS-12 (PSS-12, shown in Fig. 9.1)[1] (Davison & Staszewski, 2002; Davison, Staszewski, & Boxley, 2001; Staszewski & Davison, 2000; Staszewski, 2004)—led a committee of senior officers at the U.S. Army Engineer School to adopt the new, scientifically based training for soldiers throughout the Army. Favorable test results for the training program designed for operatorss of the recently deployed AN/PSS-14[2] (shown in Fig. 9.2), which is gradually replacing the PSS-12, led to its adoption by the Army as well. In recognition of the critical contribution of properly trained operators to the PSS-14's effectiveness, the Army adopted a policy of distributing the training program and the new equipment only as an integrated package. Soldiers trained in these programs now use both the PSS-12 and -14 in countermine operations overseas. The PSS-12 training has dramatically increased the capability of soldiers to find modern landmines with plastic bodies and minimal metallic content using late-1980s vintage metal-detection technology. The new, advanced-technology PSS-14, which incorporates separate sensors for metal detection and ground-penetrating radar, along with sophisticated digital signal processing, is hailed by troops in the field as a leap forward in mine detection capability (82nd Airborne Division Public Affairs Office, 2003). In short, these projects have improved the U.S. military's countermine capability and protection for those exposed to the extraordinary hazard that landmines pose. This outcome is due, in part, to cognitive scientists' efforts to understand visuo-spatial thinking and learning.

THE PROBLEM DOMAIN: LANDMINES AND LANDMINE DETECTION

The deployment of landmines poses a problem of considerable cost, scope, and complexity (MacDonald, et al., 2003). A brief introduction to

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[1]Manufactured by the Schiebel Corporation.

[2]Developed by the U.S. Army Office of the Program Manager, Close Combat Systems, Ft. Belvoir, VA, and manufactured by CyTerra Corporation.

Fig. 9.1.
The AN/PSS-12 is the U.S. Army's standard equipment for landmine detection. Fielded in 1992, this system uses electromagnetic induction to sense the metallic content of landmines.

Fig. 9.2.
The AN/PSS-14 shown in operation in Afghanistan, April 2004.

these weapons (examples are illustrated in Fig. 9.3) and to the multilayered problem created by landmine warfare provides context for understanding how visuo-spatial research has contributed to managing the problem.

Landmines pose a major threat to the success of military ground operations—both combat and peacekeeping—and to the personnel involved (Hambrick & Schneck, 1996; LaMoe & Read, 2002). Once deployed, unless landmines are removed or destroyed, their longevity also threatens the physical, psychological, and economic welfare of civilian populations decades after the conflicts that motivated their use have ended. They exact a sobering toll (International Campaign to Ban Landmines, 2004; U.S. Department of State, 2004).

Safe removal or neutralization of buried and, thus, visually hidden landmines involves more than detection. Relevant procedures before detection efforts begin include confirming the presence of mines and establishing the boundaries of the region in which they are hidden. Verification, excavation, and disposal follow. However, detecting the locations

Fig. 9.3.
Exemplars of the four basic categories of landmines are shown. Row 1 shows metallic anti-tank (AT-M) mines. Row 2 shows newer anti-tank mines with plastic bodies and minimal metal content in their firing mechanisms (AT-LM). Row 3 shows anti-personnel mines containing substantial metal content compared to the low-metal anti-personnel mines (AP-LM)) shown in Row 4. The latter are divided into two subgroups on the basis of physical size and are distinguished in results on HSTAMIDS test results. Note that the larger circular AT mines are roughly 12 inches in diameter, whereas the M14, which contains but 0.6 grams of metal, is 2.2 inches in diameter.

of individual pieces of ordnance is the critical and most dangerous aspect of mine clearance.

Relatively recent changes in the design of landmines have increased both the difficulty of detection and the hazard of clearance efforts. Until the last decade or so, landmines targeting armored vehicles (anti-tank or AT mines) and ground troops (anti-personnel or AP mines) consisted of explosives and triggering mechanisms enclosed in metal shells. Since World War II, handheld equipment employing the principle of electromagnetic induction (EMI) served as the principal equipment for detection (MacDonald et al., 2003). This generic technology senses the substantial metal content of earlier generation mines quite easily, leading to relatively high detection rates. Landmine design has evolved in response, however. Contemporary landmines are built with plastic bodies and miniscule amounts of metal in their triggering mechanisms, vastly increasing the difficulty of detection for systems that rely on EMI—that is, all fielded detection technologies with the exception of the recently developed PSS-14. For instance, tests of the PSS-12 carried out just before its adoption (U.S. Army Test and Experimentation Command, 1991) and more recently (Staszewski & Davison, 2000) showed that operators receiving standard Army training could easily find older metallic mines, but detection rates against M14s, a small AP mine with minimal metallic content (AP-LM), were 0.04 and 0.16, respectively.

HANDHELD DETECTION EQUIPMENT

Since the early 1990s the PSS-12 has been the U.S. Army's standard equipment for mine detection. It is also widely used for humanitarian demining operations. The Army officially designates PSS-12s as metal detectors because they are EMI devices that locate mines by sensing the presence of metallic components found in the vast majority of landmines.

The PSS-12 senses buried metal by transmitting electromagnetic pulses into the ground via one of two concentric coils in its sensor head. The energy pulses create a magnetic field in the ground that induces weaker, secondary "eddy currents" in conductive materials within its field. The sensor head's second coil acts as a receiver, detecting changes in the eddy currents' voltage. Signal processing circuitry then converts readings above a set threshold into auditory output signals indicating the presence of conductive material.

Mines with metal bodies (M) are detected easily with the PSS-12 due to their relatively high metal content. However, newer mines with plastic bodies and minimal metal in their firing chains (LM) pose serious problems for detection as the test results cited above indicate. The proliferation of LM mines (Hambric & Schneck, 1996) and the poor detection rates achieved with the PSS-12 explain both the escalating threat and the motivation to develop new technology to defeat it.

That new technology was the handheld stand-off mine detection system (HSTAMIDS, later renamed the PSS-14 upon deployment). By 1998, nine years and $38M had been spent to develop this system. Its novel design feature was its use of two independent sensor technologies. It combined EMI hardware and software for detecting the metal contents of landmines and ground-penetrating radar (GPR) capable of detecting objects buried several inches beneath the ground surface. Unfortunately, initial field tests of the prototype showed that it performed no better than the PSS-12 against AP-LMs.

Cognitive Psychology's Role

The U.S. Army's search for solutions to the countermine problem went beyond technology development. A program sponsored by the Army Research Office explored equipment operators' contribution to landmine detection. This initiative included a project that sought to exploit research on human expertise. This project's goal was to investigate individual differences in detection performance among PSS-12 operators, with priority given to identifying superior performers. If empirical testing could identify experts, information processing analyses could be conducted to "reverse engineer" their skills. The resulting model would be used as content for designing training for novices, because basic research had shown that training novices to use experts' strategies was an effective instructional intervention (Biederman & Shiffrar, 1987; Chase & Ericsson, 1982; Staszewski, 1988, 1990; Wenger & Payne, 1995).

This same approach was applied to develop new training for HSTAMIDS operators after a "Red Team"[3] review of the prototype's disappointing operational test results (Guckert, 2000). This review identified the training that operators received as a key contributor to the substandard performance of the HSTAMIDS. Close examination of the results also identified an operator whose detection rate far exceeded those of the others tested. His being the most experienced HSTAMIDS operator suggested the feasibility of using a cognitive engineering approach to designing new training. This initiative was included in a "second chance" extension of the HSTAMIDS development program.

Analyses of Expert Landmine Detection

Visuo-spatial research influenced the PSS-12 and HSTAMIDS projects in each of their two main phases. First, analyses of how the expert operators of these systems achieved superior detection rates suggested that visuo-spatial representations and information processing played a central role. The literature on expertise in spatial domains (Chase, 1986), in particular, prospectively guided the analyses. Second, training design activities sought to support novices' acquisition of the procedures and thinking used by the experts of each system. Teaching novices to apply the experts' strategies would therefore require facilitating their acquisition of task- and strategy-specific visuo-spatial thinking skills. The analyses of expert

[3]A red team review is an assessment of a system's vulnerabilities or weaknesses by a group of specialists independent of the system's proponents and developers.

performance and key findings are outlined in the following sections, first for the PSS-12 project and then for the HSTAMIDS. How the findings were applied to designing the training programs follows, again highlighting the influences of visuo-spatial research.

Expert PSS-12 Operation

An operator with extensive experience and an impressive record of success (RR) offered his expertise for the PSS-12 study (Staszewski, 1999). Data collection involved capturing multimodal records of RR's activities while his skills were tested in mine lanes at Fort A. P. Hill's Range 71A.[4] Observations included continuous viewpoint video of the PSS-12's search head as RR visually tracked its movements during testing, along with two synchronous and independent channels of audio. One recorded all output signals of the PSS-12. The other recorded all statements made by RR as he gave concurrent verbal reports, as per instructions, while using his customary techniques to find and mark suspected mine locations.

Analysis consisted of coding all recorded events, starting with sequences that ended in successful detections, followed by those related to missed targets, and finally those related to false alarms, for roughly 30 hours of continuous video.

Findings

Several striking regularities appeared. First, analysis revealed that what, on initial observation, appeared as a Jamesian "blooming, buzzing confusion" was extremely orderly. Except for procedures RR used to check for drift in the equipment's sensitivity, the model shown in Fig. 9.4 accounted almost completely for his activities within the test lanes. Elaboration of this model will identify (a) three features of RR's detection procedures that implicated visuo-spatial cognition and (b) issues for training design that the visuo-spatial literature framed and helped to resolve.

RR's successful detection of targets involved three sequential stages: search, investigation, and decision. Search involved placing the sensor head on the ground with its center on or outside the lane[5] boundary and

[4]Details on targets used in testing and the testing environment can be found in Staszewski (1999) and Davison & Staszewski (2002).

[5]Areas designated for clearance in testing and in live operations are referred to as lanes. Lanes are roughly the width needed to extract casualties. Army doctrine sets lane width at 1.5 m. This lane width is used at all training and testing sites described here.

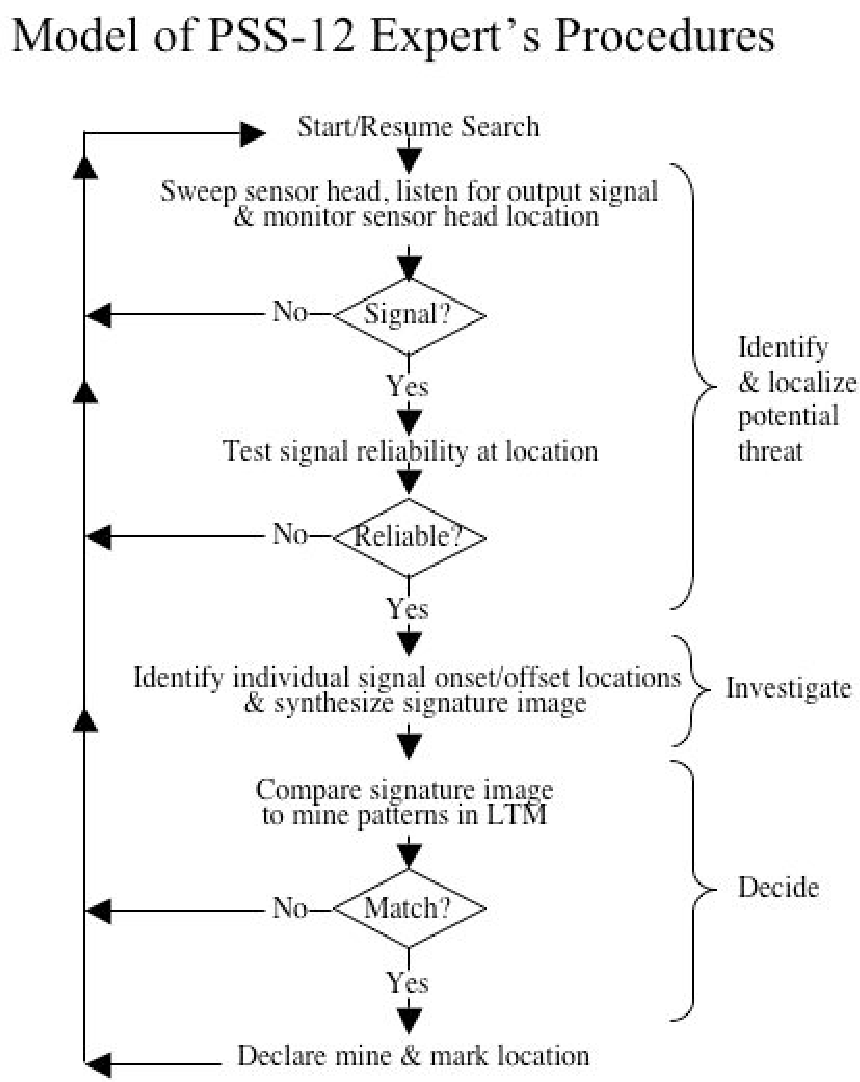

Fig. 9.4.
Model of the basic procedures used by the PSS-12 expert.

gliding it lightly over the ground surface at a rate of about 1 ft. per sec in a path across the lane. If no signal came from the PSS-12, RR continued to glide the sensor head on a cross-lane trajectory until its center was either on or outside the lane boundary. At this point, the search head would be raised just enough to advance it about 15 cm—or about the radius of the search head—and another lane "sweep" would proceed across the lane in the opposite direction. With a trajectory parallel to the previous cross-lane sweep, the search head's path would overlap the area covered by the previous sweep by roughly half. The overlap ensured exhaustive surface coverage with the sensor head, if the sweep was executed properly. Such cross-lane sweeps in alternating directions would continue until the detector produced an output signal, RR paused to perform a sensitivity setting check, or RR had covered the entire lane.

When an output sounded, RR typically would pause and gaze at the location of the sensor head. He would then complete his cross-lane sweep and move the sensor head back over the area where the alert occurred. With movements shorter and slower than used in the cross-lane search, he would try to reproduce the output in the same spot. If the signal could not be reproduced in the same location after several attempts, search forward would resume with successive cross-lane sweeps. If a signal reliably sounded in the same location, search head movements marking the beginning of investigation would follow, immediately adjacent to the alert's location.

In the investigation phase, RR would proceed to explore the area near the alerting signal with sensor head movements like those used to confirm the alerting signal's reliability. The movements radiated progressively outward from the alerting signal's location. Movement on specific trajectories would stop when an ongoing signal stopped and remained off for a few more inches of the sensor head's movement. A backtracking movement would occur on the same trajectory to make the signal recur at the same point as previously and persist either as the sensor head continued for a few inches or remained stationary. If the locations of such "edge" or signal transition points appeared to move on different individual movements, additional back-and-forth movements were used to establish the edge points reliably.

Once an on-off transition point was located reliably, the process was repeated a few inches away to establish the location of another on-off point. These operations continued until they defined a region within whose boundaries or "edges" the PSS-12 sang and outside of which it produced no output. Occasionally, RR physically marked edge points on the ground surface (on bare soil lanes, where such marking was possible, versus lanes with crushed stone surfaces) using the point of the trowel he carried.[6] On crushed stone surfaces, he might note in his verbal reports the location of

[6]RR used the trowel for checking his equipment for drift from the set sensitivity in the context of testing, as described in Staszewski (1999). He also used this tool to excavate suspected mines in live operations—thus providing timely and valuable feedback for detection and discrimination learning.

an edge if he found a distinctive stone to use as a landmark. Although his use of physical landmarks was infrequent, these instances served as clues that prompted a comprehensive spatial analysis of PSS-12 signals.

The area covered with such investigatory actions varied, first as a function of whether the signals were coming from landmines. If the investigation occurred where a low-metal LM mine was buried, on-off points tended to cluster within a foot or so of one another. Alternatively, if a high-metal mine was investigated, the area circumscribed by on-off points would form a semi-circle, called the metallic (MD) halo, sometimes more than a meter in diameter. If the signals were produced by conductive material not related to mines (whose locations were obtained for the analyses), that is, clutter, the areas they encompassed varied much more in size and shape than the spatial signatures of mines.

When RR ended investigation, he would pause briefly and scan the area investigated. If he decided the halo was produced by a mine, he would move the sensor head to its center and direct the experimenter to place a marker in the spot marked by the search head's position. Otherwise, he resumed cross-lane sweeps searching for another alert.

In analyzing the video records, which involved mapping the locations at which signal onsets or offsets occurred relative to the locations of targets that RR accurately and confidently marked, a nonintuitive regularity emerged. The contours created by onset-offset or "edge" points described semi-circular halos with mines at the center, where the arcs completed to form circles. The length of the radii for these arcs covaried positively with the metallic content of the target. Although any single edge point could be obscured and moved outward by the presence of metallic clutter, in the absence of clutter the signatures showed "good" form as described by Garner (1974). Some examples of the spatial patterns produced by RR are shown in Fig. 9.5.

These regularities in RR's many successful detection episodes led to the counterintuitive inference that he located mines by sequentially finding edge points defined by the detector's auditory outputs, holding them in memory, and creating spatial patterns in his mind's eye by linking the contiguous edge marker locations. This process resembled that of visual synthesis, studied originally by Klatzky and Thompson (1975), and subsequently by Finke (1990), Palmer (1977), Pearson and Logie (2000), and Thompson and Klatzky (1978). RR presumably then matched these patterns against signatures held in his knowledge base of previously detected mines. Thus, spatial pattern recognition appeared to support expertise in landmine detection, consistent with findings from laboratory studies of expertise in a variety of visuo-spatial task-domains (Chase, 1986).

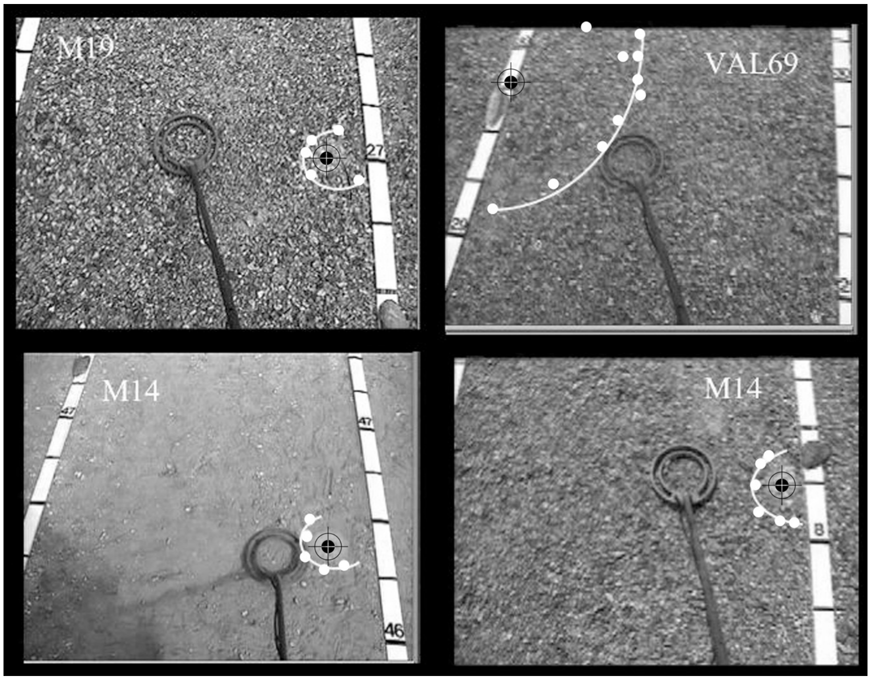

Fig. 9.5.
Spatial patterns derived in analyses of the PSS-12 expert's successful detection of mines in performance testing. Crosshair marks indicate the approximate centers of the buried targets; solid white circles indicate the "edge" locations defined by either onset-offset or offset-onset of the PSS-12's auditory output signal; the white arcs shown are fitted by hand to the edge points.

HSTAMIDS Expertise

Progress made in understanding the PSS-12 expert's skill guided efforts to analyze the skill of the most successful operator of the HSTAMIDS prototype. Discussion of this influence, however, will be prefaced by a description of the functional features of the HSTAMIDS. This provides background for discussing the analysis of its best operator's skill and for understanding the challenges involved in using the results to develop training for novice operators.

The prototype HSTAMIDS system developed by CyTerra Corporation and illustrated in Fig. 9.6 consists of two main physical components. One is its search head, which houses the system's EMI and ground penetrating

Fig. 9.6.
The HSTAMIDS prototype shown in configuration used for training development and testing in its extended product development risk reduction or "second-chance" phase.

radar (GPR) antennae in a plastic case. The head is attached to an adjustable-length wand that has a set of controls at its opposite end. Here, on a panel just above the pistol grip used by the operator to hold the unit, are switches that power the system up or down, adjust sensitivity levels of the GPR subsystem, and adjust the volume of the unit's auditory outputs. Cabling runs along the shaft, linking the sensors to the controls. Another cable connects the wand's components to a rectangular metal-cased unit weighing about 35 lbs. and worn like a backpack by the operator. This unit houses electronics circuitry for the two independent sensor channels that process the raw signals taken in by each sensor, using separate detection algorithms, and generating auditory outputs based on the results.

To enable the operator to control movements of the search head from side to side just above the ground surface 3 to 4 ft. forward of his feet, a velcro belt that attached to the shaft just below the control unit cinched the shaft to the operator's upper forearm. By holding the pistol grip, located an adjustable distance down the wand, the operator made the wand an extension of his forearm permitting search of the ground ahead of him with some buffer between his feet and potential threats.

Analysis of the HSTAMIDS Expert

Because the HSTAMIDS, like the PSS-12, used EMI sensing—albeit in a more sophisticated way that reflected roughly a decadee's progress in sensor technology and digital signal processing—it was reasonable to expect similarities in its response to the metallic content of mine targets. If the constraints off task environments mold the skills of human experts as Simon (1990) theorized, similarities in the ways the PSS-12 and HSTAMIDS experts used EMI were expected. Learning how information afforded by GPR sensing was acquired and used would be a matter of exploration, but at least the preceding study of PSS-12 expertise provided some guidance in modeling the HSTAMIDS expert's skill.

The benefits of this prospective approach to analysis of HSTAMIDS expertise were magnified because of some undesirable factors that limited data collection substantially. First, there was only one prototype system for the expert to operate. Observations of the expert's use of the system were thus limited to widely spaced test sessions dedicated to system development. System development involved nearly continuous changes to detection algorithms, with system software undergoing changes continuously up to the month before the first training test. Moreover, some of the changes proved much less successful than intended. This and less-than-optimal system reliability both limited the corpus of observations of the experts' detection processes that were available for analysis and complicated their interpretation.

Instrumentation used for data collection also added challenges to the analytic task. A computer-controlled camera system being developed to give trainees feedback on sweep coverage (Herman & Inglesias, 1999; Herman, McMahill, & Kantor, 2000) also doubled as the tool for capturing the expert's activities. Reliability issues, not unexpected with any complex technology under development, limited the corpus of observations available for off-line analysis to far fewer observations than expected. Thus, analysis of the expert's skill relied heavily on direct, real-time observations of system operation as the empirical basis for abstracting regularities. These observations covered an estimated 90 to 120 hours of observation spread over five developmental test sessions at three different test locations and roughly 850 mine encounters with targets like those shown in Fig. 9.3. A much smaller, unsystematic sample of these observations, totaling roughly 10 hours of audio/video recording, was captured and available for detailed examination. These records were used to test tentative findings about the expert's techniques and thought processes based on the live observations. Such are the challenges of applied field investigations involving advanced technology development.

Findings

Observations of the HSTAMIDS expert's detection procedures showed that the model of RR's procedures generalized surprisingly well.[7] The model shown in Fig. 9.7 with its procedural sequence of search, investigation, and decision operations provided an excellent characterization of his detection activities. An alerting signal encountered during search sweep, received as an output from either the MD or GPR subsystem, would trigger investigation in the area where the alert occurred. KJ then typically started investigation with the metal detection system, using it in a way that was functionally similar to RR's procedures for investigating alerts. That is, he used the MD to locate MD edges and build in a piecemeal fashion the contours of the patterns that constitute the metallic halos of mines. His MD investigation was characterized by relatively slow continuous movements of the sensor head (roughly 2–8 cm/sec) in scallop-shaped trajectories producing consistent changes in the frequency of the MD output signal. These changes allowed him to continuously trace the edges of an MD halo, first working from the "six o'clock" position to the "three o'clock" and then back around to the "nine o'clock" position.

[7]RR and his techniques were unknown to KJ until similarities were pointed out to him by the author, at which point this knowledge had no influence on his technique.

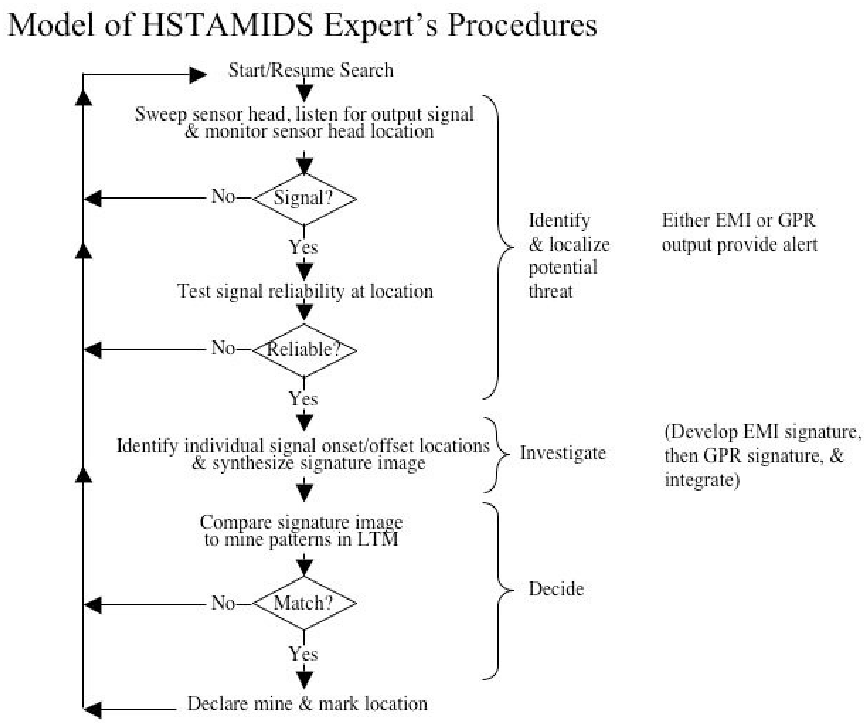

Fig. 9.7.
Model of the HSTAMIDS expert's basic procedures. Note the similarity to that of the PSS-12 expert model in Fig. 9.4.

He would then use the established MD pattern, particularly if it described the semi-circular pattern produced by mines, along with his knowledge of the sizes and shapes of mines to guide investigation with GPR. If MD investigation produced a large semi-circular contour .75 to 1.5 m at its widest—characteristic of an AT-M or AP-M target—GPR investigation would be conducted inside the metal halo. If the MD halo was small (~ 2.5–8 cm), suggesting a low-metal target, investigation would start outside the halo, especially if the alerting signal came via GPR followed by an MD signal as detector head sweeps advanced beyond the GPR alert. If the alert occurred first via MD, GPR investigation proceeded either inside or over the edges of the MD halo, depending on its size. GPR investigation involved movements that were typically performed at a speed 1–5 cm per sec faster than head velocities in MD. The sensor head trajectories for GPR investigation involved back-and-forth movements on a path anywhere from 10-20 cm in length running perpendicular to the six o'clock–twelve o'clock axis of the MD signature. For AP targets, the initial trajectories would carry the head back and forth over the three o'clock–nine o'clock axis with GPR outputs starting as the head passed over the edge of the mine and ceasing after the head passed over the far edge. Pulling back to the six o'clock position, KJ applied similar back-and-forth movements in a forward direction, producing GPR outputs as the head passed over the near edge of a mine target and continued toward the three o'clock - nine o'clock axis. Further "GPR short sweeps" that advanced forward would then produce GPR outputs that diminished in frequency (for mines with circular shape) until the sensor head passed over the far edge of the target and GPR outputs ceased. For the larger AT mines, GPR investigation would be performed first at the three o'clock position, then at the nine, then at the six, and finally at the twelve. Essentially, when a mine was present, GPR output signals occurred whenever the search head passed from off the body of the mine to over it, and continued until the head's sweep carried it off the body. By mapping where GPR outputs occurred and where they didn't, it was possible to infer the shape of the buried target. The patterns and the spacing of GPR onset and offset points for the major categories on mines are shown in Fig. 9.8 and 9.9.

Although KJ's decision process, like RR's, was based on pattern matching, the additional information provided by GPR changed its complexity in two ways. First, the contours produced by GPR investigation were matched to the expert's familiarity with the various sizes and shapes of mines. This was reflected in statements like "OK, we've got a M19. It's square," or "This looks small, maybe an M14." The spatial relations between the MD and GPR patterns were considered in his "mine/no mine" decisions. This was suggested by a statement KJ commonly made prior to successful mine declarations: "Got MD. Got solid GPR. MD and GPR are correlated." His explanation of "correlated" was essentially that MD arcs and GPR shapes produced by investigating mines shared common axes of symmetry, whose intersections were spatially coincident. Thus, for mines with circular bodies, the MD halo and the GPR outline in his mind's eye would have to share the same center point for him to make a mine declaration. His declaration mark would also be placed precisely at that point.

Completion of site preparations for the initial HSTAMIDS training test provided an opportunity to prospectively test the validity of the above observations about target patterns. Buried targets to be used for training drills were marked at their centerpoints, but their identities were unknown to the expert operator. KJ's task was to locate the MD and GPR

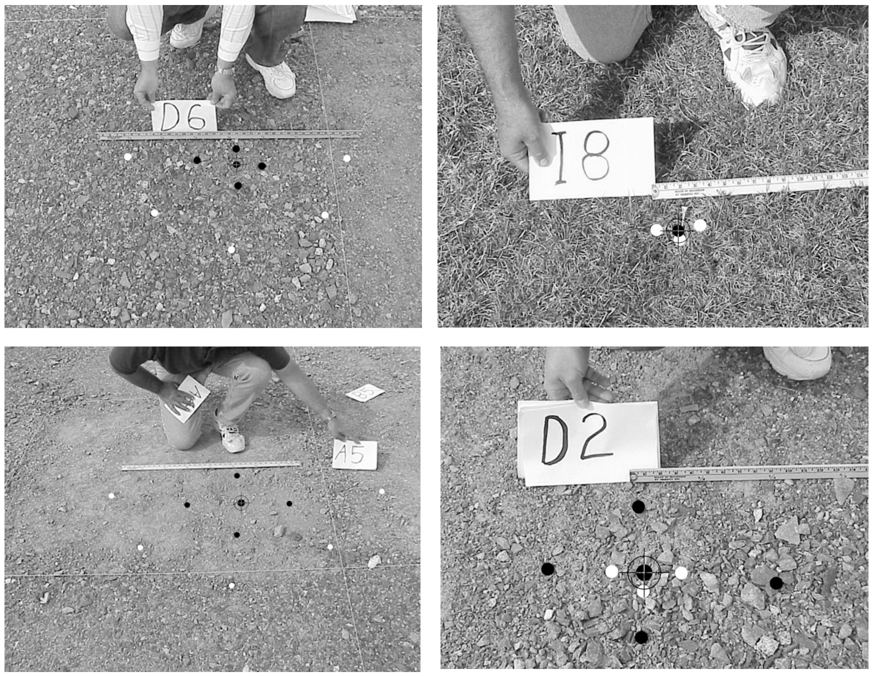

Fig. 9.8a-d.
Multimodal landmine patterns for an M16 (AP-M) (a); an M-14 (AP-LM-S) (b); an M15 (AT-M) (c); and a TM62P3 (AT-LM) (d); buried in the HSTAMIDS training area at Aberdeen Proving Ground, MD. White markers indicate edges of metallic halo. Target centers are marked with crosshairs. Black markers show onset/offset locations of GPR signals. Signal processing algorithms for GPR return signals detect changes in the returned radar signal produced by the differential dielectric constant values of a mine's body and the surrounding soil.

pattern edges on designated vectors radiating from each target's center mark for each of 81 targets. Exemplars of the mines in the target set are shown in Fig. 9.3. Each edge point was marked and its distance from the center point was measured. Examples of the resulting patterns for specific targets are shown in Fig. 9.8.

Analysis procedures followed the approach used by Rosch, Mervis, Gray, Johnson, and Boyes-Braeme (1976) to identify prototypes of basic-level perceptual categories. Radial distances for the same edge points of targets within five broad target groupings were averaged. The resulting

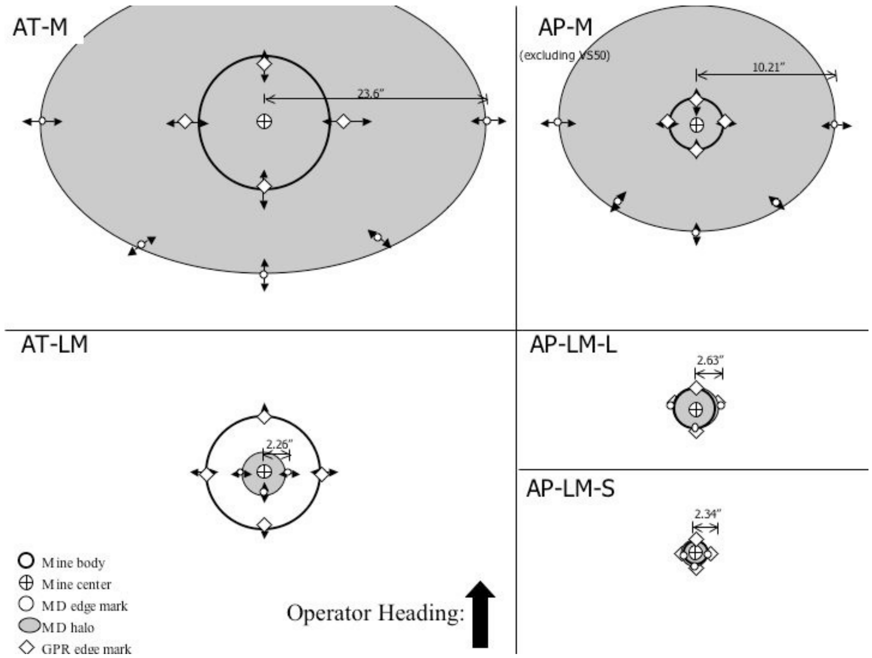

Fig. 9.9.
Prototypical HSTAMIDS footprints for mine categories produced by averaging the distances from target center point to edge markers for multiple exemplars of each of the five mine categories. Signals are shown relative to the target center points (crosshairs) and the averaged mine body perimeters (outlined in black).

patterns shown earlier in Fig. 9.9 emerged. Despite local variability, overall very stable signature prototypes emerged for each category, as seen by the relatively small standard errors associated with each mean. These results confirmed and quantified the tentative conclusions about HSTAMIDS mine patterns derived from observations taken during developmental tests.

To sum up, analyses of expert operators of the PSS-12 and PSS-14 suggest that like experts in other areas, both expert operators rely on recognition of visuo-spatial patterns created and held in memory to locate buried mines successfully. Both employ a search process, that is, search sweep, to identify the general area where mine patterns are located. The location of the sensor head at the time of an alerting signal marks the general area. The patterns that identify mines are not found whole at these locations, however. Rather, the experts appear to use a mental construction process similar to that described in the literature on mental synthesis (Finke, 1990; Klatzky & Thompson, 1975; Palmer, 1977; Pearson & Logie, 2000; Thompson & Klatzky, 1978). The pattern parts are acquired by iterative investigation routines that serially identify a series of locations held in the mind's eye where each system's auditory outputs define pattern boundary or edge points. Imaginary connection of adjacent edge points constructs contours (for both MD and GPR, in the case of the PSS-14), whose sizes and shapes are matched against those produced by the operators' previous investigations of mines. If the pattern produced by investigation is sufficiently similar to the patterns of previously encountered mines, the operator declares a mine and marks its location.

TRAINING NOVICE OPERATORS TO USE EXPERT STRATEGIES

Designing training for novice operators of the PSS-12 and HSTAMIDS focused on teaching them the expert's techniques and thinking, as well as providing requisite practice opportunities to support their skill development. Thus, the instructional content was known and known to work—for the experts, at least. The design challenge was to develop effective training procedures around this content. The scientific literature guided efforts that met the challenge.

Design Challenges and Solutions

Among the general principles that guided training design, three played particularly prominent roles in the design effort. They were (1) providing practice with feedback on drills, (2) limiting the quantity of instructional content delivered at any one time to avoid overloading students' working memory limitations, and (3) accommodating individual differences, particularly in the areas of spatial and imagery abilities.

Incorporating minimal amounts of task practice for each drill and feedback into the prototype training for both systems posed challenges. Although the roles of practice and performance feedback on complex skill acquisition have been established for more than a century (Bryan & Harter, 1899; Woodworth, 1899), resource limitations, including target and trainee availability, past institutional training practices, the nature of the equipment, and the need to train multiple operators in a training cohort imposed non-trivial design constraints.

A comprehensive discussion of the problems involved and the manner in which they were solved is beyond the scope of this chapter. Suffice to say, their solutions produced training programs that were radically different from the operator training previously used by the Army for the PSS-12 or the HSTAMIDS original operational testing. Designing the new training programs involved developing and using simulated mine targets (for PSS-12 training), generating a novel training site design, and developing new tools for scoring declarations (described in Davison & Staszewski, 2002; Davison, Staszewski, & Boxley, 2001; Staszewski & Davison, 2000) and technology for assessing trainees' techniques (Herman & Inglesias, 1999; Herman, McMahill, & Kantor, 2000). The training schedules were designed to accommodate modest (at best) amounts of practice for each drill along with performance measurement and feedback delivery for each. This resulted in 12 to 16 hours of hands-on drill and practice per man for the prototype PSS-12 training. HSTAMIDS trainees received 28 to 32 hours of instruction and supervised drill and practice. These durations far exceeded the 4-hour length of the existing PSS-12 training for new operators, of which roughly half was classroom instruction.

Learning a novel skill requires trainees to retain cues, events, responses, and their ordering long enough to execute and practice activities prescribed by instruction (Anderson, 1983; Fitts & Posner, 1968). Because working memory capacity (Miller, 1956; Miyake & Shah, 1999) limits the length of such sequences, instructional design must parse instructions to accommodate this general constraint. Sequences short enough to permit correct execution allow for task practice that reduces the load on working memory (Law, Morrin, & Pellegrino, 1995) and frees up resources for further learning. Once parts of tasks are learned well enough to be performed correctly on a consistent basis, these additional resources allow acquired part-task skills to be practiced together and properly integrated.

Training the pattern development aspect of the investigation task posed a special challenge if inferences about how the mine detection experts performed this task were correct. It appeared that they had to hold pattern-edge locations in memory while simultaneously operating the system to identify edges in adjacent locations, and then fuse the retained and newly acquired locations into a single pattern. Explorations of the mechanisms supporting mental synthesis (Pearson & Logie, 2000) suggest that this activity places demands on all components of working memory as it is described in Baddeley's (1986) influential model, including the phonological loop and central executive as well as the visuo-spatial sketchpad. Relevant to the current context, performance suffers under concurrent task conditions, as are suspected to occur in the experts' synthesis of target signatures.

The expert models already on hand not only provided the content for the PSS-12 and -14 training programs, their control structures guided decisions about how to scale instructional units. Reasoning that skills represent stable solutions to routine problems – in this case the problem being to find one mine at a time—they should be hierarchically organized in a manner that reflects subgoals, whose sequential attainment leads to a problem's solution (Newell & Simon, 1972). This assumption guided the analyses that produced the models shown in Figs. 9.4 and 9.7. Both illustrate three high-level subgoals and their conditional ordering: (1) acquire and localize an alerting signal, (2) acquire a signal pattern through investigation of area adjacent to the alert, and (3) decide if the pattern acquired by investigation corresponds to patterns produced by mines. The first was further decomposed for both systems into (a) a single sweep of the detector head across the width of the designated lane and (b) forward movements by the operator that advanced subsequent cross-lane sweeps to incrementally cover new territory. The investigation process was further parsed into goals involving recursive definition of pattern edge points, shown in Figs. 9.5 and 9.9. Instructional units were thus designed to describe and demonstrate the sequence of thoughts and actions that achieved each goal, followed by drills enabling practice of each part-task with feedback. Tasks for the PSS-12 training are found in Staszewski and Davison (2000), Davison and Staszewski (2002), and Davison, Staszewski, and Boxley (2001). Both formative assessments and summative performance assessments suggested that the strategy employed to avoid information overload in training was successful.

Individual differences (IDs) in cognition are always a primary concern in instructional design (Dillon & Schmeck, 1983). Accommodating individual differences was of paramount concern to the PSS-12 and -14 training development efforts for several reasons. First, trainee selection on the basis of psychometric abilities was not an option; training procedures would have to handle the range of abilities found in the ranks of soldiers qualifying for engineer military occupation specialties (MOS 12B, 12C). Second, the expert models suggested that processes related to acquisition, retention, synthesis, and comparison of spatial information in the mind's eye were fundamental components of expert skills. Thus, supporting trainees' acquisition of the relevant spatial skills would be a critical part of training.

This posed no trivial challenge because individual variability in spatial ability is well documented in the psychometric literature (Carroll, 1993), and spatial ability predicts success on a variety of significant occupations including engineering, surgery, mechanical drawing, aviation, mathematics, and the physical sciences (Hegarty & Waller, in press; Shea, Lubinski, & Benbow, 2001). Miyake, Friedman, Rettinger, Shah, and Hegarty (2001) have found that performance on spatial ability tasks is moderately to strongly related to performance on working memory processing and storage tasks as well as STM retention tasks. Along with individual differences found in both working memory capacities and spatial abilities, individual differences in visual imagery (Finke & Shepard, 1986) compounded the design challenge.

The literature on WM limitations and IDs in spatial and imagery abilities prompted a search for ways to reduce any impediments that these factors might impose on development of pattern acquisition skills. Fortunately, the literature also suggested two mitigating factors. First, the MD halos (and the GPR patterns for the HSTAMIDS) exhibited symmetry, if clutter was not present to distort their shapes. Garner's (1974) studies of visual form perception have shown that symmetry is a property related to formal "goodness" and facilitates pattern processing. Consistent with Garner's work, Palmer's (1977) studies of mental synthesis showed that subjects integrated items exhibiting "good" form more quickly and accurately than those with intermediate or "bad" form. Second, some hope for overcoming IDs in spatial ability came from studies (Carpenter & Just, 1986) showing that training on psychometric test items raised performance on psychometric tasks that measure spatial ability.

One training requirement added to the already multifaceted challenge of training soldiers on the entirely novel skills of pattern acquisition and recognition. The distortions caused to target halos by clutter meant that training programs would need to support acquisition pattern-recognition skills that were sufficiently flexible and abstract to enable trainees to recognize the patterns produced by targets, despite unpredictable distortions in their shapes. Thus, the training would need to support acquisition of abstract visual representations to handle the variability in target patterns produced by "clutter." Here, the concept-learning literature, especially the work of Posner and Keele (1969, 1970**)** and that of Rosch and her colleagues (1976) informed training design in ways that will be described shortly.

The manner in which training was designed to support acquisition of pattern acquisition and recognition skills and how it was guided by fundamental cognitive science will now be addressed.

Decomposition of a complex task into components for training is not a new solution to minimizing working memory load. However, it is worth noting again that the expert models' goal structures facilitated decisions about how to parse the experts' action sequences into instructional units and accompanying exercises. "Edge location" was clearly the fundamental operator and the most basic skill that needed to be trained. Thus, after instruction, demonstration, and practice on preparing the respective equipment for operation, trainees received instruction, demonstrations, and practice for learning edge detection techniques. Drills consisted of a set of trials in which operators would encounter a mine target of unknown type buried at standard operational depth. A poker chip was placed on the ground marking the center of each target. Following instructions and demonstrations of edge detection for targets of each mine category included in the target sets, trainees proceeded to locate with their equipment the metallic halo edge point immediately to the right of the target center. The edge point for each trial would be marked with a marker and the distance from the center point to the mark measured and recorded by the "buddy" trainee with whom each operator was paired. Immediately afterward, the specific type of target used in the trial and the broader category to which it belonged (AT-M, AT-LM, AP-M, AP-LM) was provided to the operator. Each operator encountered 10 targets from each of the four categories. The task concluded with the operator-buddy pair reviewing the set of measurements by mine type to obtain a conception of the within-category consistency as well as variability in edge locations.

The *Footprint Development Exercise* introduced trainees to the patterns or "footprints" that identify and locate buried mines and the sequence of actions and thinking used to acquire them. In the exercises, a trainee repeated the previously described edge detection technique from at least five different directions, for example, advancing the sensor head from different perimeter points (E, S, W, SE, SW) toward a poker chip marking the center of an unknown mine target. Each edge was to be marked, with all marks remaining in place until the task was complete. All center-to-edge distances were measured, recorded, and reported to the operators. Each operator was asked to identify the mine category of each target, and his battle buddy gave feedback on the target's identity and category. Trainees were instructed to describe explicitly the size and shape of each resulting pattern and compare and contrast the patterns obtained across trials.

How did this simple task address the design issues discussed above? First, Posner, Keele and colleagues (Posner, Goldsmith, & Welton, 1967; Posner & Keele, 1969, 1970) demonstrated that subjects could abstract and retain prototypes when permutations of dot patterns were presented to them as exemplars in concept learning experiments. Second, Finke's (1984) work on visual imagery compared and contrasted results of experiments on vision and imagery, insightfully pointing out functional equivalences between them. His conclusions suggested a way to finesse some of the threats to learning posed by working memory limitations as well as spatial and imaginal individual differences. The solution was to make the training of footprint development not a task requiring imagery, but a visual perception task. This was done by having operators find and mark edge points at the designated compass locations in relation to a target center mark and then leaving each marker in place until the all of the designated edge marks were in place, measured, and recorded, and the feedback given on the required mine category judgment. The intent was to transform what was thought to be a very demanding representational task into a simpler visual concept-learning task of the sort Posner and Keele used.

The same strategy was used to solve the problem of delivering feedback to support operators' learning of proper search sweep techniques. The challenge to trainees (and trainers) is to ensure that cross-lane sweeps overlap and thus cover *all* of the area designated for clearance with the search head. The difficulty lies in remembering where the sensor head was on the previous sweep. This task turns out to be extremely difficult even for observers focusing only on the sensor head's movements, let alone trainees monitoring the sensor head's speed and trajectory as they sweep.

The solution for PSS-12 training involved using a soft surface soil in the training areas. Practicing expert PSS-12 sweep technique, which involves the sensor head's gliding over the ground surface, displaces surface soil and leaves a visible wake that serves as a reference for guiding the operator's subsequent sweeps.

The solution for PSS-14 training involved using the Sweep Monitoring System described earlier (Herman & Inglesias, 1999; Herman, McMahill, & Kantor, 2000) as a tool for feedback delivery. This computer-based system records the position of the sensor head at all times during sweep. Later replay of the recorded data via a graphical interface shows observers and trainees a visual image that "paints" all locations where the sensor head had—and hadn't—been. Fig. 9.10 shows the display of sweep coverage that this system produces..

SURPRISING OUTCOMES

The effects obtained by initial administrations of each program were unexpectedly strong, given the novelty of the programs and the amount of task practice each permitted. Results from the initial test of PSS-12 training are shown in Fig. 9.11. Results from the first and second test of the HSTAMIDS training are shown in Fig. 9.12.

Another measure of the surprising strength of the training effects was the uniformly high detection rates achieved by all trainees in both

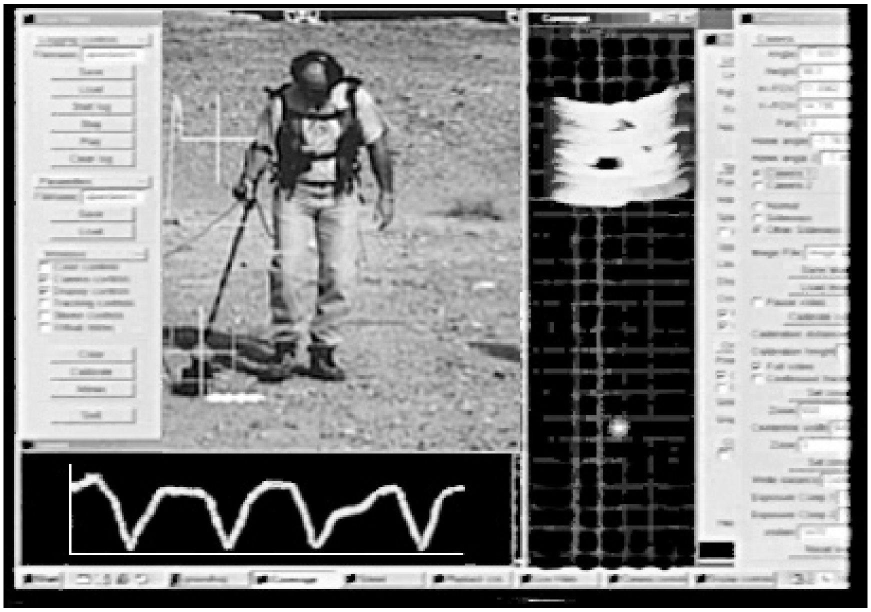

Fig. 9.10.
The visual interface of the Sweep Monitoring System showing the area covered by the HSTAMIDS sensor head in the expert's search sweep. The SMS display here shows a color coding of search head velocity; yellow indicates a speed within the functional thresholds set by GPR sampling and signal processing speeds. The red borders of the color display reflect the lower speeds related to deceleration and acceleration of the head related to reversal of sweep direction at the mine lane's lateral boundaries.

programs (discussed in Staszewski & Davison, 1999, for the PSS-12 program). A further surprise was the speed with which trainees acquired near-expert performance levels in the initial blind search exercises, which represented the first time trainees were required to integrate the subskills they had learned and execute the full task of detecting targets in unknown locations. In all training administrations, detection rates of 0.90+ were achieved, with the detection rates for M14s always exceeding those of reference measures by multiple factors.

Additional surprises came from subsequent administrations of the PSS-12 training. In August 2001, the author and collaborator (Davison) built a permanent mine detection training site at the Joint Readiness Training Center (JRTC), Ft. Polk, Louisiana, and administered the still-experimental PSS-12 training. This activity came at the request of combat

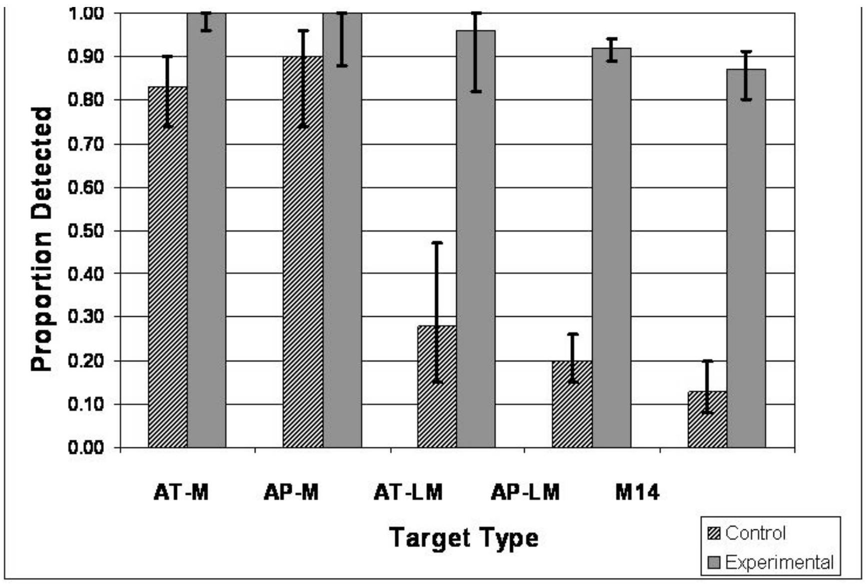

Fig. 9.11.
First PSS-12 Test results showing proportion of target detected as a function of target category for combat engineers receiving experimental training and controls who had only standard Army training. Error bars represent 95% confidence intervals. Note that pretesting of both groups showed them performing at equivalent levels.

engineer and military police units scheduled for overseas deployment to areas where landmines were a major threat. Severe weather and last-minute changes in the availability of troops for training reduced the time for drill and practice to the range of 3 to 4 hours per soldier. Summative assessments showed a decrement in detection rates; however, the training effects (shown in Fig. 9.13) proved far more robust than the instructors anticipated.

Yet another surprise came from an administration of the PSS-12 training by JRTC personnel in charge of combat engineer training and assessment. JRTC personnel who had been trainees in the training described above served as instructors.[8] They trained six platoons of combat engineers (approximately 180 soldiers) from the U.S. Army's 10th Mountain

[8]The author and Davison were not present and did not participate in the administration of this training.

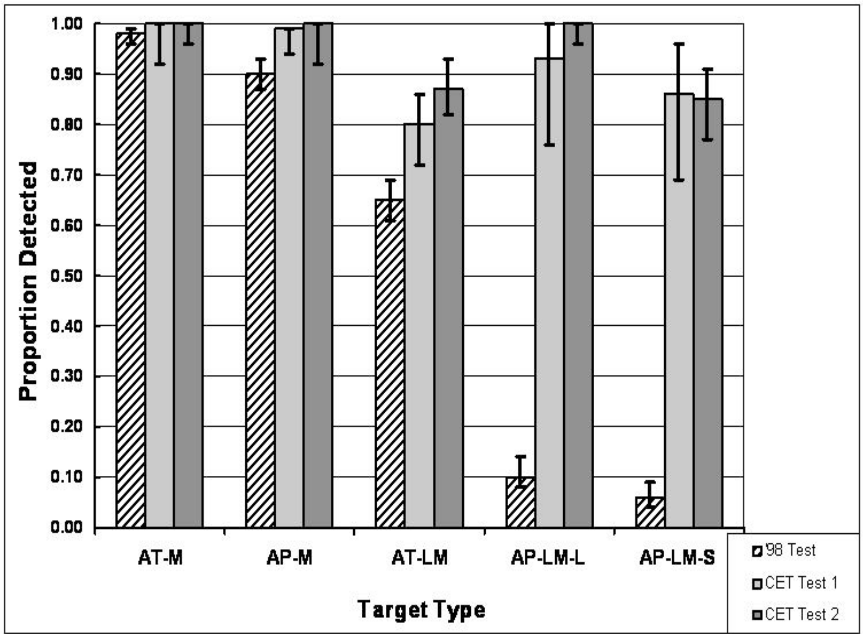

Fig. 9.12.
Proportion of targets detected as a function of target category for each of two tests of the HSTAMIDS training program. Results from original operational testing of the HSTAMIDS prototype are shown for reference. Error bars represent 95% confidence intervals. Note the asymptotic performance shown for AT-LM and AP-LM-S targets that served to diagnose system limitations that were remedied by subsequent hardware/software modifications.

Division who were scheduled for immediate deployment. They used materials and training aids left from the previous exercise and followed its procedures—including pretesting trainees using the previously taught then-standard Army techniques and posttesting following the experimental training—with one exception: schedule constraints limited drill and practice time to approximately 1 hour per trainee. The pre- and posttest detection rates achieved by the trainees are shown in Fig. 9.14.

In short, the PSS-12 training effects have remained relatively robust in spite of circumstantial variation on a variety of factors that can impair equipment performance. These factors include training time, ground surfaces, weather conditions, soil moisture and humidity levels, mine targets, equipment condition, trainee rank and military experience, military and

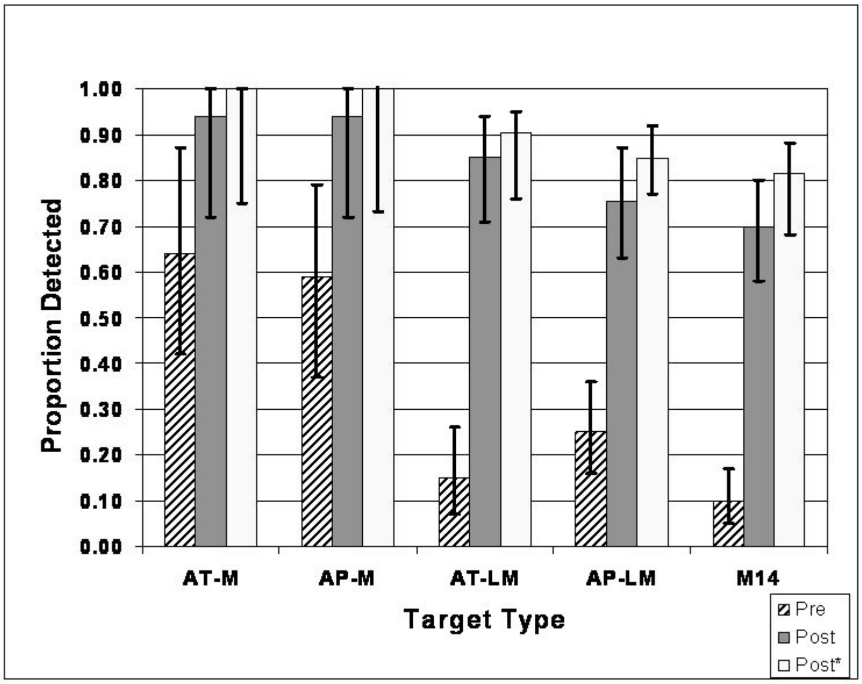

Fig. 9.13.
Pretest and posttest performance as a function of mine type for non-commissioned officers trained at the Joint Readiness Training Center, Ft. Polk, LA, in August 2001. Results for group labeled Post* eliminate the data of two soldiers whose posttest detection rates were 5 and 7 standard errors below that which both had shown in earlier blind search drills. Both showed an apparent loss of motivation upon learning that a long holiday weekend leave, which had been scheduled to begin upon conclusion of the mine detection training, was cancelled and that their unit would start 2 weeks of field training immediately.

training specialization, instructor experience, and more. The PSS-14 training has also proven pleasantly robust to variables such as these and more (e.g., variations in sensor head height and velocity).

No studies have been performed that manipulate the components of either training program or the parameters of these components to evaluate their impact on soldiers' detection capabilities. Thus, no conclusions about the contribution of specific components of the training programs on trainees' learning are available. One "natural" manipulation of this sort has occurred, however, involving the amount of pattern or footprint

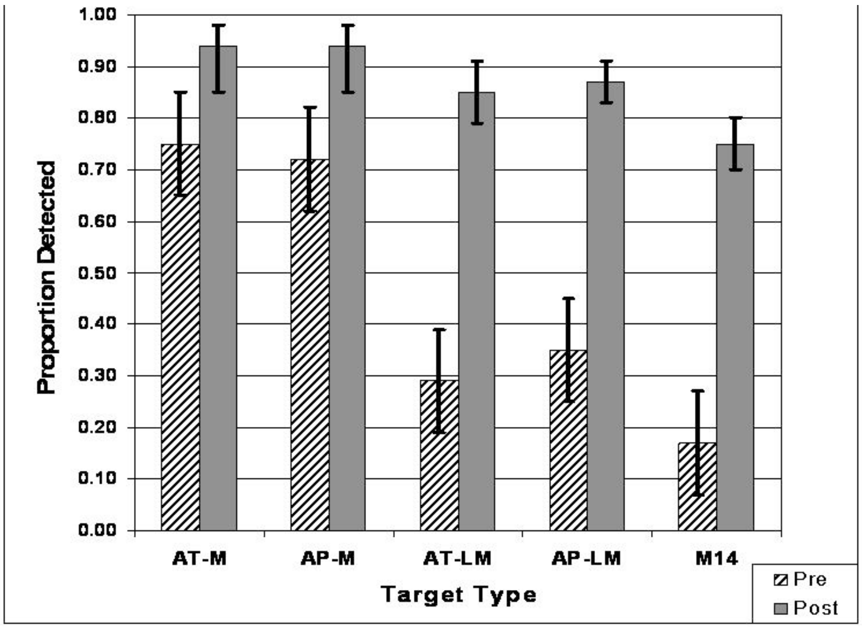

Fig. 9.14.
Pretest and posttest performance as a function of target type for combat engineers from the 10th Mountain Division. The training was administered by JRTC NCOs trained in the August training exercise and allowed for only 1 hour for drill and practice of the new expert detection techniques. Data collected by JRTC training personnel and provided courtesy of LTC Tommy Mize.

development instruction and practice given to soldiers receiving PSS-14 training.

A recently completed field assessment of multiple PSS-14 training delivered by different groups of military trainers and contractors has observed positive covariation between the amount of training on this subskill and detection rates for low-metal targets. The low number of observations involved and multiple confounding variables preclude attributing the observed variations in detection rates (especially the decrements observed relative to those achieved in operational testing and reported by Santiago, Locke, and Reidy (2004) to variability in the training of this instructional component. Nonetheless, given the stakes involved, the U.S. Army Engineer School leadership has authorized restoration of the time and procedures used in the original HSTAMIDS training to the current PSS-14 training program.

PRACTICAL PROBLEMS AND SCIENTIFIC PROGRESS

The field of cognitive psychology is entering its second half century according to accounts of its birth given by founders such as Miller (2003), Newell, and Simon (Newell and Simon, 1972). The occasion invites reflection on the field's achievements over its relatively brief lifespan. It is within the context of assessing our field's progress that the contributions of the work described in this chapter and its companions in this volume will be discussed.

Has cognitive psychology developed into a mature science? Rather than daring to define scientific maturity comprehensively and to the satisfaction of all, consideration will focus on two criteria that might be considered "prototypical." One takes an internal disciplinary perspective on the issue, the other, external.

A widely-acknowledged index of maturity, sometimes lamented for its absence by (Miller, 1986, Newell, 1973), highlighted by others (Anderson, 1983; Simon, 1980), and valued and encouraged by all is theoretical integration. In this regard, the recent emergence of large-scale computational theories or cognitive architectures, such as ACT-R, SOAR, EPAM, and EPIC is positive development. Each of these broad theoretical systems integrates a substantial accumulation of "local" theories and empirical principles produced by cognitive research in the past 50 years. Although the multiplicity of architectures and the differences among them show there is considerable work ahead to narrow the field of candidates, even physics, with a few centuries head start, has yet to narrow its field to a single, grand unified theory.

Scientific disciplines neither emerge nor develop in vacuums, however much the limited focus demanded for in-depth fundamental inquiry sometimes makes it appear. More than a century ago, Hall (1898) recognized the value of external influences, noting "Mere knowing disaggregates if divorced from practical life." Not only have societal and national needs inspired important scientific advances, especially in the US since the end of World War II, government policy has provided essential support for scientific growth, in no small way stimulating the birth of cognitive science and nurturing its development. Of course, a quid pro quo is assumed (see Stokes, 1997), and, as George Miller has recognized: "A healthy science must generate technology and meet human needs; psychology is no exception' (Miller, 1986, p. 295). The point is that the extent to which the products of basic research from a scientific discipline support engineering, that is, practical problem solving, that benefits the public is an important measure of its maturity.

By this criterion, this chapter, others in this volume, and other successful applied efforts (Allen & Rachotte, 2006; Loomis, Marston, Golledge, & Klatzky, 2005; Wu, Klatzky, Shelton, & Stetten, 2005) demonstrate the practical value of the fundamental knowledge that cognitive psychology has accumulated on spatial cognition. These accomplishments signify maturation, if not full maturity.

These contributions hold significance beyond benchmarking a disciplinary coming of age. Government and private philanthropy annually invest substantial sums to support scientists' pursuit of fundamental knowledge on the assumption that the products can be applied to solve practical problems and enhance public health and welfare. Non-trivial investments of a different kind come from within the scientific community. Scientists dedicate considerable time and effort to lead disciplines into new intellectual territory and expand a body of knowledge whose future applications and practical value can only be imagined. The successful applications described in this volume will hopefully reward all investors with returns that will encourage sustained and, perhaps, increased levels of investment that can spur further theoretical progress and new practical contributions.

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