CHAPTER 23

Air Traffic Control and Human Factors Integration

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23.1 INTRODUCTION

This chapter draws heavily on the reports of the National Academy of Sciences' Panel on Human Factors in Air Traffic Control Automation.[1,2] Over a four-year period (1994 to 1998), the panel reviewed the air traffic control (ATC) system from a human factors perspective and assessed future automation alternatives as they related to the role of the human operator in ensuring safety and efficiency. Two reports were published: *Flight to the Future* (Wickens et al., 1997) and *The Future of Air Traffic Control* (Wickens et al., 1998).

The ATC system and its development and management by the Federal Aviation Administration (FAA) provide an excellent opportunity for examining the role of human factors and human-centered design in a safety-critical, complex system. The American airspace system is impressive in its capacity and safety. In addition to maintaining safety, the ATC system is charged with the efficient flow of traffic from origin to destination. The joint goals of safety and efficiency are accomplished by controllers through an intricate series of procedures, judgments, plans, decisions, communications, and coordinated activities. The success of the current system is demonstrated by the safe and rapid response of the system immediately following the terrorist attacks on September 11. Within 3 hours, all aircraft flying over the United States were safely landed (Bond, 2001).

The primary purpose of this chapter is to illustrate the challenges and benefits of applying human factors integration (HFI) to a large complex system. This will be accomplished by using the national ATC system as a case example. To help the reader better understand the issues underlying HFI applications to ATC, some general background is provided below on the ATC system.

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23.1.1 Air Traffic Control System

The most familiar aspects of the ATC system to the public are the communication and coordination between the pilot and the controller. However, many operations take place out-of-sight as standard procedures. For example, the task of ATC includes several phases: ground operations from the gate to the taxiway to the runway, takeoff and climb operations to reach a cruising altitude, cross-country flight to the destination, approach and landing operations at the destination, and finally, taxi back to the gate (or other point of unloading). The traffic to be controlled includes not only commercial flights but also corporate, military, and general aviation flights. Three general classes of controllers accomplish control, each resident in different sorts of control facilities. First, ground and local controllers (both referred to as tower controllers) handle aircraft on the taxiways and runways. Second, radar controllers handle aircraft from their takeoff to their cruising path at the origin (departure control) and return them through their approach at the destination (approach control) through the busy airspace surrounding airport facilities. This region is referred to as a terminal radar control approach (TRACON). Third, en-route controllers working at the air route traffic control center manage the flow of traffic along the airways between the TRACON areas.

The functions of ATC have evolved from a few crude navigation aids for pilots to a technologically sophisticated system using satellites, wireless digital communications, various forms of radar, and high-speed, high-capacity computers both on the ground and in the aircraft. For many flights, only relatively passive monitoring of the flight path is needed during the cruise portion of the flight. However, during taxiing and departure and arrival—that is, in the near vicinity of an air terminal—safe passage is likely to require several instructions for change of path or altitude from the ground-based controller to the pilot. In any case, it is the responsibility of the controller to oversee all movements of the aircraft to ensure avoidance of collisions with other aircraft or obstacles. The fulfillment of this responsibility has become increasingly complex over time. The main source of complexity is in the growth in the volume of flights and the diversity of aircraft.

Complexity raises the demand on controller–machine workload, which suggests a number of HFI issues in any attempt to handle the increased workload with the right combination of human operators and new technology. HFI issues could include, for example, the following questions:

- Should the number of controllers be increased or decreased?
- What special needs for increased team training are required?
- How much automation can be introduced to simplify controller workload?

This last question is of special concern to the committee because increased automation is frequently the solution offered by the engineering community for handling increased complexity in human operations. However, the goals of safety and efficiency required by the FAA cannot be met by simply automating those features that are capable of being automated.

23.1.2 Automation and the Goals of Safety and Efficiency

Even given the very low accident rate in commercial and private aviation, the need remains to strive for greater safety levels: This is a clearly articulated implication of the "zero-accident" philosophy of the FAA and of current research programs of the National Aeronautics and Space Administration (NASA). These research activities typically incorporate human factors concerns and often are directed explicitly at human factors questions. Solutions for improved air traffic safety have been explored in a number of areas, including automation, changing procedures, improving training and selection of staff, and introducing technological modernization programs that do not involve automation per se.

As noted above, the topic of particular interest to the panel was whether human factors applied to decisions about automation. The approach was driven by the philosophy of human-centered automation defined as follows (Wickens et al., 1998, p. 2):

> The choice of what to automate should be guided by the need to compensate for human vulnerabilities and to exploit human strengths. The development of the automated tools should proceed with the active involvement of both users and trained human factors practitioners. The evaluation of such tools should be carried out with human-in-the-loop simulation and careful experimental design. The introduction of these tools into the workplace should proceed gradually, with adequate attention given to user training, to facility differences, and to user requirements. The operational experience from initial introduction should be very carefully monitored, with mechanisms in place to respond rapidly to the lessons learned from the experiences.

Automation has the capability both to compensate for human information processing vulnerabilities and to better support and exploit human strengths. Controllers, such as human operators in other complex domains, are vulnerable in the following areas:

- monitoring for and detection of unexpected low-frequency events,
- expectancy-driven perceptual processing,
- extrapolation of complex four-dimensional trajectories, and
- use of working memory to either carry out complex cognitive problem solving and planning or temporarily retain information.

In contrast to these vulnerabilities, when controllers are provided with accurate and enduring (i.e., visual rather than auditory) information, they can be very effective in solving problems, and if such problem solving demands creativity or access to knowledge from more distantly related domains, their problem-solving ability can clearly exceed that of automation. Furthermore, to the extent that accurate and enduring information is shared among multiple operators (i.e., other controllers, dispatchers, and pilots), their collaborative skills in problem solving and negotiation represent important human strengths to be preserved. In many respects, the automated capabilities of data storage, presentation, and communications can facilitate these strengths.

A considerable amount of automation has already been applied to ATC tasks for the en-route, TRACON, and tower environments, and future automation is likely to be significant for all environments. This automation has been applied to support controller tasks across all levels of cognitive complexity. However, the application of highly automated features, which often virtually replace controller actions, has to date been largely reserved for tasks of lower cognitive complexity. When automation has been applied to tasks of higher cognitive complexity, the automation was used to provide assistance to controllers.

In its second report, the panel provided an analysis of human factors issues associated with several ATC automation efforts. These analyses are instructive in that they lay out the system functions, the context for development, and the human factors issues associated with design, testing, and implementation.

The analysis of the Center TRACON Automation System (CTAS)—designed to provide support for controllers in the "TRACON" region, surrounding major airports—was particularly illustrative of how HFI principles were incorporated by the FAA at various acquisition stages.

This chapter first reports the panel analysis for CTAS as an example of how HFI was incorporated into the design and development of an automated ATC system. Next, we consider how well the CTAS has been implemented to date and speculate on what this example might illustrate in terms of the HSI principles for organizational maturity. Finally, we discuss the types of coordination and integration issues that are frequently associated with harmonizing several systems (some already in existence and some under development) for an organization as complex as the FAA.

We focus on the CTAS for three reasons. First, the CTAS supports controllers in the approach phase of flight, which appears to be the greatest source of bottleneck in the national airspace system, as well as the most dangerous phase of flight, as defined by risk of accident. Second, based on the panel report, the CTAS appears to have a particularly positive record of human factors input in its development. Third, there have been a number of agency system integration difficulties in acquiring a fully deployed system throughout TRACON facilities, in spite of the strong operational need and positive human factors features inherent in the CTAS design.

Many other ATC automation systems were also considered in the panel's report, such as those that support planning for en-route controllers, those that address issues of safety on conflict avoidance on the runway surface, or those that address communications between pilots and air traffic controllers. The interested reader should consult this report (Wickens et al., 1998) for more detail on these systems.

23.2 HFI IN THE DEVELOPMENT OF AN AUTOMATED ATC SYSTEM

The main impetus toward the development of the CTAS was the desire to maximize the use of capacity in airport arrivals and landings. Limitations in prediction of trajectories and weather led to spaces on the final approaches that were not occupied by an aircraft, thus creating delays and not meeting the actual capabilities of an airport's true capacity. In the 1980s, NASA and the FAA Technical Center began an in-house research-and-development project to develop the software tools for achieving this optimization (Erzberger and Tobias, 1986), working closely with controllers and human factors professionals to create a fielded system. During the mid-1990s, this system has received several field tests at Dallas–Fort Worth International Airport and the Denver Airport and Center. It was also being installed at Schiphol Airport in Amsterdam, the Netherlands. Two components of the CTAS (the traffic management advisor and the final approach spacing tool), described below, are currently being installed by the FAA at a larger number of airports as part of its Freeflight Phase 1 program (Nordwall, 2001). The future status of the decent advisor is unclear.

23.2.1 Center TRACON Automation System

The primary objective of the CTAS is to assist the air traffic controller in optimizing the traffic flow in the terminal area (Erzberger et al., 1993). Delays are reduced and flight paths are flown in a more economical fashion so that potential fuel savings are estimated to range from 45 to 135 kg per landing (Scott, 1994). These benefits are accomplished by providing assistance in prediction, planning, and control in both routine and unexpected circumstances (e.g., changes in runway configuration). The CTAS is also capable of providing advice to controllers regarding particular airline preferences. The CTAS is comprised of three separate components, each supporting different classes of ATC personnel, located in different facilities, and coordinating different phases of the approach:

1. The traffic management advisor (TMA) supports the TRACON and en route traffic management controllers, primarily in developing an optimal plan, to assign each aircraft a scheduled time of arrival at a downstream point, such as a final approach fix or runway threshold, and a sequence of arrival relative to other aircraft approaching the terminal area. The TMA begins to compute these for inbound aircraft at a point about 200 miles or 45 minutes from the final approach. The plan is designed to optimize the overall flow of the set of aircraft as well as the fuel consumption of each individual aircraft. At the same time, it accounts for various constraints on runway availability and aircraft maneuverability. The plan is also accompanied by an assessment of flight path changes to be implemented in order to accomplish the plan. A set of three displays assists the traffic management coordinator in evaluating the plan. These include a time line of scheduled and estimated times of arrivals for the aircraft, a listing of alternative runway configurations, and a load graph that indicates the anticipated traffic load across designated points in the airspace in 15-minute increments. The displays can be presented in large-screen formats for group viewing. The actual implementation of the plan generated by the controller with the assistance of the TMA is carried out by the other two elements of the CTAS, the descent advisor and the final approach spacing tool.

2. The descent advisor (DA) provides controllers at the final sector of the en route center with advice on proper speed, altitude, and (occasionally) heading control necessary to accomplish the plan generated by the TMA. The critical algorithm underlying the DA is a four-dimensional predictor that is individually tailored for each aircraft, based on that aircraft's type and preferred maneuver, along with local atmospheric data. This predictor generates a set of possible trajectories for the aircraft to implement the TMA plan. The DA then provides the controller with a set of advisories regarding speed, top of descent point, and descent speed. In cases in which these parameters are not sufficient to accomplish the plan, path-stretching advisories are offered that advise lateral maneuvers. The DA also contains a conflict probe that will monitor for possible conflicts up to 20 minutes ahead. If such conflicts are detected, it will offer resolution advisories based initially on speed and altitude changes. If none of these is feasible, lateral maneuvers will be offered as a solution.

3. The final approach spacing tool (FAST) is the corresponding advisory tool designed to support the TRACON controller in implementing the TMA plan by issuing speed and heading advisories and runway assignments necessary to maintain optimal spacing between aircraft of different classes (Davis et al., 1994; Lee and Davis, 1995). An important secondary function of the final-approach spacing tool is its ability to rapidly adjust to—and reschedule on the basis of—unexpected events such as a missed approach or a sudden unexpected runway closure. Like the DA, the controller receives advice in the fourth line of the data tag and also has access to time lines. The final approach spacing tool exists in two versions: The passive FAST provides only aircraft sequence and runway assignments, and the active FAST includes speed and heading advisories.

23.2.2 Human Factors Implementation

Human factors have played a relatively important role in the maturation of the CTAS, from concept, to laboratory prototype, to simulation, to field test (Erzberger and Tobias, 1986; Tobias et al., 1989; Harwood et al., 1998). From 1992 to 1997, approximately 30,000 person-hours of human factors expertise have been devoted to CTAS development and fielding. In part, the successful implementation of the human factors input was a result of the fact that the development took place at NASA laboratories, with ready access to human factors professionals and active participation of controllers in developing the specifications. The development was not under constraints related to contract delivery time or required specifications. Human factors implementation was also facilitated in part by the frequent input of controllers to the design concepts of functions at all phases and frequent human-in-the-loop evaluations at varying levels of simulation fidelity. The controller's input was filtered by human factors professionals (Lee and Davis, 1995; Harwood et al., 1998).

Another important factor is that these evaluations (and system changes based thereon) continued as the system was field tested at the Dallas and Denver facilities (Harwood et al., 1998). In particular, developers realized the need for extensive input from a team of controllers at the facility in order to tailor the system to facility-specific characteristics. The introduction process was quite time consuming, taking place over several years. This proved necessary (and advantageous) both in order to secure inputs from controllers at all levels and also in order for human factors professionals and engineers on the design team to thoroughly familiarize themselves with the culture and operating procedures at the Denver and Dallas–Fort Worth facilities; this, in turn, was necessary in order for the trust of the operational controllers to be gained and for the CTAS advisories to be employed successfully.

It is also important to note that the system was designed to have a minimal effect on the existing automated systems and procedures. Finally, the CTAS was presented to controllers with the philosophy that it is an advisory aid, designed to improve their capabilities, rather than as an automation replacement. That is, nothing in the CTAS qualitatively alters the way in which controllers implement their control over the aircraft.

23.2.3 HFI Issues

The integration of human factors into the system design process requires that a team of knowledgeable specialists undertake a set of analytical steps. The results of these analyses can be used to help evaluate alternative design features as they are proposed for inclusion in the evolving system. The analytic steps carried out in the CTAS design effort is summarized below.

Cognitive Task Analysis A cognitive task analysis reveals that the CTAS supports the controller's task in three critical respects. First, its four-dimensional predictive capabilities compensate for difficulties that the unaided controller will have in predicting and visualizing the long-term (i.e., 5-minute) implications of multiple, complex, speed-varying trajectories subjected to various constraints, such as fuel consumption, winds, and runway configuration. Second, its interactive planning and scheduling capabilities allow multiple solutions to be evaluated off-line, with the graphics feedback available in the time lines, to facilitate the choice of plans. Here also the system supports the workload-intensive aspects of planning (Johannsen and Rouse, 1983; Tulga and Sheridan, 1980), particularly prevalent when multiple plans need be compared. Finally, the CTAS, particularly the final-approach spacing tool, supports the controller's ability to deal with the high workload imposed by unexpected and complex events, characterized, for example, by a missed approach or unanticipated runway closure. The first and second of these tasks primarily affect the efficiency of system performance, whereas the latter has direct and beneficial safety implications.

Workload A stated objective of the CTAS is that it will not increase controller workload; indeed, field tests of the system reveal that this criterion has been met (Harwood et al., 1998). As noted above, the CTAS has the potential to reduce workload during the "spikes" imposed by unexpected scheduling and spacing requirements due to a missed approach or closed runway. However, it is also the case that workload may be shifted somewhat with the introduction of the CTAS. Relying on an added channel of display information, rather than the controller's own mental judgment, may impose an increase in visual workload. In fact, any new set of procedures (such as those associated with the CTAS) would be likely to impose some transient workload increase.

Finally, although not yet reported, a tool such as the CTAS does have the potential of advising maneuvers that create an airspace considerably more complex than that viewed under unaided conditions (Wyndemere, 1996). In such a case, controller monitoring and perceptual workload may be increased by the controller's effort to maintain a full level of situation awareness of the more complex airspace.

Training The general approach to training for the CTAS is to first provide simulation and then provide a shadowing of the real traffic off-line in the system. In the shadowing mode, CTAS elements provide the advice, and the controller can compare clearances that he or she might provide on the basis of that advice with clearances more typical of an unadvised controller and evaluate the differences (Lee and Davis, 1995). The controller can then determine the rationale behind the automated advisory. This builds confidence that the computer can provide advice to maintain separation. One might anticipate the need for some training of pilots regarding the CTAS, not because procedures are altered, but because the nature of the clearances and instructions may be changed, relative to the more standardized, space-based approaches (i.e., using the standard terminal arrival system) in a non-CTAS facility.

Communication and Coordination Because of the philosophy by which the TMA plans are implemented via the DA and the final-approach spacing tool advisories, the CTAS imposes a relatively heavy communication load between operators and facilities. This is supported via digital data transfer rather than voice communications. Furthermore, the philosophy of repeated displays across different environments supports greater communications and coordination between operators, in that these can better support a shared situation awareness of the implications of different schedules. The extent to which ground–air communications are altered by the CTAS remains unclear. At least one field study of the final-approach spacing tool (Harwood et al., 1998) carried out at the Dallas Airport over a six-month period indicated that the system imposed no increase in overall communications, although the nature of the communications was altered somewhat, involving more messages pertaining to runway assignments and sequencing.

23.2.4 Automation Issues

In its report and review of the literature, the panel identified a number of important cognitive issues and lessons learned pertaining to automation of systems in other domains, particularly automation on the flight deck (see reviews by Billings, 1996a, b; Parasuraman and Riley, 1997; Parasuraman et al., 2000). It then applied these to several proposed ATC automation tools and to the CTAS in particular.

The CTAS remains sufficiently recent in its introduction that there has not been time to identify specific human factors automation issues on the basis of operational experience (e.g., operational errors or aviation safety reporting system incidents). However, analysis of system capabilities does suggest at least some that might surface.

Mode Errors The CTAS contains some multimode operations. For example, with the DA, controllers can choose a route intercept or a waypoint capture mode for individual aircraft as well as one of three possible speed control modes for all aircraft (Erzberger and Nedell, 1989). However, the system appears to be designed so that different modes are prominently displayed, and active decisions must be carried out to change modes, so that mode errors would appear to be very unlikely.

Mistrust There is a possibility that the advice offered by the CTAS could be initially mistrusted by controllers if it differs substantially from the way in which control is typically accomplished. Accordingly, trust must be carefully built through careful training with both simulated and live traffic. Indeed, Harwood et al. (1998) noted an increase in controller confidence after they had used the system (and relied on the final-approach spacing tool advice) with live traffic. This provided the opportunity to see the real improvement achieved in traffic flow (13 percent).

Overtrust and Complacency Currently the philosophy of system implementation safeguards against undue complacency. This is because controllers must still give the actual clearances orally, as they would in a nonaided situation. Hence, they remain more likely to actively think about those clearances, for example, than they would in a system in which CTAS-advised clearances could be relayed via data link with a simple keystroke. Complacency is not generally recognized as a concern until an incident of automation failure occurs, in which the human's failure to intervene or resume control appropriately is attributed to such complacency. No such incidents have been observed with the CTAS. The advice-giving algorithms were thoroughly tested and in operational trials have yet to fail; alternatively, if inappropriate advice was ever provided, controllers were sufficiently noncomplacent that they chose to ignore it.

Past experience with other systems indicates that systems can fail in ways that cannot be foreseen in advance (e.g., the software does not anticipate a particular unusual circumstance). Furthermore, despite the design philosophy that appears to keep the controller a relatively active participant in the control loop, it is also the case that the primary objective of the CTAS is to increase the efficiency (and therefore saturation) of the terminal airspace. Such circumstance would make recovery more difficult should problems emerge for which the CTAS would be unable to offer reliable advice.

Skill Degradation As with complacency, so with skill degradation: The CTAS has not been used long enough to determine whether this is an issue. Yet, it is easy to imagine circumstances in which controllers increasingly begin to rely on CTAS advice, relaying this as instructions to pilots, losing the skills at selecting maneuvers on their own. This may be more problematic still, to the extent that the maneuvers recommended by the CTAS are qualitatively different from those that would previously have been issued by unaided controllers. At this time, a clear tabulation of maneuver differences with and without the CTAS has not been carried out.

Organization The organizational implications of the CTAS remain uncertain. A strength of the system is that it is designed to be advisory only; by not directly affecting required procedures, the negative impact on organizational functioning should be minimized. However, it is possible that subtle shifts in authority from the R-side controller to the D-side (who is more likely to have direct access to CTAS advisories) could have unpredictable consequences. We explore these consequences further in the discussion of conflict probes in the following section.

23.2.5 Conclusions Regarding CTAS

The CTAS appears to be a well-conceived automation concept addressing a valid concern of the less automated system and designed with an appropriate philosophy that is based on automated advice giving rather than automation-based control. As such, it is characterized by a relatively low level of automation that accordingly diminishes (but does not eliminate) the extent of concern for complacency. Finally, the CTAS has been developed and introduced gradually in a manner sensitive to human factors issues and to the importance of filtered controller input into the functioning of the system. Careful human factors monitoring of the system's field use should be continued.

The CTAS has the potential to radically alter the procedures of pilot–ATC coordination, pilot choices, and flight plans. Yet there are other systems in the airspace that also have similar impacts, such as the pilot's flight management system or the digital "datalink" communications between ground and air. The panel saw the vital need to "harmonize" any new automation system, such as the CTAS, with other systems currently in existence, under development, or proposed—an issue we address in the following section.

Unfortunately, in spite of the promising results of early HFI reviews and evaluations by NASA, during field tests at Dallas–Fort Worth and Denver (Harwood et al., 1998), the CTAS has yet to realize long-term success in system integration. Subsequent to its transfer from a developmental version to a fully deployed ATC system, implementation in TRACON facilities has been limited, difficult, and expensive. Of the three major CTAS components, one (TMA) has been partially implemented and another (FAST) has to this date seen, adoption at only two sites.

When we look at the 10 HSI principles of Chapter 1, we may find a clue for the mixed results of the CTAS as part of the national ATC system. The early positive results the panel's report relied upon to indicate an HFI success with the CTAS were based upon many of the 10 principles being utilized appropriately. For example, there was top-level support (1), a focus on the operator as a central design philosophy (2), an integrated approach to system documentation (4), proper use of HFI technology (7), and application of the appropriate human factors skills throughout the design and development process and initial field evaluations (9).

However, it appears that at least two principles—quantitative human performance (6) and test and evaluation (8)—were weak throughout the process of system acquisition by the FAA. While much was done to demonstrate, evaluate, and revise designs, there were few quantitatively established endpoints for human–system performance. "Goodness" was defined by user acceptance, which was generally nonquantifiable in total system performance terms, and the user acceptance criteria tended to vary throughout the program's development.

23.3 HARMONIZATION OF MULTIPLE SYSTEMS

The idea of harmonization or integration is central to the process of systems engineering. Basically, integration refers to the compatibility of the components of a particular system. Electronic and electromechanical systems, in particular, may generate many instances in which some elements or components are unable to communicate with each other. The development of such systems to the point of effective utility is a challenge for engineer designers. In 1998, the developmental pipeline contained a series of substantial ATC subsystems that were proposed for inclusion in the national airspace system. The panel's report concluded that more research was needed to determine if the new subsystems could perform as well as expected and whether they fit together to make an effective total system. At that point in time, subsystems had been developed in relative isolation from one another and from the overall modernization program. For example, the specifications for the Standard Terminal Automation Replacement System (STARS) and Display System Replacement (DSR) required that developers provide an architecture that would allow future plug-in of preplanned product enhancements. However, no human factors analysis of how these enhancements would be integrated with one another or with the STARS and DSR baselines was evident.

The lack of evidence of a unifying human factors analysis for advanced automation products in order to guide their integration into complementary workstation designs or procedures is exemplified by the CTAS. Although NASA's in-house scientists and their supporting contractors were also working on projects such as cockpit automation and data link in ATC, the role of data link with respect to the CTAS and the potential constraints of data link on the CTAS did not receive significant attention of CTAS researchers.

In general, tests that determine inter-subsystem compatibility should immediately follow the tests that demonstrate subsystem performance. When the compatibility between pairs of subsystems has been established and possible sources of confusion resulting from conflicting sensors, databases, and algorithms have been identified, the assembly should be enlarged to include other innovations until the subsystems that must be used together have been included in an overall test. At each stage, the evaluation should include a comparison against the base case represented by the current operational system.

Typically, despite careful analysis and validation efforts, not all human errors can be predicted. The human–computer interface is not the only source of error; new systems can introduce new sources of error (e.g., mode, logic, and procedural errors). This may be especially true when a given system will be integrated within a set of existing systems or when systems in parallel development will be implemented together because such integration can produce unexpected and unintended consequences. Reason and Zapf (1994) note that testing components in isolation and then putting them together open the opportunity for previously unidentified "resident pathogens" to strike. Systems designed without consideration of the implementation context risk incorporating such error-inducing features as computer interface logic that conflicts with that of other systems, information that unnecessarily duplicates (and possibly conflicts with) that provided by other systems, information whose interpretation or use requires data from other remotely located systems, information that confuses what is offered by other systems, alarms that distract the user from those of other systems, and disruption of team work flow (Miller et al., 1996). It should be noted that even field testing can miss unanticipated errors caused by combining new systems if systems planned for simultaneous implementation are not field tested together. For example, the parallel runway approach system, which is ground based, uses distance as a separation algorithm while a proposed cockpit-based system uses time-to-contact for separation. The ground-based system relies on radar; the airborne system uses the Global Positioning System (GPS). These differences in technology are important should a redundant system involving both air and ground alerts be considered. If technologies are different and they provide conflicting advice, which should be followed?

Such cumulative or interactive effects must be taken into account throughout a system development process that anticipates the integration of system elements. In addition, since controller training, sector staffing, operational procedures, control room conditions, and equipment maintenance affect system effectiveness, system development and testing should include attention to how these context factors affect controller tasks, workload, and performance during use of the system under development and test (Grossberg, 1994). Modeling and analytical techniques as well as prototyping and simulation are all important methodologies for examining possible interactions between new technologies and the equipment and procedural contexts into which they are introduced.

While these techniques do not obviate the need for operational validation with controller-in-the-loop simulation in the actual ATC context, the panel's report recognized the critical importance of valid human performance models in the particular area of the human response to unexpected failures in otherwise highly reliable automation systems along with the impact of that response on system safety. Statistically reliable data regarding such responses from empirical studies are extremely difficult to obtain because, by definition, such events must be rare to be unexpected; if they are rare, there will be a very small sample size of observations per subject (Wickens, 2001). Yet, the complexity of the real-world systems involved inhibits the design of experiments using a large number of subjects. Valid models thus become vital in predicting the impact of system failures.

23.4 NATIONAL AIRSPACE SYSTEM: AN ORGANIZATIONAL HFI EXAMPLE

The panel's reported conclusions on the requirements for effective management of human factors for the national airspace system illustrate the types of challenges and benefits inherent in attempts to fully integrate human factors into an organization's systems acquisition process.

One conclusion from the panel's report was that effectiveness of human factors activities requires coordination and oversight by a central human factors management within the organization. In reaching that conclusion for the FAA, the report considered requirements for an effective human factors program. Although this conclusion applied to all human factors activities within the agency, the report focused on the development and acquisition of automation systems for ATC. As an example, the specific activities of a centralized human factors program management reported as necessary included

- coordinating communication of human factors performance data across integrated product teams and between researchers, developers, users, and testers in the United States as well as in other countries;
- developing and monitoring human factors program plans;
- monitoring and guiding the activities of contractors' human factors representatives;
- developing policies and procedures for the application of human factors to the development, test, and implementation of automated systems;
- evaluating the qualifications and performance of human factors specialists; and
- guiding the trade-offs pertaining to cost and schedule of human factors activities.

Human factors management plays a key role in identifying the appropriate mix of research and test methods that support system development. Human factors management should interface with engineering and program management personnel within an agency and with its support contractors to ensure that human performance requirements drive specifications and that hardware and software developers are responsive to the human performance requirements. Poor alternatives are the unfortunate situations in which human factors specialists become documenters of previously written computer code for the human–computer interface or in which training is expected to compensate for poor design.

It is also the role of human factors management to remind program managers, as necessary, that good human factors is a "pay now or pay more later" proposition. By the time a system reaches late stages of development or testing, major design commitments have been made, resources have been spent, and there is reduced motivation to discover design flaws that threaten deployment schedules. An example pointed out by the panel was the many downstream adjustments required in the STARS system.

It is not unusual for system designers or program managers to request that human factors specialists devise improved training programs to compensate for discovered design problems after system designs are frozen. Training, however, is not considered a substitute for effective design (reliance on training will not prevent errors if the design itself is inadequate), and flawed systems often require redesign despite improved training methods. Systems in which human factors are not properly addressed may require costly redesign after inadequacies are discovered (Grossberg, 1994; Stein and Wagner, 1994).

An effective human factors program presumes the activity of knowledgeable human factors specialists. In addition, it is important that researchers, system developers, and developers of policies, procedures, and regulations share appreciation of the importance of human factors activities and understanding of fundamental human factors principles. There are several avenues by which a systems acquisition organization can pursue development of human factors understanding throughout the agency as well as the enhancement of human factors expertise:

- The human factors management function, as stated above, includes coordination of information sharing between researchers and system developers. One appropriate vehicle is a human factors newsletter broadly disseminated within and beyond the agency to summarize studies, lessons learned, and issues raised by fielded systems, as the FAA has done after fielding the pilot based automation aid for collision avoidance, known as the TCAS system (Wickens et al., 1998).
- Widespread appreciation of fundamental human factors principles requires education of those within the agencies who perform research, support system development and testing, and establish regulations and procedures.

- Government acquisition programs have generally relied on development contractors and subcontractors to perform human factors activities. Qualifications of good human factors specialists, however, are often not made clear during the hiring of personnel by contractors. One function of the human factors management is to review the qualifications of human factors specialists hired by contractors.
- It is important to work toward an agency infrastructure in which some human factors training is provided to personnel and program managers at all levels of the organization (and to contract teams).
- The federal government increasingly supports integrated product teams with well-trained human factors specialists assigned to the team. It is important that these specialists be responsible to human factors management within the agency as well as to project managers.

23.5 CONCLUSION

In conclusion, the nation's ATC system is the prototype of a complex, high-risk system whose effectiveness and safety have the potential to benefit from well-conceived human-centered automation availed by advanced technology. Yet, the final goal of integrating such technology effectively is a lengthy process requiring many steps: careful task and workload analysis of operator needs and demands, good human factors in design and evaluation, effective training and cautious introduction of technology into the workplace, harmonization with other existing systems and procedures, consideration of the sorts of errors that can be committed, and the ways in which low-frequency events could seriously jeopardize the safety of the new technology. Finally, successful integration requires the full commitment and support to human factors of top-level managers in the organization who are responsible for design, acquisition, and deployment. Fulfilling all of these steps is a difficult challenge, but it is one that we believe will underlie the safe adoption of new technology and the satisfaction of the controllers who must supervise that technology.

NOTES

1. The views expressed in this chapter do not reflect the views of the National Academy of Sciences or the National Research Council.
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