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Air Traffic Controller Working Memory: Considerations in Air Traffic Control Tactical Operations

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September 1993

DOT/FAA/CT-TN93/37

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U.S. Department of Transportation
Federal Aviation Administration

Technical Center
Atlantic City International Airport, N.J. 08405

technical note technical note

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/CT-TN 93/37		

4. Title and Subtitle	5. Report Date
Air Traffic Controller Working Memory: Considerations in Air Traffic Control Tactical Operations	September, 1993
	6. Performing Organization Code
7. Author(s) Earl S. Stein, Ph. D and Daniel Garland, Ph. D	8. Performing Organization Report No. DOT/FAA/CT-TN 93/37
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Directorate for Aviation Technology Atlantic City International Airport, NJ 08405	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered Technical Note October 1992-September 1993
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The Air Traffic Control (ATC) environment is characterized by a continuous sequence of ever-changing, transient information, such as a series of aircraft being handled by an air traffic controller which must be encoded and retained, primarily, for tactical use (3 to 5 minutes) and secondarily, for strategic planning. This information is complicated by the limitations and constraints of human memory, in particular, working memory. Working memory can potentially degrade performance.

The primary objective of this report is to raise an awareness of the memory requirements of ATC tactical operations by presenting information on working memory processes that are relevant to ATC tasks, and the vulnerability of these processes to disruption. This report focuses on developing an understanding of the role working memory plays in air traffic controller performance by emphasizing the constraints, and the factors that may overcome or or minimize memory loss of critical ATC information. 229 references are cited in this report.

17. Key Words	18. Distribution Statement
Air traffic control (ATC) Memory enhancements, Controller memory, Controller performance, Memory lapses, Working memory	Available to the public through the National Technical Information Service Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	67	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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EXECUTIVE SUMMARY

During the last decade, the air traffic control (ATC) system has been challenged due to dramatic increases in the amount and complexity of air traffic in the United States. Increases are expected to continue into the 21st century, demanding significant changes in the current ATC system which was not designed to handle the heavy traffic demands forecast for the future. In order to modernize the National Airspace System (NAS) while maintaining safety and efficiency, the Federal Aviation Administration (FAA) has initiated one of the largest efforts in history to automate a highly complex and dynamic system. The FAA's plan for NAS modernization calls for major improvements which will change the way air traffic is managed.

The dramatic systems changes of the Advanced Automation System (AAS) will not only replace existing ATC technology and equipment, but will also fundamentally change the way in which controllers conduct their job. AAS will achieve remarkable and welcomed benefits, but it will not likely resolve all the problems of ATC. While the automation of routine tasks and the implementation of automated aids may decrease the controller's workload, they may also have impact on the controller's understanding and memory of the air traffic situation.

The ATC environment is characterized by a continuous sequence of ever-changing, transient information,such as a series of aircraft being handled by an air traffic controller, which must be encoded, and retained primarily for tactical use (3 to 5 minutes) and secondarily, for strategic planning. This information is subsequently discarded. The ability to manage flight information is complicated by the limitations and constraints of human memory, in particular, working memory. The frailties of working memory are severe enough to potentially degrade performance.

Working memory allows the controller to retain intermediate (transient) products of thinking and the representations generated by the human perceptual systems. Functionally, working memory is where all cognitive (mental) operations obtain their information and produce their outputs or responses. Working memory allows the controller to retain relevant information for tactical operations. Such tactically relevant information may include altitude, airspeed, heading, call/sign, type of aircraft, communications, weather data, runway conditions, current traffic picture, projected traffic picture, immediate and projected conflicts, etc. Working memory is heavily dependent upon long-term memory for such cognitive tasks as information organization, decision making, and problem solving. Working memory is also heavily constrained and limited by such time-dependent processes as attention, capacity, and forgetting. Essentially, working memory permeates every aspect of the controller's ability to process air traffic information and control live traffic.

The primary objective of this report is to raise an awareness of the memory requirements of ATC tactical operations by presenting information on working memory processes that are relevant to ATC tasks and the vulnerability of these processes to disruption. This report focuses on developing an understanding of the role working memory plays in air traffic controller performance by emphasizing the mechanisms of working memory, the nature of its limitations and constraints, and the factors that may overcome or minimize memory loss of critical ATC information. Awareness of the limitations and constraints of working memory, and the conditions under which they occur, are critically necessary to avoid situations that can result in airspace incidents and accidents. The final section of this report briefly deals with some of the potential human factors consequences of new automated technologies on air traffic controller working memory.

Human memory is integrated into every aspect of person-machine interaction in ATC. It can not be separated out mechanically from the other aspects of the job. It is both an essential asset and a basic limitation. As long as human operators work in the ATC System, memory will have its role to play.

This report draws extensively from the cognitive psychology literature, applying theory and research to ATC tactical operations. It is written for a multidisciplinary audience composed of those concerned with ATC operations.

1. INTRODUCTION.

"The safe, orderly, and expeditious flow of air traffic" (Hopkin, 1991a, p. 3) are traditionally the fundamental objectives of air traffic control (ATC) (see Federal Aviation Administration, 1989a). During the last decade, these objectives have been challenged due to dramatic increases in the amount and complexity of air traffic in the United States. As an example of the magnitude of the airspace traffic, there were 47 million instrument operations logged by the Federal Aviation Administration's (FAA) airport control towers in 1990 (FAA Administrator's Fact Book, June 1993, p. 8). Air traffic increases are expected to continue into the 21st century, demanding the evolution or replacement of the current ATC system which was not designed to handle the heavy traffic forecast for the future. The FAA forecasts 53 million instrument operations to be handled by FAA airport control towers in 1995 (FAA Administrator's Fact Book, June 1993 p. 36). Further, the FAA estimates that, in the United States alone, delays resulting in air traffic problems result in economic losses of over five billion dollars per year. These losses are expected to exceed ten billion dollars per year by the year 2000 if no changes are made (Wise, Hopkin, & Smith, 1991).

In order to maintain and modernize the National Airspace System (NAS), while maintaining safety and efficiency, and to address the potential financial burden, the FAA has initiated one of the greatest efforts in history to automate a highly complex and dynamic system. The FAA's plan for NAS modernization calls for major improvements in the ATC system, including new weather, radar, communications, and automation systems. The plan is designed to maintain aviation safety, reduce flight delays, and ease the workloads of pilots and air traffic controllers (see Federal Aviation Administration, 1989b).

Beginning in the mid-1990s, ATC systems will be equipped with hardware and software enhancements through the implementation of the Advanced Automation System (AAS). The first phase of AAS is the Initial Sector Suite System (ISSS), a collection of new work stations that provide for the electronic display of flight data and other enhancements. Before this system is operational, all Full Performance Level (FPL) en route controllers will require transition training in order to apply their existing operational knowledge of ATC to the new system's capabilities. The implementation of AAS, while beneficial, will not likely resolve all the problems of ATC. In fact, new problems are inevitable (Ammerman & Jones, 1988; Wise & Debons, 1987; Wise, Hopkin, & Smith, 1991). For example, while the automation of routine tasks and the implementation of automated aids for memory and decision making may decrease controller manual and mental workload, they may also influence their understanding and memory of the traffic situation.

The FAA has become increasingly concerned about actual and potential operational errors of ATC (Operational Error Analysis Work Group, 1987). This concern has been heightened with the planned implementation of AAS and the need for effective transition training for controllers who must be able to use ISSS to control live traffic. The dramatic system changes of AAS will not only replace existing ATC technology and equipment, but will also fundamentally change the way in which air traffic controllers conduct their job (Garland, 1991). The FAA is particularly concerned with the potential effects of the ATC conversion on the controller's cognitive (mental) processing of information. Specifically, increased automation may impose requirements on the controller that are incompatible with the way the controller processes information, more precisely, the way a controller attends, perceives, remembers, thinks, decides, and responds.

The cognitive requirements of ATC involves the processing of a great volume of dynamically changing information (Kirchner & Laurig, 1971; Means, Mumaw, Roth, Schlager, McWilliams, Gagne', Rosenthal, & Heon, 1988). Cognitive processing of flight data (i.e., call/sign, aircraft type, sector number, planned route, assigned speed, heading, altitude, time over posted fix, etc.) is crucial to virtually every aspect of a controller's performance. It is essential for the controller to manage available information resources in such a way that accurate information is available when needed. The ease with which information (e.g., flight data) is processed and remembered depends on how it is displayed and how the operator interacts with it. Consequently, the dramatic changes to information display and analysis resulting from the new ATC conversion may significantly alter the processing of vital flight information, potentially affecting ATC performance.

It is important to understand how controllers think, and how they interact with their equipment. Performance measurements of the controller have consistently involved tasks and variables derived from ATC and produced findings expressed in ATC terms (Hopkin, 1980). Another, possibly more beneficial, approach would be to trace the origins of the practical difficulties (e.g., memory lapses) which the controller encounters to fundamental limitations in human cognitive capabilities, and to use basic psychological knowledge to explain, measure, and resolve them. It is fundamental to consider the controller's task in human terms in order to provide perspectives, explanations, and insights into the cognitive processes which support ATC (Hopkin, 1980).

The ATC environment is characterized by a continuous sequence of ever-changing, transient information, such as a series of aircraft being handled by an air traffic controller, which must be encoded and retained primarily for tactical use (3 to 5 minutes), and secondarily for strategic planning. This information is subsequently discarded. The ability to manage flight information is complicated by limitations and constraints of human memory, in particular working memory (Finkelman & Kirschner, 1980; Kirchner & Laurig, 1971; Wickens, 1984). According to Dr. John Lauber (1993):

"A fundamental characteristic of human performance is that forgetting is all too easy. Short-term memory, as psychologists refer to it, is highly vulnerable to intervening events disrupting it. Add a distraction here and a little time pressure there, and presto, people forget- even very important things (p. 23)".

Essentially, working memory, like short-term memory, is the part of the memory system which deals with ongoing, transient information (working memory will be further defined in a subsequent section). Working memory limitations and constraints are routinely severe enough to significantly degrade performance. Awareness of the limitations and constraints of working memory and the conditions under which they occur are critically necessary to avoid situations that can result in air space incidents and accidents.

1.1 PURPOSE.

The primary objective of this report is to examine the memory processes that influence tactical ATC. Particular attention will be paid to the relevant memory components of importance to air traffic controllers and the vulnerability of these components to disruption, decay, or loss.

This report will focus on developing an understanding of the role memory plays in air traffic controller performance by emphasizing the mechanics of human memory, the nature of its limitations and constraints, and the factors that may overcome or minimize memory loss of critical information. The final section of the report will deal with some of the potential human factors consequences of the AAS on air traffic controller memory.

1.2 THE HUMAN INFORMATION PROCESSING SYSTEM.

In order to understand the implications that memory has in the ATC environment, we will deal with it in terms of human information processing. Several information processing models have been developed (Broadbent, 1958; Smith, 1968; Sternberg, 1969; Welford, 1976; Wickens, 1984), each assuming various stages of information processing, characterized by stage-specific transformations on the data. The present approach will be to present a description of human information processing, consisting of three interacting subsystems.

The three interacting subsystems are: (a) the perceptual system, (b) the cognitive system, and (c) the motor system. Each has its own information processing capabilities (Card, Moran, & Newell, 1986). The perceptual system consists of sensory systems and associated memories. These are responsible for translating information about external stimuli intc internal representations. The cognitive system receives information from the perceptual system, puts it into working memory, and uses long-term memory information to make decisions about how to respond. This subsystem is the most complex and will be the focus of this report. The motor subsystem is responsible for carrying out the response. The interaction of these three subsystems allows the controller to perform the fundamental duties of monitoring airspace traffic and, if necessary, to intervene to keep the traffic flowing safely and efficiently. It should be emphasized that the interaction of the subsystems is extremely dynamic, adapting to the information processing capabilities and limitations of the operator while considering task and situational demands.

The three subsystems may interact in series or in parallel. For example, some tasks like marking the flight strip in response to an altitude change require serial processing. The tasks are accomplished in sequence one after the other. Other tasks such as radar/flight strip scanning, flight strip marking, ground-air-ground communications, may require integrated, parallel operation of the three subsystems. The controller detects a potential conflict between TCA-483 and TWA-358. The controller places these flight strips next to each other to call attention to them. TCA-483 is contacted and instructed to climb to altitude 320. The controller crosses out 300 and writes 320, the new proposed altitude. Concurrently, TWA-358 informs the controller it has reached the assigned cruising altitude of 300 and the controller makes a notation next to the altitude. While this appears to an observer as a series of acts, the controller is processing, thinking, deciding and acting simultaneously to produce a smooth and organized operation.

After receiving information about the present condition of the traffic, the controller evaluates the situation based on safety and efficiency criteria. If a potential conflict arises, demanding intervention, the controller takes the necessary control actions. The control actions, once implemented, change the situation, providing new information to the controller. The control actions require two basic information processing steps. First, the present situational information is received, analyzed, and evaluated. Fundamental to this step is an adequate knowledge base, training, and experience. Second, the controller responds based on the available data, training, and experience. In addition to the immediate demands on information processing, the controller must process additional system information derived from coordination between different controllers. This coordination is essential to traffic planning and keeping the picture of the traffic under control (reference Ammerman, Fligg, Pieser, Jones, Tischer, & Kloster, 1983; Ammerman & Jones, 1988; Bisseret, 1971; Kinney, Spahn, & Amato, 1977; Kirchner & Laurig, 1971: Means, Mumaw, Roth, Schlager, McWilliams, Gagne', Rosenthal, & Heon, 1988 for more detailed information).

Memory plays a role in all human information processing. ATC is a very complex command and control system which places many processing demands on the controllers. How those men and women deal with the memory requirements of the job is critically important; the literature describes the theory and practice defined by research. It can help us to better understand how controllers do it.

2. AIR TRAFFIC CONTROLLER MEMORY.

Based on the information processing perspective, human memory is depicted as a continuously active system that receives, modifies, stores, retrieves, and acts upon information (Baddeley, 1976, 1986; Klatzky, 1980). More specifically, working memory has been referred to as the "site of ongoing cognitive activities - for instance, meaningful elaboration of words, symbol manipulation such as that involved in mental arithmetic, and reasoning" (Klatzky, 1980, p. 87). Further, working memory is seen as "the part of the memory system where active information processing takes place" (Chase & Ericsson, 1982, p. 40) and the "space in which information can be stored temporarily while it is being processed" (Klapp, Marshburn, & Lester, 1983, P. 240). The subsequent discussion of memory and its implications to the ATC system will focus more on the transient characteristics of working memory than on the more permanent representations in long-term memory. This emphasis is based on the psychological knowledge that long-term memory storage and retrieval are relatively automatic processes, presenting fewer formidable disruptions to performance (Baddeley, 1976, 1986; Klatzky, 1980; Wickens, 1984). In contrast, working memory is severely effected by the constraints of limited processing resources. Wickens (1984) emphasized that occasional limitations of, and constraints on working memory are often responsible for degraded decision-making.

Working memory allows the controller to retain intermediate (transient) products of thinking and the representations generated by the perceptual system. Functionally, working memory is where all cognitive operations obtain their information and produce their outputs. It allows the controller to retain relevant information for tactical operations. Such tactically relevant information may include altitude, airspeed, heading, call/sign, type of aircraft, communications, weather data, runway conditions, current traffic picture, projected traffic picture, immediate and projected conflicts, etc. Working memory is dependent upon long-term memory for such cognitive tasks as information organization, decision making, and problem solving. It is also constrained and limited by such time-dependent processes as attention, capacity, and forgetting (Card, Moran, & Newell, 1986, Wickens, 1984).

The following sections will present information on the mechanisms of working memory and the nature of its limitations and constraints which directly and/or indirectly influence ATC.

2.1 MEMORY CODES.

Immediately after the presentation of an external visual stimulus, like an aircraft target with accompanying data tag on the radar display, a representation of the stimulus appears in the visual image store (iconic memory) of the perceptual system. This is a preliminary mental picture. There is also a corresponding auditory image store (echoic memory) for external auditory stimulus. Ground-air-ground communications are examples. These sensory memories, also known as codes, are representations of external physical stimuli. They are vital to working memory, because they prolong the external stimulus representations long enough for relevant processing to take place in working memory (Card, Moran, & Newell, 1986). The sensory memories, while not demanding the operator's limited attentional resources, are important for partial activation of the visual and phonetic primary codes in working memory (Baddeley, 1986, Wickens, 1984).

While the sensory codes are generated exclusively by external physical stimuli, primary visual and phonetic codes represent a higher level of processing. They may be activated by either external stimuli, which lead to sensory codes, or from inputs into working memory from long-term memory. The primary visual and phonetic codes, along with semantic and motoric codes, form the foundation of our attention-demanding working memory, which is fundamental for all ATC tactical operations (Baddeley & Hitch, 1974). Semantic codes are abstract representations based on the meaningfulness of the stimuli. These can include the controller's knowledge of specifics of the sector map, the location of data on the flight strip, aircraft characteristics, etc., and are vital for activating information in long-term memory. Motoric codes are sensory and motor representations of actions, which are involved in the encoding of past and future activities (Koriat, Ben-Zur, & Nussbaum, 1990).

The encoding of future actions, which has been a neglected issue in memory research, is of critical importance to ATC operations. For example, a controller instructs TWA-348 to climb to a new cruising altitude of 290, having forgotten to previously instruct AAL-584 to descend from 290 to 270 for eventual handoff. This forgotten to-be-performed action may subsequently result in an airspace conflict.

In the following pages, the visual, phonetic, semantic, and motoric codes will be given further treatment. Emphasis will be on the nature of these memory codes and their implications for ATC working memory. Specifically, information will be provided about the characteristics of these codes and their susceptibility to disruption and enhancement.

2.1.1 Visual Codes.

Visual representations or images of spatial information are normally maintained in working memory by way of visual codes (Wickens, 1984). These can include a controller's pictorial mental representation of an aircraft's location, orientation, and velocity after a brief scan of the radar display and/or the flight strip bay. However, visual input is not necessary nor sufficient for the generation of visual representations. External visual stimuli do not automatically produce visual or spatial images. That is, simply looking at something will not ensure its processing in working memory. In addition, Kosslyn (1981) has reported evidence indicating visual images can be generated by nonvisual sources, such as information that has been experienced, and subsequently stored in long-term memory. That information can include the sector map and previous conflict situations. Verbal (phonetic) stimulus material can also be a stimulus.

Primary visual codes, which are representations or images, are highly transient in nature, requiring a great deal of effortful attention-demanding processing in order to persist in working memory (Goettl, 1985; Posner, 1973, 1978; Posner & Mitchell, 1967). Despite the attention-demanding characteristics of visual encoding, Bencomo and Daniel (1975) report evidence for visual code preservation when the stimulus to be encoded was primarily visual in nature. This suggests visual codes are more likely to persist when processing involves more natural visual/spatial materials, than verbal or auditory materials.

2.1.2 Phonetic Codes.

Verbal information when, for example, the controller at Chicago Center instructs TWA-484 to "descend and maintain one thousand, report leaving one two thousand", is normally maintained in working memory by phonetic or auditory rehearsal (Wickens & Flach, 1988). This phonetic rehearsal in working memory is known as maintenance rehearsal, also called Type I, primary, or rote rehearsal, and is used only to maintain information in working memory, presumably by renewing the information before it is subject to time-dependent loss (Bjork, 1972; Craik & Watkins, 1973, Klatzky, 1980). The phonetic primary code is automatically generated from an echoic sensory code, and represents continued processing at a shallow, acoustic level (Wickens, 1984). In addition, Conrad (1964) has demonstrated that phonetic codes can be automatically generated from visual stimuli or iconic codes. Conrad's (1964) results indicated that when subjects were to recall visually presented letters, recall intrusion errors tended to be acoustic rather than visual. For example, an air traffic controller may have a tendency to write, by mistake, letters such as Z instead of T. Further, Conrad and Hull (1964) demonstrated that recall information that was phonetically similar created greater recall confusion than information that was phonetically dissimilar.

A series of laboratory studies on phonetic codes and information presentation have concluded that verbal working memory can be enhanced by employing speech as an information display mode (Murdock, 1968; Nilsson, Ohlsson, & Ronnberg, 1977, Wickens, Sandry, & Vidulich, 1983). A primary basis for this conclusion is the fact that echoic (auditory) memory is retained longer that iconic (visual) memory and that auditory displays are more compatible with the auditory nature of maintenance rehearsal in working memory (Wickens, 1984).

There are also significant human factors implications for future uses of an auditory information display to present transient information to be used in working memory. Such information will be less susceptible to loss when presented via auditory channels, such as natural or synthetic speech. For example, Wickens, Sandry, & Vidulich, (1983) demonstrated that pilots can retain navigational information better with auditory display in comparison to visual display, and this finding was enhanced under high workload conditions. These findings suggest that auditory display of information may be advantageous when rapid information presentation is necessary, the information is of a transient nature, and visual display space cannot afford further cluttering (Wickens, 1984). However, auditory displays present formidable challenges to the human factors specialist, in that they cannot be easily monitored on a time-sharing basis.

2.1.3 Semantic Codes.

Semantic codes are responsible for representing information in working memory in terms of meaning rather than physical (i.e., auditory, visual) attributes. Semantic codes provide the critical link between working memory and the permanent long-term memories. For example, Card, Moran, and Newell (1986), when noting the intimate association between working memory and long-term memory, suggested that "structurally, working memory consists of a subset of the elements in long-term memory that have become activated." Semantic codes are primarily responsible for information storage and organization in working memory, and subsequently in long-term memory. Acquiring and maintaining these codes involves elaborate rehearsal techniques which the operator may use without even being able to define the process.

Elaborative rehearsal involves deep, meaningful processing in which new information is associated with existing meaningful knowledge in long-term memory. This meaningful processing, in contrast to the previously cited maintenance rehearsal, facilitates the retention of information in working memory and enhances information transfer to long-term memory by way of semantic codes. Elaborative rehearsal, using semantic encoding in working memory, requires thinking about information, interpreting the information, and relating the information to other information in long-term memory. These processes are fundamental for enhancing retrieval of information from long-term memory and for planning future actions (Klatzky, 1980).

Semantic codes afford working memory the ability to actively retain and analyze information. Wingfield and Butterworth (1984, p. 352) suggest that rather than passively retaining auditory and visual information in working memory, we are "continuously forming hypotheses about the structure of what they are hearing and forming predictions about what they have yet to hear. These are working hypotheses, either confirmed or modified with the arrival of new information." Klapp (1987) notes that working memory actively formulates and stores hypotheses, resulting in abstract representations such as semantic codes in working memory in addition to auditory or visual codes.

Semantic codes are vital for the organization, analyses, and storage of ATC tactical information in working memory and long-term memory. They are the invaluable link between working memory and long-term memory, providing and facilitating the ability to actively manipulate and analyze data and to generate decision-making and problem resolution alternatives. In order for an air traffic controller to make an informed and accurate assessment of a potential conflict between two aircraft, a great deal of flight information is required about the two aircraft. The controller needs altitude, heading, airspeed, type of aircraft, current traffic picture, projected traffic picture, etc. These flight data must, in turn, be analyzed and interpreted against a knowledge and experience data base in long-term memory to accurately construct and assess a pictorial mental representation of the current and projected airspace. Alternative hypotheses about the traffic situation can be generated from long-term memory and retained in working memory to be analytically integrated with the flight data. This process of hypothesis formulation and evaluation is complicated by the limitations and constraints of working memory and long-term memory decision biases (Wickens & Flach, 1988).

2.1.4 Motoric Codes.

Motoric codes are integrated sensory and motor (i.e., sensorimotor) representations of actions retained in working memory, which are involved in the encoding of past and future activities (Koriat, Ben-Zur, & Nussbaum, 1990). The encoding of action events in general are of critical importance to air traffic controllers. For example, a controller, in examining the flight strip bay, detects a potential conflict between TCA-483, AAL-284, and TWA-343 before TCA-483 is displayed on the radar display. The controller must remember to take an appropriate control action, or to inform the radar-side controller of the conflict. Since TCA-483 has not entered the sector and a potential conflict is some time away, the controller must take steps to remember the control action in the future.

Recent research on memory for action events has focused on memory for past activities (Anderson, 1984; Backman, Nilsson, & Chalom, 1986; Cohen, 1981, 1983; Johnson, 1988; Kausler & Hakami, 1983; Koriat & Ben-Zur, 1988; Koriat, Ben- Zur, & Sheffer, 1988). A consistent and general finding of these studies is that memory for performing a task is superior to memory for verbal materials, due to the beneficial effects of motoric enactment. The process of physically performing a task seems to enhance the encoding of and subsequent memory for the task. Richard Held and Alan Hein (1958) referred to this as reafferent feedback. The superior memory for performing tasks "has been generally attributed to their multimodal, rich properties, assumed to result in richer memorial representations than those formed for the verbal instructions alone" (Koriat, Ben-Zur, Nussbaum, 1990). One author of this current report recalls the words of a high school french teacher who exhorted his students to write, write, and write. The reason he explained was that the fingers have a memory.

These results are particularly relevant when discussing the impact of automation on ATC systems and the potential human factors consequences. Several researchers (Hopkin, 1988, 1989, 1991b; Narborough-Hall, 1987; Wise & Debons, 1987; Wise, Hopkin, & Smith, 1991) have suggested that routine task performance facilitates controller tactical operations. Hopkin (1991b) asserts that physical interaction with the flight progress strip is fundamental to a controller's memory for immediate and future traffic situations.

Further research is needed concerning the potential impact of automating routine controller tasks. This will remove the physical marking of the flight strips that currently facilitate the development of the controller's picture. This is particularly true with the near-term planned implementation of ISSS, which calls for the replacement of current flight progress strips with electronic Flight Data Entries (FDE) (i.e., electronic flight strips). Of the 43 unique data fields provided by the flight progress strips and FDEs collectively, only six of the present data fields will remain. The other 37 represent data fields which are new, omitted, or changed (Ammerman & Jones, 1988).

The ATC environment is characterized, not only by the necessity to remember past activities to support ongoing tactical operations, but also activities to be performed in the future. Memory for to-be-performed activities is known as prospective memory (Harris, 1984; Wilkins & Baddeley, 1978; Winograd, 1988). In some cases, information for future control actions need only be retained for a short period of time. A recent study investigating the nature of the representations underlying prospective memory, found a significant beneficial effect of imaginal-motoric enactment of the future activity (Koriat, Ben-Zur, & Nussbaum, 1990). The operator works through the expected behavior mentally. This imaginal-enactment of the future activity is consistent with the research on memory for past activities. This beneficial effect can also be attributed to the multimodal and contextual properties of having actually performed the task, and in addition, the intentional (or unintentional) visualization of the task, which promotes visual and motor encoding (Backman & Nilsson, 1984; Koriat, Ben-Zur, & Nussbaum, 1990).

Koriat, Ben-Zur, and Nussbaum (1990) suggest that the process of encoding future activities involves an internal, symbolic enactment of the tasks, which enhances memory. Consequently, this implies that maintenance and/or elaborative rehearsal, or repeated internal simulation of the procedure to-be-performed will enhance memory at the time of testing, in much the same manner that maintenance rehearsal retains verbal material in working memory. They also suggest that, if rehearsal takes advantage of the modality-specific properties of the future task, not only will memory for content be enhanced, but, under proper conditions, memory retrieval cues will be enhanced.

Given the previous example of a potential conflict between TCA-483, AAL-284, and TWA-343, before TCA-483 is displayed on the radar display, the controller is responsible for retaining and eventually conveying this information, along with additional information concerning the status of other aircraft under control, to the relief controller on the next shift. In order to remember this potential crisis situation, the controller encodes the future task (briefing or execution of control actions needed to avoid a pending crisis situation) in terms of the sensorimotor properties, the internal visual representation of the projected traffic picture and/or physical performance requirements of the control action of the task that will enhance the actual performance at the time of test. It is suggested that this type of encoding will facilitate the activation of memory with the appropriate external retrieval cues such as the flight strips for TCA-483, AAL-284, and TWA-343 being placed adjacent to each other, with the TCA-483 flight strip cocked (Koriat, Ben-Zur, & Nussbaum, 1990).

Directly related to memory codes, particularly motoric encoding, is a robust memory phenomenon known as the generation effect (Dosher & Russo, 1976; Erdelyi, Buschke, & Finkelstein, 1977; Johnson, Taylor, & Raye, 1977; Slamecka & Graf, 1978). Simply stated, the generation effect refers to the fact that information actively and effortfully generated (or information which you are actively involved) is more memorable than passively perceived information. The essence of this memory phenomenon is expressed in the "sentiment that there is an especial advantage to learning by doing, or that some kind of active or effortful involvement of the person in the learning process is more beneficial than merely passive reception of the same information" (Slamecka & Graf, 1978).

The generation effect has direct relevance to ATC tactical operations, where the active integration of the controller's information processing capabilities with the relevant support systems is important for the integrity of the understanding and memory of the traffic situation. Means, Mumaw, Roth, Schlager, McWilliams, Gagne', Rosenthal, and Heon (1988) using a blank flight strip recall task, demonstrated controllers' memory for flight data is a function of the level of control exercised. Their data indicated that memory for flight information of hot aircraft, which required extensive control instructions, was significantly better than memory for flight information for cold aircraft, which required little controller intervention (e.g., overflight).

The foregoing discussion suggests the importance of a direct manipulation environment (Hutchins, 1986; Jackson, 1989; Jacob, 1986; Schneiderman, 1983) for ATC. Such an environment seems essential to maintain and potentially enhance the integrity of ATC tactical operations. In a most insightful analysis of flight progress strips, Hopkin (1991b) indicates the cognitive significance of flight strip manipulation:

> "Strips help the controller to organize work and resolve problems, to plan future work, and to adjust current work in accordance with future plans. The physical act of transferring the strip from the pending to the active bay or assuming control responsibility for an aircraft involves a recapitulation and review of knowledge and previous decisions. This process reinforces the picture of the traffic as a whole, and the details recalled about each aircraft. The physical action in moving a strip aids memory of its contents, of its location on the board, and of why it is there.

Writing on flight strips seems more memorable than watching the automatic updating of information."

Hopkin (1991b) further comments:

"..., whatever form electronic flight strips take, it is essential to define beforehand all the functions of paper flight strips, in order to discard any unneeded functions deliberately and not inadvertently, to confirm that familiar essential functions can still be fulfilled electronically, and to appreciate the functional and cognitive complexity of paper flight strips. Electronic flight strips have major advantages in compatibility with computer-based ATC systems, but their compatibility with human roles is less obvious, requires positive planning, and depends on matching functions correctly with human capabilities."

Consequently, manipulative control actions, both routine and strategic, required by the controller appear to be fundamental for tactical operations. An obvious concern for current and future ATC systems is optimizing controllers direct manipulation of the system. This optimal manipulation seems fundamental for ATC system performance.

2.2 CODE INTERFERENCE IN WORKING MEMORY.

The primary phonetic/acoustic-verbal and visual/spatial codes essentially form two independent systems of working memory, one for processing phonetic information, and the other for processing visual information (Baddeley, Grant, Wight, & Thompson, 1975; Baddeley & Hitch, 1974; Baddeley & Lieberman, 1980; Brooks, 1968; Crowder, 1978; Healy, 1975). These two systems are susceptible to interference by different concurrent tasks (Baddeley, Grant, Wight, & Thompson, 1975). Recall is degraded as items become more similar in memory. This similarity refers to the mental representation, phonetic or visual, of the item retained in working memory (Card, Moran, & Newell, 1986). Given phonetic or verbal rehearsal as the primary maintenance technique for retaining information, items in working memory will be more susceptible to phonetic interference. For example, intrusion errors are more likely to occur between items that sound similar such as B for P, K for J.

The practical human factors implication of the distinction between the two primary codes of working memory is that tasks should be designed to minimize code interference and to take advantage of the cooperative nature of the two primary codes (Posner, 1978). For example, a fundamental requirement for the air traffic controller is to create and maintain a transient, dynamic pictorial representation of the airspace traffic under

control (Schlager, Means, & Roth, 1990; Sperandio, 1974; Whitfield, 1979; Whitfield & Jackson, 1982).
The construction (and/or reconstruction) of this airspace traffic picture requires a great deal of spatial working memory. In order to minimize visual code interference and maintain the integrity of spatial working memory, this primary task should not be performed concurrently with tasks that require similar spatial demands in working memory. Rather, concurrent tasks will be better served if they take advantage of phonetic representations in working memory (Wickens, 1984).

Questions still remain as to whether the codes described are an exhaustive representation of those present in working memory. For example, if there are auditory-verbal and visual-spatial codes or systems, perhaps there are also olfactory or kinesthetic codes (Klapp, 1987). It is also not clear whether separate systems exist within working memory, each with specific processing codes or different codes within the same working memory system (Klapp, 1987; Phillips & Christie, 1977). Several memory-loading studies have concluded that a single-system view of working memory is tenuous at best and largely unsubstantiated (Hellige, & Wong, 1983; Klapp, Marshburn, & Lester, 1983; Klapp & Philipoff, 1983; Roediger, Knight, & Kantowitz, 1977). A general implication of these studies is that tasks using systems with different codes, visual vs. auditory, will not result in performance degradation due to interference as readily as tasks using similar system codes. These studies are consistent with the multiple-resource view of information processing (Monsell, 1984; Navon & Gopher, 1979; Wickens, Sandry, & Vidulich, 1983) which predicts that if two tasks use the same resources, for example, auditory-verbal, interference will be reliably greater than if the two tasks use different resources like auditory-verbal vs visual-spatial.

2.3 ATTENTION AND WORKING MEMORY.

The volatility of information in working memory could be the greatest contributor to operational errors in ATC tactical operations. This transient characteristic of working memory has been clearly established since the late 1950s, when a series of experiments demonstrated that in the absence of sustained attention, information is forgotten from working memory in approximately 15 seconds (Brown, 1958; Peterson & Peterson, 1959). Over the past 30 years, hundreds of experiments have confirmed this finding.

Information loss from working memory is particularly profound when distracting or concurrent events demand an attention shift from primary information retention. For example, controllers frequently find themselves in situations where they must perform some kind of distracting activity, like making notations on flight strips or consulting a chart, between the time primary information is received and the time this information must be acted upon. This has a negative impact on information retention. Further, while air traffic controllers usually have the status of relevant information continuously available on the radar display or in the flight strip bay, allowing responses based on perceptual data rather than memory data, there are always occasions when attention is directed away from the displays. Any type of information display failure can place even heavier demands on working memory.

In a memory study of simulated communications similar to those delivered to pilots from ATC, Loftus, Dark, and Williams (1979) obtained what has become the universal result of hundreds of studies on working memory retention when rehearsal is prevented: "performance is very high at a retention interval of 0 and then declines to some asymptotic (or stable) level by about 15 seconds" (p. 170), with minimal information being retained after 15 seconds. The authors concluded that since "forgetting occurs over an interval of 15 (seconds) following the initial reception of a message..., a message should be responded to as soon as possible after it is received" (p. 179). In addition, the authors replicated research findings (Murdock, 1961) indicating that as working memory load increases, the probability of correctly recalling information from working memory decreases. The practical implication of this finding is that "whenever possible, as little information as is feasible should be conveyed... at any one time. In particular, no instruction should be conveyed until 10 (seconds) or so after the previous instruction has been acted upon" (p. 179).

Based on the previous discussion, one might conclude that sustained attention using, for example, maintenance rehearsal on one item of information, is necessary to maintain the information in working memory. Contrary to this intuitive conclusion, several studies have demonstrated that information is more volatile early in the retention interval (Dillon & Reid, 1969; Kroll, Kellicut, & Parks, 1975; Peterson & Peterson, 1959; Stanners, Meunier, Headley, 1969). These studies generally concluded that information loss from working memory was less profound when rehearsal occurred immediately after information was received. Klapp (1987, p. 16) further elaborated that:

> "A few seconds of rehearsal can largely protect (working memory) from the usual loss attributed to distraction. The potential Human Factors implications of this finding appear to have been overlooked. One would suppose that retention of information, such as directives from ATC, would be improved by brief rehearsal when that information cannot be used immediately. The extent to which this can lead to successful recommendations which can be implemented in practice needs to be investigated. For example, pilots

might be instructed to rehearse directives which can not be implemented immediately, or transmission of additional non-emergency directives might be delayed until rehearsal (or immediate implementation) of the first directive has been accomplished."

Therefore, the practical implication of these studies is that if early rehearsal is practical, information retention in working memory will be enhanced.

Another important aspect of the dramatic attentional demands on working memory is the influence of practice on performance. It is well known that practice is the single most powerful factor improving the controller's ability to perform ATC tasks. Nothing is likely to offset the frailties of working memory as will practice. The influence of practice on the attentional demands of working memory has received considerable attention within the framework of automatic and controlled processing (Schneider & Shiffrin, 1977).

2.4 AUTOMATIC AND CONTROLLED PROCESSING.

Considerable research has identified two qualitatively distinct ways we process and/or respond to information, automatic and controlled processing. These processes have direct relevance to the information processing differences found between expert and novice controllers (Fisk, Ackerman, & Schneider, 1987; James, 1890; Kahneman & Treisman, 1984; LaBerge, 1973, 1975, 1976, 1981; Logan, 1978, 1979, 1985a, 1985b; Norman, 1976; Posner & Snyder, 1975; Schneider, Dumais, & Shiffrin, 1984; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

In automatic processing (automaticity), the operator has developed a well-formed representation of the stimuli in memory as a result of extensive practice (Schneider & Shiffrin, 1977). This extensive practice allows the development of automatic links or associations between stimuli and responses that can be operated with minimal processing effort (Gopher & Donchin, 1986). The defining characteristics of automaticity are well understood and documented. They provide substantial evidence for the fundamental differences between automatic processing and controlled (nonautomatic) processing. Automatic processing is fast, parallel (Logan, 1988a; Neely, 1977; Posner & Snyder, 1975), effortless (Logan, 1978;, 1979; Schneider & Shiffrin, 1977), autonomous (Logan, 1980; Posner & Snyder, 1975; Shiffrin & Schneider, 1977; Zbrodoff & Logan, 1986), consistent (Logan, 1988a; Mcleod, McLaughlin, & Nimmo-Smith, 1985; Naveh-Benjamin & Jonides, 1984), and not limited by working memory capacity (Fisk, Ackerman, & Schneider, 1987). It also requires no conscious awareness of the stimulus input (Carr, McCauley, Sperber, & Parmalee, 1982; Marcel, 1983), and it can be learned with extensive practice in consistent environments (Durso, Cooke, Breen, & Schvaneveldt, 1987; Fisk, Oransky, & Skedsvold, 1988; Logan, 1979; Schneider & Fisk, 1982; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In simple terms, the operator doesn't have to think about what he is doing. On the other hand, controlled processing is characterized as relatively slow, serial, mentally demanding, dependent upon working memory capacity, and requiring little or no practice to develop. Controlled processing is also used to process novel or inconsistent information, and essentially characterizes novice performance. Novices apply rules serially and their efforts often appear ponderous to experts who have developed the automatic links between stimuli and responses.

While initial theoretical treatments viewed automaticity in terms of little or no attentional resource demands (Hasher & Zacks, 1979; Logan, 1979; 1980; Posner & Snyder, 1975; Shiffrin & Schneider, 1977), new theoretical treatments of automaticity as a memory phenomenon appear to be the most viable. This is particularly true in terms of skill acquisition and training applications. According to the memory view, automaticity is achieved when performance is dependent on "single-step, direct-access retrieval of solutions from memory" (Logan, 1988b, p. 586). For example, an experienced controller who is familiar with the spatial layout of the ATC console visually searches for information automatically. This assumes that the search goal along with current display features allow retrieval of prescriptive search strategies from memory. An inexperienced controller could not do this, because the necessary visual search strategies would not be present in memory. This requires the novice to rely on general search skills and pay deliberate attention to all the potentially relevant information.

The training of automatic processing could have tremendous implications for ATC and the quality of the controller's working memory. We have seen that the volatility of information in working memory places a tremendous burden on a controller's flight information management performance. Automaticity would allow increased information processing without decrements in working memory performance. The potential of automaticity training for complex tasks, such as ATC, has been questioned by several researchers who have suggested that only simple tasks can be automated (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980). However, Fisk, Ackerman, and Schneider (1987) have challenged this suggested limitation, noting "those researchers...do not clearly define what makes a task simple or complex. Complex tasks can be performed via automatic processing, controlled processing, or most likely, through a combination of both processes. Simple tasks can also be performed by either automatic or controlled processing. The type of processing is not determined by the complexity (or simplicity) of a task, but rather by the consistency and, if the task is consistent, the amount of practice" (Fisk, Ackerman, & Schneider, 1987, p. 191; Fisk & Schneider, 1981, 1983; Logan, 1988b).

However, the extent to which automaticity can lead to profitable training guidelines and recommendations which can be implemented in the complex and dynamic ATC environment is not clear and needs investigation. A fundamental part of such an investigation would be the identification of the ATC tasks and subtasks that would afford automatic processing and those that would afford controlled processing.

Further, research is also needed to investigate the influence of ATC automation on automatic processing. Specifically, what influence will ATC automation have on the development of over-learned (automatized) patterns of behavior which are fundamental for reducing the attentional demands of a controller's working memory? A key issue that must be addressed is the concern that the cognitive structures (For example: memory processes, conceptual knowledge) associated with over-learned patterns of behavior, which work to reduce the current load on working memory, may not be available to those controllers who grow up in a more automated ATC environment. The cognitive requirements of ATC will be ever changing with continued increases in ATC automation, making it difficult to reliably appreciate the nature of automatic processing in future ATC systems. Currently, it is unclear to what degree future ATC systems will afford automatic processing for the controller. One can safely conclude that the development of automaticity in AAS will be different than automaticity development in the current system.

While there is extensive literature on the psychology of memory and its influences on automaticity and the allocation of attention, questions still remain as to whether increased attention facilitates improved memory (Vortac, 1991). In particular, is additional attention beyond the minimum attentional threshold for a stimuli (i.e., the minimum amount of attention needed to activate a memory representation) necessary or sufficient for memory improvement? Several empirical studies (Mitchell, 1989) have demonstrated that if sufficient attentional resources are available to allow the activation of a memorial process, additional attentional resources will not strengthen the activation nor improve the memory operation. Rather, the additional, unnecessary attentional resources will result in unnecessary memory loading and decreased working memory efficiency.

The previous brief discussion of attention and memory suggests that, depending on the memorial processes required for a task, deliberate attention may or may not be necessary or sufficient for activation. For example, automatic processes will be activated regardless of the attentional resources available or expended. However, controlled or nonautomatic processes will not operate without the attentional resources necessary to exceed the minimum attentional threshold.

2.5 CHUNKING AND ORGANIZATION.

The principal of chunking has long been recognized as a means to expand the limits of working memory (Miller, 1956). Essentially, chunking is any operation that combines two or more items of information into one. The resulting one item or chunk, can then be stored as a single information unit in working memory, making available additional working memory capacity to allocate elsewhere. For example, a controller becomes familiar with the aircraft call sign TWA-354 and processes it as a single chunk, requiring only one space in working memory, rather than a series of six alphanumerics, requiring six spaces in working memory. Further, a potential conflict between three aircraft, AAL-348, TWA-548, and DAL-35, will likely be organized as one chunk, rather than three, because the controller will likely not think of one without recalling the others.

Before addressing this topic, a qualification is in order to clarify the relationship between chunking and organization. These terms refer to essentially the same processes. However, their applications are traditionally different (Klatzky, 1980). Chunking is generally associated with recent working memory storage of a relatively small number of items which will be available for immediate recall. Organization, on the other hand, is generally associated with long-term storage of a considerable amount of information. While the terms traditionally apply to different situations, they share the fundamental underlying process of combining (organizing/chunking) two or more items of information into one. Further, since chunking is recognized as a fundamental process for the initial organization and encoding of information into long-term memory, using elaborative rehearsal as one technique, it is reasonable to conclude that organization also occurs in working memory (Klatzky, 1980). In practical terms, there is relatively little substantive difference between the two terms.

In general, chunking operations can be divided into two related forms. First, chunking may be facilitated by combining items based on temporal or spatial properties, that is, combining items which occur closely in time or space. In this manner, chunking occurs without the items necessarily forming a meaningful unit (Bower & Winzenz, 1969; Huttenlocher & Burke, 1976). This sort of chunking is often referred to as grouping (Klatzky, 1980). Closely related to grouping is parsing. Parsing is the process of "placing physical discontinuities between subsets that are likely to reflect chunks" (Wickens, 1984, p. 222). That is, retention of relatively meaningless information will be facilitated by putting gaps or breaks within the information sequence. For example, the telephone number 516 347 0364 would be better retained than 5163470364 (Wickelgren, 1964). Loftus, Dark, and Williams (1979), in their study of working memory retention of ATC communications, reported that, in certain circumstances, four-digit items (e.g., 7382) were better retained when parsed into two pairs of double digits (e.g., "seventy-three, eighty-two").

Second, chunking may be facilitated if it "utilizes information from (long-term memory) to meaningfully relate many incomplete items to a single known item" (Klatzky, 1980, p. 92). The degree of the inherent meaningful relationship between the separate items is fundamental to this form of chunking. For example, the potential conflict between AAL-348, TWA-548, and DAL-35 allows these three aircraft to be chunked as one item, due to the shared meaningfulness of each being a contributor to a potential conflict.

Chunking essentially benefits two qualitatively distinct processes in working memory (Wickens, 1984). First, chunking helps the retention and maintenance of information in working memory for a brief period of time, after which time the information is directly or indirectly dumped. For example, controllers typically deal with a continuous flow of aircraft through their sector of responsibility. When aircraft are handed-off, the associative information for that aircraft is no longer needed, therefore it is beneficially dumped from memory. Second, chunking facilitates the transfer of information into long-term memory. For example, controllers must process a considerable amount of information concerning the status of several aircraft which must be integrated and stored in long-term memory in order to initially create and subsequently revise the internalized picture of the airspace traffic.

The contribution of organizational processes like chunking to good memory are well demonstrated and documented in the psychological literature (Ellis & Hunt, 1989). The organization of input information and its subsequent retrieval have been shown to reliably differentiate levels of expertise in many cognitive skills. Specifically, experts can take in a large quantity of task-specific information in a brief period of time and subsequently recall the information in meaningful units or chunks. Chase and Simon's (1973a, 1973b) study of chunking of stimulus information by chess experts demonstrates that experts are able to encode more information in a limited time when compared with nonexperts, and subsequently to recall the information in meaningful units.

Chase and Simon (1973a, 1973b; Simon & Chase, 1973; Simon & Gilmartin, 1973) proposed a perceptual chunking hypothesis. Perceptual chunking involves perception by coding the position of entire chunks or several items, by storing chunk labels in working memory, and subsequently by decoding at the time of

recall. Two critical features of the perceptual chunking hypothesis are that chunks are independently perceived and that recall requires decoding chunk labels in working memory. This generates heavy processing demands on working memory.

Egan and Schwartz (1979), however, have pointed out several problems with these critical features. First, chunk independence does not allow for global processing. For example, an ATC specialist can perceive the global characteristics, like a developing conflict situation in a traffic pattern, on the radar display in addition to the individual features of the display to include the aircraft targets and data tags. Second, a group of display features may not form a functional unit or chunk, independent of other functional units. The functional units must be context dependent. As another example, the controller, in identifying and processing two concurrent potential conflict situations, will form two chunks, for example, conflict A and conflict B. These chunks are not independent of each other in that the resolution of conflict A will have an influence on the resolution of conflict B and vice versa, due to shared airspace. In addition, the two conflict resolutions will influence, and be influenced by, the surrounding non-involved air traffic. Third, some studies have shown that various intermediary tasks have no influence on recall performance of skilled chess players (Charness, 1976; Frey & Adesman, 1976). These studies strongly question Chase and Simon's position that task-specific information places substantial demands on working memory capacity.

As an alternative to perceptual chunking, Egan and Schwartz (1979; Garland & Barry, 1990a; 1991) have proposed a conceptual chunking hypothesis, which links chunking and skilled memory to the organization of concepts in long-term memory. Conceptual chunking consists of a few primary features. First, skilled operators rapidly identify a concept(s) for the entire display, or segments of the display (overflights, climbing aircraft, descending aircraft, military aircraft). Second, skilled operators may systematically retrieve functional units and their elements that are related to the identified conceptual category stored in long-term memory. Flights DAL-1134, TWA-45, UAL-390, and TCA-224 are elements identified as part of the conceptual category, such as overflights. Third, conceptual knowledge of the display enables skilled operators to systematically search displays to verify details suggested by the conceptual category. For example, a controller is able to systematically search and detect aircraft which possess identifying flight characteristics that are consistent with the defining characteristics of the conceptual category.

Based on the available research (Egan & Schwartz, 1979; Garland & Barry, 1990a; 1991), the conceptual chunking hypothesis appears to overcome the problems of the perceptual chunking hypothesis, by linking skilled memory and chunking to the organization of concepts in long-term memory. The available data indicate that skilled operators are reliably better at recalling display features after a brief exposure time. This superior recall performance may be based on the use of a "generate and test" process (Egan & Schwartz, 1979). This means that emphasis on processing information related to a conceptual category, such as potential air traffic conflict, allows skilled operators to systematically retrieve elements which include the defining features of the potential conflict and the involved aircraft. These are meaningfully associated with the conceptual category. Yntema's (1963) research on dynamic memory indicated that recall performance was better in a monitoring situation when the subject was responsible for a few objects (aircraft) that vary on a number of attributes (flight data), than when subjects were responsible for a large number of objects with few attributes. These findings are consistent with conceptual chunking, in that recall of the primary object or concept, facilitated recall of the associative elements or attributes from long-term memory. Tulving (1962) suggested that the ability to access the whole functional unit allows for systematic retrieval of all the information within a unit or chunk. He stressed that this ability is contingent upon a good organizational structure of the task-specific knowledge in long-term memory.

As discussed earlier, the primary features of conceptual chunking emphasize the role of long-term memory, and particularly, its organization. An indication of the importance of organization in superior memory is evident from studies involving active rearrangement of randomly presented verbal and nonverbal items (Ellis & Hunt, 1989; Palmer, 1975). Even when items from various categories were presented in random order, participants grouped the items into their appropriate categories at recall. This meaningful regrouping of the randomly presented items is evidence of chunking in recall. Thus, clustering is an important indicator of the active encoding process of organization.

Ellis and Hunt (1989) have noted that the question of how organization affects memory is very important and equally complex. Although memory and organization are two different processes, Ellis and Hunt suggest that the two processes are positively correlated, resulting in the assumption that "organization processes contribute to good memory." Mandler (1967) provides support for this assumption, suggesting that organization is effective because of "economy of storage." Simply, organization is similar to chunking, in that individual units are grouped into large functional units, reducing the number of items to be stored in working memory and/or long-term memory. Mandler's approach assumes that organization occurs during encoding.

In a supportive yet alternative approach, Tulving (1962) has suggested that organization benefits memory because of its effects at retrieval. Tulving agrees that the organization of information occurs at encoding; however, he stresses that memory is facilitated by the ability to access the functional units or the whole entity at retrieval. This ability to access the whole functional unit allows for systematic retrieval of all the information within a unit. Tulving's arguments are consistent with conceptual chunking, in that knowledge of a conceptual display would allow subjects to systematically retrieve functional units that are related to the previously identified conceptual category that has been accessed in long-term memory. In addition, conceptual knowledge of the display would enable skilled operators to systematically search the conceptual category in long-term memory to verify details suggested by the initial conceptual category.

Ericsson (1985) has pointed out apparent parallels between experts' superior memory performance in their domain of expertise and normal memory for meaningful materials, such as texts and pictures. Kintsch (1974) has demonstrated that a competent reader can form a long-term representation for the text's meaning very rapidly and extensively, without deliberate effort (automatic processing). In addition, pictures which constitute spatial information appear to be fixated in long-term memory in less than one second (Potter & Levy, 1969). Those results appear consistent with the process of conceptually driven pattern recognition, which involves recognition decisions being guided by long-term memory rather than by sensory information (Ellis & Hunt, 1989).

Based on the available data, the superior perceptual skill of experts in a variety of skill domains may not involve rapidly decoding independent chunk labels from a limited-capacity working memory; rather, as Egan and Schwartz (1979) have proposed, perceptual skill may be linked to the organization of task-specific concepts in long-term memory. It is suggested that expert memory performance may be more conceptual in nature, enabling skilled operators to (a) rapidly identify a concept for an entire stimulus display, (b) systematically retrieve functional chunks that are related to the conceptual category stored in long-term memory through a generate and test process, and (c) systematically search displays to verify details suggested by the activated conceptual category.

The compatibility of the encoding processes with the retrieval processes is a related and fundamental aspect of the memory organization and its effect on efficient information retrieval. Information retrieval is enhanced when the meaningful cues used at encoding are also present at retrieval. If the encoding and retrieval cues are not compatible, then memory will fail (Godden & Baddeley, 1980). In the ATC setting, the flight progress strips and their manipulation serve as significant retrieval cues, since they contain essentially the same information present during initial encoding.

Although research on ATC memory, specifically controller memory organization and chunking behavior, is disappointingly minimal, a study by Means, Mumaw, Roth, Schlager, McWilliams, Gagne', Rosenthal, and Heon (1988) of controller memory, provides some interesting data. In an airspace traffic drawing task, controllers were presented a sector map at the end of a 30 to 45 minute ATC simulation, and subsequently instructed to group associated aircraft in the sector by drawing a circle around them. It was assumed that the aircraft groupings reflected the manner in which controllers organize airspace traffic. The findings indicated that aircraft groupings could be characterized by various kinds of traffic properties or concepts. These include: landing aircraft, overflights, climbing aircraft, traffic crossing over a fix, etc.

In addition, the researchers gathered data indicating controllers who performed in a radar scenario condition (control traffic with radar and flight progress strips) tended to group aircraft based on the potential to conflict, while controllers in a manual scenario condition (control traffic with flight progress strips only) tended to group aircraft based on geographical proximity. Controllers in the manual scenario condition had not controlled traffic without radar in a number of years, therefore, were less competent in controlling traffic under the experimental conditions than were the radar scenario controllers who had available the necessary displays. These data suggest that the controllers using methods with which they were familiar tended to use higher-order grouping criteria like potential conflicts than did the handicapped controllers who tended to use simpler grouping criteria (i.e., geographical proximity). These data are consistent with conceptual chunking in that the controllers tended to group or organize the airspace around a number of ATC concepts and potential control problems. Further, the radar scenario controllers appeared to use more discriminating grouping criteria based on the strategic dynamics or conceptual nature of the airspace, unlike the manual controllers, who appeared to use criteria based on simpler airspace spatial properties. An example of this is that the aircraft are close to one another. This implies that more experienced and skilled controllers may use a larger, more discriminating conceptual knowledge base in order to control traffic. Under unfamiliar conditions, controllers will fall back on simpler concepts.

2.6 WORKING MEMORY CAPACITY.

A number of textbooks in cognitive psychology (Klapp, Marshburn, & Lester, 1983) and human factors (Adams, 1989; Kantowitz & Sorkin, 1983; Sanders & McCormick, 1987) propose a single, limited capacity system theory of working memory. This is based primarily in laboratory memory methods designed to measure static memory using techniques like the recall of randomly presented alphanumerics, or words. The standard claim is that the maximum capacity of working memory is limited to "seven plus or minus two chunks" (Miller, 1956). Although this concept was first produced over 30 years ago, it has had remarkable resilience. A chunk was defined as a single unit of information temporarily stored in working memory. The presumption was that the static memory paradigm taps into a single, limited capacity system, which supports working memory. This standard single-system theory suggested that once working memory is filled to its five to nine chunks, maximum capacity is reached, full attention is deployed, and no further memory-involved tasks can be processed without degrading performance on concurrent tasks.

This view may underestimate human information processing performance in situations such as strategic planning, decision making, and the processing of visual-spatial material, where extensive amounts of information are processed and retained (Chase & Ericsson, 1982; Klapp & Netick, 1988). However, it may be unreasonably optimistic in dynamic memory situations, "in which an observer must keep track of as much information as possible, when signals arrive in a continuous stream with no well-defined interval for recall" (Moray, 1986, p. 40-27).

Several authors have presented data to support a multi-component working memory system, which includes, but is not limited to static memory (Baddeley, 1986; Brainerd, 1981; Chase & Ericsson, 1982; Hitch, 1978; Klapp & Netick, 1988; Klapp, Marshburn, & Lester, 1983; Moray, 1980). For example, Baddeley (1986) postulated a working memory system which consists of a central executive that coordinates and directs the operations of two slave systems, the articulatory loop and the visual-spatial scratchpad. Essentially, these two slave systems are responsible for processing verbal and non-verbal information, respectively. Baddeley's model is very much a multiple-resource model like Wickens' (1984) model. Information on three lines of research, multiple resources, dynamic memory, and the skilled memory effect will be briefly presented to demonstrate the dynamic nature of working memory capacity.

2.6.1 Multiple Resources.

The literature on working memory capacity (Klapp, 1987) suggests that, rather than a single working memory system capable of being easily overloaded, there appear to be several systems with multiple resources, each system capable of being overloaded without interference from the other. Multiple resource theory (Navon & Gopher, 1979; Wickens, Sandry, & Vidulich, 1983), has been successful in describing performance in dual-task situations in which the operator must perform two or more tasks at the same time. For example, Klapp and Netick (1988), in examining dual-task performance in working memory, reported data suggesting that there are at least two working memory systems (i.e., auditory-verbal and visual-spatial) that differ in resource composition. The data demonstrated that if two tasks use the same resource such as auditory-verbal interference will be reliably greater than if the two tasks use different resources, auditory-verbal vs visual-spatial.

There are additional advantages of multiple resources theory which have potential for improving the use of memory aids so we can recall more information. Wickens, Sandry, and Vidulich (1983) developed the principle of "stimulus/central processing/response compatibility." It describes the optimal relationship between how information is displayed and how it is coded into memory. Displays should be designed in a format that actively helps the individual encode information into working memory. The presentation display format should be compatible with the code used in working memory for the particular task. For example, the encoding and storage of ATC information is better served if it is presented in a visual-spatial format. The authors suggested, however, that a reciprocal recommendation is optimal for retrieving material from memory aids. These include, but are not limited to computerized menu systems and spatially-organized aids such as a mouse. In order to reduce retrieval interference, the resource modality needed to operate the memory aid should not be similar to the storage modality in working memory. ATC tasks, which are heavily dependent upon visual-spatial resources, will be better served by semantic-based computer menu systems or auditory-verbal systems for memory aiding.

The application of multiple resource theory to working memory affords the potential to develop approaches to improving complex and dynamic ATC tasks. Klapp and Netick's (1988) data suggested that in order to optimize working memory resources, tasks and subtasks need to be appropriately allocated across independent subsystems of working memory. The data also indicate that it may be equally as beneficial to optimize working memory resources by way of training as with improved task configuration. The general guidelines offered by multiple resource theory need to be extensively investigated to determine their profitability in improving ATC tactical operations.

2.6.2 Dynamic Memory.

In comparison to the amount of work that has been done on static memory, remarkably little data are available on dynamic memory (Moray, 1981, 1986). Dynamic memory tasks, which require operators to keep track of a continuous sequence of information with no well-defined recall intervals, are more analogous to the complex and multidimensional nature of "real life" tasks. Air traffic controllers, for example, must be competent in responding to the nature of an individual aircraft under control, while concurrently handling the entire series of aircraft. The multidimensional nature of this task requires the controller to keep track of a large number of identified aircraft, each varying in flight data. Flight data also varies along a number of values (e.g., 12,000 feet, 45 degrees North, 350 mph). Further, the number of aircraft and associated flight data are periodically updated, requiring the controller to continually acquire and forget relevant flight information to revise the memory representation of the airspace traffic.

The research that does exist overwhelmingly suggests that dynamic memory capacity is only about three items, much less than the traditional memory capacity of seven items using a static memory paradigm (Baker, 1963; Kvalseth, 1978; Mackworth, 1959; Moray, 1980; Rouse, 1973a; 1973b; Yntema, 1963; Zeitlin & Finkleman, 1975). Based on a dynamic memory task, analogous to that of an air traffic controller, Yntema (1963) suggested three possible solutions to reduce the severe limitations of dynamic memory capacity. First, recall performance is much better in a monitoring situation when the operator is responsible for only a few objects/aircraft that vary on a large number of flight data attributes than a large number of objects with a few attributes. This recommendation is consistent with work on conceptual chunking, which indicates that recall of a primary object or concept, precipitates recall of attributes from long-term memory (Egan & Schwartz, 1979; Garland & Barry, 1990a, 1990b, 1991, in press). Additional information on conceptual chunking will be presented in a subsequent section. Second, the amount of information about each attribute has relatively little influence on dynamic memory integrity. This result is also consistent with conceptual chunking. Therefore, information precision can be increased without degrading dynamic memory performance. Third, dynamic memory performance is enhanced when each attribute value has its own unique scale. This makes the attributes easier to separate and the influence of interference due to item similarity is reduced.

Yntema's (1963) suggestions for dynamic memory enhancement were not based on ATC tasks. While the conclusions are based on sound controlled laboratory experimentation, research investigating their usefulness in an ATC setting is not available. An investigation of the applicability of these suggestions to an ATC setting is needed.

The nature of the dynamic memory tasks present in the available literature, invariably involves the presentation of a time series of random and meaningless information, which the subject simply observes, (Baker, 1963; Kvalseth, 1978; Mackworth, 1959; Moray, 1980; Rouse, 1973a, 1973b; Yntema, 1963). The general finding of dynamic memory capacity limited to approximately three items may simply be a product of these task characteristics (Moray, 1986). Skilled operators like air traffic controllers, who have to deal with complex and multidimensional information, often exceed the three item capacity of dynamic memory. These operators process heavy information loads and are competent in recalling a considerable amount of information from their dynamic displays on demand. This superior ability may simply be a result of meaningful information processing using dynamic interaction and direct manipulation of the displays. This direct manipulation, as compared to monitoring alone, may allow the operator more meaningful encoding and retrieval strategies, which facilitate recall of the information. This explanation has definite ATC automation implications. More specifically, direct manipulation environments may facilitate dynamic memory performance, while monitoring may degrade or unnecessarily restrict dynamic memory to the three item limit.

Increased dynamic memory capacity in naturalistic environments may also be due to outcome feedback. Specifically, outcome feedback may allow the operator to appear as though complex sequences of information are being fully processed, when in fact, relatively small amounts of information are viable at any given moment (Hogarth, 1981). This conclusion is supported by several authors who suggest that small memories may be sufficient for dynamic decision making (Baxa & Nolte, 1972; Bechtel & Amos, 1975; Gonzales & Hovington, 1977; Mullis & Roberts, 1968; Taylor, 1975).

It is tenuous at best to generalize the available dynamic memory results found in the laboratory, using meaningless material, to real life dynamic environments, where operators skillfully construct the form and content of the information they need to remember (Moray, 1986). Consequently, extensive research is needed to identify the features of controllers' dynamic memory that will contribute to the development of corrective solutions and training guidelines to reduce the effects of severe memory constraints in an ATC setting. Such research is especially important with the onset of ATC automation, where the integrity of system decision making (which is based on information monitoring), is highly dependent on dynamic memory capacity.

2.6.3 Skilled Memory Effect.

The intimate relationship between working memory and long-term memory provides the means to substantially increase working memory capacity beyond the traditional limits. Baddeley (1976, 1981, 1986) and his colleagues have functionally described working memory as a product of several memory system components which, in combination, allow for skilled tasks like reading to exceed the traditional working memory capacity limits. Further, in a series of experiments examining memory performance as a function of practice, Chase and Ericsson (1982) demonstrated that individuals can substantially increase their working memory capacity. The authors suggested that with increased practice, working memory develops rapid access mechanisms in long-term memory.

Over the past 25 years a solid base of empirical evidence has accumulated for the skilled memory effect (Chase, 1986). The literature, which covers research on a wide range of perceptual-motor and cognitive skills, generally concludes that experts in their area of expertise are able to retain information far in excess of the traditional limits of working memory (Chase, 1986; Chase & Ericsson, 1982). Based on now classic studies with the game of chess, Chase & Simon (1973a, 1973b) theorized that for search-dependent domains like the game of chess, domain-specific expertise can be differentiated based on how memory is organized. It was suggested that "the chess master has acquired a very large repertoire of chess patterns in long-term memory that he can quickly recognize, although both masters and weaker players have the same working memory capacity" (Chase, 1986, p.28-55).

The skilled memory effect has been replicated many times in various search-dependent domains, such as chess (Charness, 1976; Chi, 1978; Frey & Adesman, 1976; Goldin, 1978, 1979; Lane & Robertson, 1979), Go (Reitman, 1976), Gomoku (Eisenstadt & Kareev, 1975; Rayner, 1958), Bridge (Charness, 1979; Engle & Bukstel, 1978), and in nonsearch domains such as music (Slaboda, 1976), computer programming (McKeithen, Reitman, Rueter, & Hirtle, 1981; Schneiderman, 1976), baseball events (Chiesi, Spilich, & Voss, 1979), electronics (Egan & Schwartz, 1979), architecture (Akin, 1982) and sport (Garland & Barry, 1990a; Starkes & Deakin, 1984). Research in nonsearch domains has identified "hierarchical knowledge structures" as a fundamental property of the skilled memory effect (Akin, 1982; Egan & Schwartz, 1979; Garland & Barry, 1990a, 1991). Specifically, these studies suggest experts use domain-specific conceptual knowledge to organize information, and this organization serves to facilitate storage and retrieval of domain-specific information from memory.

Based on the accumulated knowledge, Chase (1986) concludes that "the skilled memory effect is due to the existence of a vast domain-specific, long-term memory knowledge base built up by the expert with years of practice. This knowledge base can be used to serve two important mnemonic functions: (1) patterns can be used to recognize familiar situations, and (2) conceptual knowledge can be used to organize new information" (p. 28-61).

In summary, the research literature suggests that the traditional simplistic view of working memory as a single, limited capacity system is not viable. Working memory capacity appears to be directly or indirectly related to several factors, such as the nature of the multiple working memory components, including:

resources, conceptual organization, task parameters, meaningfulness of materials, and operator skill and experience. Despite the incredibly vast research literature on memory, Klapp (1987) justifiably asserts that a "detailed breakdown and mapping of (working) memory systems onto tasks is not yet understood (p. 6) ...largely because of our ignorance concerning the nature of the memory systems" (p.17).

2.7 MENTAL MODELS (THE CONTROLLER'S PICTURE).

Several times throughout this report we have used the rather common ATC phrase, the controller's picture, to refer to the controller's mental representation of the airspace. At this time, an attempt will be made to address this cognitive phenomenon, which has such an important role in ATC memory and tactical operations.

A mental model is a theoretical construct which provides the user with a framework for thinking about a complex domain of which they are a part. Mental models may be specific to a given situation or more global to the entire task domain which could include the entire flight sector. They may, or may not, include abstractions concerning functional relationships, operating guidelines, and systems goals and objectives (Mogford, 1991; Norman, 1986; Rassmussen, 1979, Wickens, 1984; Wilson & Rutherford, 1990). Theoretical descriptions of mental models are varied (see Mogford, 1991). For example, Rouse and Morris (1986, p. 351) suggest:

> "Mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states."

Further, Norman (1986, p. 46) states:

> "Mental models seem a pervasive property of humans. I believe that people form internal, mental models of themselves and of the things and people with whom they interact. These models provide predictive and explanatory power for understanding the interaction. Mental models evolve naturally through interaction with the world and with the particular system under consideration. These models are highly affected by the nature of the interaction, coupled with the person's prior knowledge and understanding. The models are neither complete nor accurate, but nonetheless they function to guide much human behavior."

Research on mental models and conceptual structures in the ATC environment is disappointingly limited (Mogford, 1991). However, the research that is available does suggest a connection between a controller's picture and their understanding of, and memory for the traffic situation (Bisseret, 1970; Landis, Silver, Jones, & Messick, 1967; Means, Mumaw, Roth, Schlager, McWilliams, Gagne', Rosenthal, & Heon, 1988; Moray, 1980; Whitfield, 1979). A general conclusion of these studies is that skilled controllers, in comparison to the less skilled, use their picture as a supplementary display in order to enhance memory for aircraft. In addition, it is generally concluded that the quality and functionality of the controller's picture is directly related to ATC expertise.

According to Whitfield (1979), the skilled controllers' picture seems to use three kinds of memory; (a) static memory- sector characteristics, separation standards); (b) dynamic memory- continual updating of aircraft flight data; and (c) working memory- current status of aircraft. Further, Mogford (1991) suggests that the controller's picture is likely maintained in working memory, with substantial influences from unconscious rules stored in long-term memory. He states that "it appears that the controller's mental model possesses various kinds of information which are reliant on different types of memory. Maps, flight plans, aircraft performance information, separation standards, and procedures are learned through training and experience and stored in memory" (p. 239).

The extent to which mental models can provide assistance with the practical problems of ATC memory enhancement is unclear. While the available research suggests a significant role for working memory in ATC picture development and utilization, research has not yet revealed empirical evidence suggesting how the controller's picture may assist in enhancing controller working memory and improving ATC tactical operations. Research on mental models in ATC is needed as ATC systems become more automated, forcing the controller into ever increasing levels of supervisory control. The dramatic changes with AAS will not only replace ATC technology and equipment, but will also fundamentally change the way controllers conduct their job.

Research is needed to investigate how increased computerization of ATC tasks influences the development of the controllers picture, and it's potential supporting influence on controller working memory. Hopkin (1980, p. 558), in addressing this very problem, notes:

> "Controllers frequently report that computer aids seem to increase the probability that they will lose the picture of the traffic under their control. This problem is the subject of research and the development of appropriate measures in ATC...in relation to concepts such as working mental models and working memory. If, as Neisser (1976) claimed, images are

anticipatory phases of perceptual activity and images are plans for obtaining information from potential environments, this may provide a theoretical framework and suggest appropriate measures for evaluating the efficacy of various forms of computer assistance, particularly predictions, as aids to imagining. It could also provide hypotheses for specifying conditions when forgetting is most likely to occur."

An understanding of ATC mental models may prove beneficial to understanding the impact of automation on designing controller training and memory aids, since to be effective, such aids must effectively interact with the cognitive processes of the controller (Hollnagel & Woods, 1983; Moray, 1988). Specifically, it is important that the organizational format of the data is compatible with the operator's conceptualization of the data. Further, Wickens (1984, p. 237) comments on a challenging and critical issue regarding advanced automation, that of design implications for computer-based data entry and retrieval systems:

> "How does the computer model or understand the user's conception of the data and logic within the computer itself? Clearly the computer should organize data in a form compatible with the user's mental model. But what if different individuals possess different styles of organization? Are different organizational formats appropriate for spatial versus verbal modes of thinking, as suggested by Schneiderman (1980)? A related question concerns the assumptions that the computer should make about the level of knowledge of the user. For the same program, a computer's interaction with a novice should probably be different from the interaction with an expert user. A novice, for example, would benefit from a menu selection program in which all options are offered, since many of them are not likely to be stored in long-term memory. For the expert, this format will probably give unnecessary clutter, since the alternatives are stored and available in LTM in any case. An intriguing question from the viewpoint of systems designs is how the computer can either explicitly assess or implicitly deduce the level of knowledge or the format of organization employed by the user."

It should be noted that while several researchers have suggested potential implications of mental models for both training and display design (Mogford, 1991; Wickens, 1984), Wilson and Rutherford (1990) recently asserted that "We have shown the several different interpretations of the concept (mental models) and its utility to be a weakness, which militates against the widespread use of mental models in system design" (p. 629).

Obviously, further work is needed on the air traffic controllers' picture.

In summarizing this brief overview of the work on chunking and organization and its relevance to ATC tactical operations, the primary conclusion seems obvious - more research is needed. In particular, research is needed in an ATC setting to better understand the conceptual structures that guide the synthesis and organization of present and future traffic situations. In support of this line of research, Whitfield (1979) has suggested that a controller's mental model is fundamental for current and future planning of the traffic situation. A further line of research is suggested by the available work on dynamic memory and conceptual organization. Perhaps, the ability of controllers to exceed the traditional limits of dynamic memory (three items) is associated with the controller's conceptualization of the ATC domain. If so, what are the features of the controller's conceptualization that may contribute to dynamic memory enhancement? Do ATC conceptual structures fundamentally change with experience and expertise, thus facilitating the enhancement of dynamic memory and skilled memory? There are obviously more questions than answers at this point. However, with increased ATC automation, the time, although limited, is ripe for extensive investigations to address these crucial questions. Harwood, Roske-Hofstrand, and Murphy (1991) note that "the complexity of ATC is inherent in the relationships between many components, concepts, and variables. To be meaningful and useful, research and applications for ATC must acknowledge this complexity."

2.8 FORGETTING IN WORKING MEMORY.

The primary reason for this report is to examine how working memory is related to controller operational errors. Controller memory lapses have been identified as a significant issue related to revising and retrieving critical operational information. While considerable information on forgetting is available in the psychological literature (Klatzky, 1980, p. 124-150), the profitable application of this material to the real-life setting of ATC is unclear. In contrast to the unforgiving nature of unintended memory failure, Hopkin (1980) notes "that the potential applications of theories of memory seem to relate to learning and remembering rather than forgetting, where the gulf between the laboratory and real life seems larger (Wetzel & Hunt, 1977). ATC requires a great deal of information, some of which must be remembered for some time, but much of which, once used, is not needed again and constitutes unwanted baggage if it is persistently recalled. Much more practical information is required about how information coding can be used to aid forgetting" (p. 558). Thus, the nature of forgetting information in the ATC setting is paradoxical, in that it has both desirable and undesirable implications.

Research on both unintentional and intentional forgetting is necessary in order to develop aids to eliminate and/or enhance forgetting during the appropriate situation. The following discussion will present some of the available information on forgetting which may be applicable to the ATC setting.

There are two classic theoretical approaches to memory retrieval failures. These are (a) spontaneous decay, which refers to a time-dependent process of information becoming less available over time, and (b) interference, which refers to the disruption of the memory trace due to competing activity. Considerable research effort has gone into trying to determine which of these mechanisms really drives forgetting (Card, Moran, & Newell, 1986).

2.8.1 Decay.

Research by Reitman (1974) initially demonstrated the separate roles of decay and interference in working memory. This research has shown that time plays a significant role. As it passes, information becomes less readily available. In addressing research on the decay mechanism as a means of forgetting, Wickens (1984, p. 216) states:

> "When verbal information is presented auditorially, the decay may be slightly postponed because of the transient benefits of the echoic (auditory) code. When information is presented visually, the decay will be more rapid. The consequence of decay before material is used is the increased likelihood of error. The pilot may forget navigational instructions delivered by the air traffic controller before they are implemented. ... In fact, Moray (1980) concludes that 'the task of monitoring a large display with many instruments is one for which human memory is ill suited, especially when it is necessary to combine information from different parts of the display and the information is dynamic'."

In addition to the rapid decay of information which has been actively attended and encoded, forgetting as a result of decay is also, in part, a function of the initial level to which the material is processed. Pre-attentive processing of information, without higher-order encoding, will inevitably result in decay.

The time-dependent decay process operates to significantly reduce the accuracy of the memory trace (Klatzky, 1980; Wickens, 1984). The extent to which the decay process is disruptive or beneficial to the controller is situation-specific. The development of techniques to optimize the decay of information seems a viable line of research. If the controller were able to reliably control the decay of information then information management would be facilitated. The reader is referred to section 2.3 in

this report for additional information related to the decay mechanism of forgetting.

2.8.2 Interference.

Considerable research has demonstrated it is more difficult to retrieve an item from working memory and long-term memory if there are other similar items in the respective memory system (Conrad, 1964; Underwood, 1957). The similarity of items in memory is contingent on the memory representation of each item. For example, interference in working memory is more likely for items which sound alike (i.e., acoustic/phonetic interference). Long-term memory is more susceptible to semantic interference. That is, items or chunks, which share similar meanings, are likely to share the same retrieval cues, which in turn disrupts information retrieval. Research on the interference effect has demonstrated that much of what is commonly referred to as forgetting is simply failure to retrieve, not actual loss or decay from memory (Card, Moran, & Newell, 1986).

Generally, the literature recognizes three sources which may contribute to the interference effect: within-list or information redundancy interference, retroactive interference, and proactive interference (Wickens, 1984). Within-list interference is attributable to the increased similarity of items within a group that must be processed in working memory. For example, Wickens (1984) illustrates that "when an air traffic controller must deal with a number of aircraft from one fleet, all possessing similar identifier codes, the interference due to the similarity between items makes it difficult for the controller to maintain their separate identity in working memory" (p. 224). This has been one of the reasons suggested for the frequency of read back/hear back errors in ATC (Monan, 1986). Obviously, in order to alleviate within-list interference, information must be presented in a manner which reduces the information redundancy.

Retroactive interference is the detrimental effect of recently acquired information which retroactively interferes with previously learned material (Underwood, 1957). For example, a controller may forget a newly assigned altitude of an aircraft because an additional item of information intervened and prevented sufficient rehearsal of the new altitude and/or notation on the flight progress strip. Further, increased similarity between the item to be retained and the intervening item will increase the probability of interference.

Proactive interference is the detrimental effect of previously acquired information which proactively interferes with recently learned material (Keppel & Underwood, 1962; Underwood, 1957). For example, the implementation of AAS will require all Full Performance Level controllers to undergo extensive transition training in order to apply their existing operational knowledge of ATC to the new system's capabilities. If the planned transition training is not completely successful, one might expect previous ATC knowledge, acquired through years of experience and training, to proactively interfere with the new knowledge and skills needed for AAS. This effect may be especially profound during labor and time intensive situations, where there is a tendency to cognitively regress back to former firmly established ways of thinking.

A considerable amount of research has been conducted to examine the processes that reduce the effects of proactive interference, or as the literature commonly describes as a release from proactive interference (Keppel & Underwood, 1962). This phenomenon refers to the fact that if the type of stimulus material like letters or numbers is changed from trial n to trial n + 1 (from numbers on trial n to letters on trial n + 1), then proactive interference will be reduced resulting in a substantial decrease in forgetting of the recently acquired material (Loftus, Dark, & Williams, 1979). Explanations for this phenomenon are generally consistent with the following example provided by Loftus, Dark, and Williams (1979, p. 172):

> "Suppose a subject must remember two pieces of information, A and B, that are presented in close temporal proximity. To the extent that A and B may be differently encoded, they will be less confusable, and hence easier to recall. Carrying this notion over to the controller/pilot situation, it seems reasonable to expect that two pieces of numerical information will be easier to remember to the extent that they are uniquely encoded."

In a study of simulated communications between controllers and pilots, Loftus, Dark, and Williams (1979) found evidence to indicate that a unique-encoding system, as compared to a same-encoding system, of ATC communications led to superior memory performance. The same-encoding system, referred to the current relatively standard ATC practice of transmitting virtually all numerical data in a digit-by-digit manner. The radio frequency 112.1 would be transmitted as "one, one, two, point, one." In contrast, "an example of the 'unique-encoding system,' would be to encode radio frequencies in the digit-by-digit manner described above, but to encode transponder codes as two pairs of double digits; "7227" would be encoded as "seventy-two, twenty-seven" (p. 171). This finding has definite memory implications for recall of multidimensional flight data. Loftus, Dark, and Williams (1979) concluded that "Attention is traditionally paid to the question of how transmitted information should be encoded so as to minimize errors in perception. The use of the phonemic alphabet is an example. However, virtually no attention has been paid to the question of how information may be encoded so as to minimize errors in memory. The unique-encoding system represents but one possible improvement in encoding of transmitted information. Potentially, there are many others" (p. 180). Unfortunately, many years have elapsed with little or no research to advance these findings.

Previously presented information on dynamic memory also supports the utility of a unique-encoding system. In particular, a series of dynamic memory studies by Yntema (Yntema, 1963; Yntema & Mueser, 1960) provide the most applicable evidence. In these studies, participants were required to keep track of a large number of objects which varied on a number of attributes. These, in turn, varied on a number of unique values. The studies indicated that memory accuracy was enhanced when the attribute values each had their own unique codes such as feet, speed, miles, compared to attribute values sharing common codes. For example, suppose a controller must identify and then enter the status of several aircraft along several flight data dimensions. Since the flight data are coded differently, altitude in feet and distance in nautical miles, performance will be superior if the controller deals in turn with all the relevant flight data of one aircraft before progressing to the next aircraft, rather than dealing with all the aircraft on only one flight data dimension before progressing to the next flight data dimension.

The unique-encoding system appears to be a profitable means by which information can be optimally encoded, enhancing working memory retention and minimizing retrieval failures of critical information. Research is needed to examine the viability of such an information encoding system in an ATC environment.

Based on the available research on interference effects, Wickens and Flach (1988, p. 124-126) have suggested four ways to reduce the effects of interference on forgetting in working memory. They are: (a) "Distribute the material to be held in (working) memory over time." This will allow proactive interference from previously acquired information to be reduced. (b) "Reduce similarity between items." This suggestion is consistent with the information presented on the "Conrad Effect" (Conrad, 1964) and the unique-encoding system. (c) "Eliminate unnecessary redundancy." This suggestion is intended to reduce the effects of within-list interference. (d) "Minimize within-code interference." This suggestion is consistent with the previously presented information on code interference in working memory. For example, in the predominantly visual/spatial ATC environment, concurrent secondary tasks should minimize the use of visual/spatial codes. Instead, they should use auditory/speech encoding. This could involve voice recognition technology.

2.8.3 Directed Forgetting.

As mentioned earlier, in addition to enhancing the integrity of working memory performance through the reduction of memory lapses, there are also times when the intentional purging of working memory information may enhance memory. Hopkin (1988) asserts that intentional forgetting may be beneficial in that the "... controller dealing with an immediate problem is not overburdened by recalling other problems not sufficiently similar to be helpful in solving the present one" (p. 12). Further, Hopkin (1980) has noted the importance of identifying and developing ATC techniques intended to aid the controller in the forgetting of unwanted baggage, which may prove to proactively interfere with current information processing. Such directed forgetting (also referred to as motivated or intentional forgetting in the cognitive literature) of information which is no longer useful would seem to be a necessary skill in a dynamic memory setting, such as ATC flight management. In this environment the ability to process incoming sequential information is contingent upon the availability of processing space in working memory. The available research indicates that when participants are instructed to intentionally forget unwanted information, there are additional attention resources for dealing with concurrent tasks (Bjork, Bjork, & Kilpatrick, 1990; Bjork, 1972; Martin & Kelly, 1974). Bjork (1972) has suggested that directed forgetting can be trained.

The information presented on the effects of decay on forgetting is relevant to the present discussion of directed forgetting. If techniques can be identified to assist the controller in reliably controlling the decay of information, directed forgetting would be a valuable product. As mentioned previously, two qualitatively different types of rehearsal strategies are involved in working memory - maintenance and elaborative rehearsal. Short-term retention of information in working memory is achieved through maintenance rehearsal, which emphasizes the phonetic aspects of the stimuli, while elaborative rehearsal is important for transfer of information into long-term memory by emphasizing the semantic aspects (meaningfulness) of the stimuli and their association with the conceptual information of the controller's mental model stored in long-term memory. Since information transfer to long-term memory facilitates the undesirable effects of proactive interference (Craik & Watkins, 1973; Glenberg, Smith, & Green, 1977), information to be retained for only a short period of time should only use phonetic maintenance rehearsal, as opposed to semantic elaborative rehearsal (Wickens, 1984). This strategy, along with directed forgetting strategies may prove useful in enhancing directed forgetting (Bjork, Bjork, & Kilpatrick, 1990; Bjork, 1972).

Based on the available data from laboratory studies, Wickens (1984) suggests that "this technique (directed forgetting), like chunking, is a potentially valuable strategy that can be learned and subsequently employed for more efficient storage and retrieval of subsequent memory items" (p. 226). However, a note of qualification is warranted. Specifically, research is needed to determine the applicability of the laboratory findings to the ATC setting. The above suggestion was based on data gathered in a laboratory setting with college students who were required to forget meaningless information, which they had no experience in actively using and/or processing. Consequently, information is needed to determine the utility of purposefully forgetting meaningful information in a real-life, labor-intensive, time-intensive environment, such as ATC. Until such data is available, instructional guidelines for the training of directed forgetting in an ATC setting will probably not be developed.

3. ATC AND WORKING MEMORY.

The discussion of working memory and its implications to ATC is by no means an exhaustive, definitive treatment of the working memory requirements of ATC tactical operations. While considerable information on working memory is available (Baddeley, 1986; Klatzky, 1980), there remain more questions than answers. Working memory permeates every aspect of the human information processing system, making it virtually impossible to get a handle on all the parameters which define its functionality. This report has attempted to raise an awareness of a few of the most salient transient characteristics of working memory and their implications for ATC. Additional areas of research which directly or indirectly influence working memory were beyond the scope of this report. These include, but are not limited to, long-term memory, stress, decision making, and workload.

The fundamental limiting factor in gaining a more comprehensive understanding of the working memory requirements of ATC tactical operations, is the simple fact that there has been relatively little human factors research on the cognitive aspects of ATC, especially on working memory. Hopkin (1980), in noting the importance of memory research in the ATC environment, commented that "the application of theories of memory to practical ATC problems must be developed more in the future,..." (p. 558). In calling attention to the necessity to reinterpret the air traffic controller's tasks in relation to cognitive psychology constructs, Hopkin (1980, p. 559) concluded:

> "The time seems ripe for a more thorough examination of the relevance of newer theoretical concepts in psychology, not initially derived from applied contexts, to applied problems such as those which arise in ATC, together with the methods of measurement associated with them. It should be possible to trace the origins of some of the practical difficulties which the controller encounters to fundamental limitations in human capabilities and to use basic psychological knowledge to explain them, measure them, and resolve them. It should also be possible to extend to ATC

contexts general psychological theories and constructs hewn in the psychological laboratory and to put their descriptive and predictive power to practical use. Success in welding psychological concepts to the human implications of advancing technology by means of common measures would constitute real progress."

Hopkin's call for the application of psychological theories to practical ATC problems has not been widely followed. The implications of increased ATC automation on the controller's cognitive processes are not completely understood. There have been some attempts to approach a better understanding of how controllers think and use their cognitive resources. An operations concept for the advanced automation system was completed in the mid 1980's (Philips, Tischer, Ammerman, Jones, and Kloster, 1984). The authors of this concept attempted, with the help of subject matter experts, to identify and decompose controller tasks into more basic units. The task structure that they achieved included cognitive activity but did not address memory directly. It implicitly assumed that once a controller received information, the data would be available whenever needed.

In a latter effort sponsored by the Office of Personnel Management, a contractor attempted to focus on en route ATC cognitive tasks as a follow up to the study (Human Technology Inc, 1990; Redding, Ryder, Seamster, Purcell, and Cannon, 1991). The goal of this effort was to examine controller internal representations in the form of mental models for the ultimate purpose of improving training. The authors attempted to identify differences between controllers based on their level of expertise. While memory did not appear in the executive summary of the 1990 report, it was cited in the work of Redding et al (1991). However, the impact of memory was subsumed under the more global construct of situational awareness. One interesting finding is that novice controllers place a higher priority on routine ATC-mandated procedures than do experts. This may imply a higher memory load for novices. When everything is considered, very little has been accomplished on controller cognition. This may complicate the transition to new technology since there is an incomplete understanding of how controllers process and think in the current system.

There are potential human factors consequences of increasing ATC automation. These consequences may have an impact on how controllers use memory resources.

3.1 MEMORY AIDS.

Considerable information has been presented concerning the volatility of information in working memory. An obvious solution to the limitations and constraints of working memory is to augment the transient visual and/or auditory information with a more reliable visual display (Wickens, 1984). Such memory aiding would allow prolongation and subsequent storing of the information, potentially enhancing the fidelity of working memory. A controller would then not need to try to overcome the frailties of working memory, because the information would be physically present, requiring only simple perceptual processing.

However, such external memory aiding is not without human factors concerns. For example, would memory aiding technologies reliably enhance working memory, or is there the potential for disruption of controller working memory? It is imperative for the controller to maintain spatial and temporal awareness of the airspace traffic in order to control live traffic. The current term for this is situation awareness. Some memory aiding technologies afford the possibility of extensive perceptual dependence, in that the controller may not actively encode and process enough information relative to traffic picture development (Bainbridge, 1982). Wickens (1984, p. 216) comments:

> "..., a memory-aiding alternative...is not free. ..., it represents one of the many tradeoffs in human engineering design, because display augmentation is generally achieved only at the cost of added display clutter. For example, in an air traffic controller's display, computer-generated (data) tags placed next to each aircraft symbol help to off-load working memory by depicting information such as flight number and altitude. But it is likely that much more information presented about each flight might be excessive, so that the added visual clutter would disrupt the controller's overall image of the flight space."

To remedy this, Smolensky (1991) has suggested a Flight Data Block Second Page as a means to augment controller working memory without unnecessary visual display clutter. Smolensky suggests the possibility of having all Flight Data Blocks toggled (with a single function key entry) to show a second page. The second page would display important, but ancillary information as determined by an information needs analysis. No slew would be needed to: (a) select a Flight Data Block, and (b) subsequently perform a toggle function.

There are information displays in current use within the FAA which could potentially lessen demand on working memory. In a limited survey of operational facilities, Gromelski, Davidson and Stein (1992) found some facilities had equipment referred to as Systems Atlanta which can provide a wide variety of information in a small display which must be configured and paged to meet the needs of the individual controller. However, paging can be distracting and because it was a retrofit type display, its location was not always convenient to the individual control position. Another noteworthy finding of this study was that many controllers did not believe in using memory tools because it somehow violated their cultural belief in self reliance. The benefits of memory enhancement tools for controllers will require long-term study.

The conflict over the usefulness of memory aides in ATC also extends to the aircraft cockpit. The current controversy over the implementation of cockpit displays of traffic information (CDTI's) in aircraft cockpits is a prime example of the tradeoff between memory aiding and display clutter (Hart & Loomis, 1980; Palmer, Jago, Baty, & O'Connor, 1980; Wickens, 1984). While the CDTI's will reduce the pilot's information load in working memory, visual processing requirements will certainly increase. The potential benefits of CDTI's as memory aids remains unclear.

These examples highlight the basic human factors concern that simple prolongation of visual information does not fully eliminate the limitations and constraints of working memory. Memory aids must be flexible enough to accommodate the controller's level of expertise, along with tactical and cognitive preferences. The current ATC paper flight strip essentially sets the standard for an optimal ATC memory aid. Unfortunately, the implementation of ISSS will see the demise of the paper flight strip, as it will be replaced with an electronic version.

3.2 ELECTRONIC FLIGHT STRIPS.

In order for controllers to successfully manage air traffic, they must have access, in working memory, to a large amount of multidimensional data about the status of the aircraft under control, its past performance, and future intentions. Currently, the processing of these data is facilitated by paper flight progress strips (FPS). These paper flight strips contain both, previously stored data (flight plans, altitudes) and new data (departure from an altitude). The paper flight strip has become an essential part of the controller's working memory system. Several researchers have identified the significant cognitive value of flight strips in preparing for future actions (Hopkin, 1989, 1991b; Vortac, 1991). One reason for the cognitive value of flight strips is they represent the history of actions, goals, intentions, and plans of pilots and controllers. These functions are elaborated in the following controller interview extract (Harper, Hughes, & Shapiro, 1989, p. 9):

> "It's a question of how you read those strips. ... an aircraft has called and wants to descend, now what the hell has he got in his way? You've got ping, ping, ping, those three, where are those three, there they are on the radar. Rather than looking at the radar, one of the aircraft on there has called, now what has

> he got in his way? Well, there's aircraft going all over the place, now some of them may not be anything to do with you, ... your strips will show you whether the aircraft are above or below them, ... or what aircraft are below you if you want to descend an aircraft, and which will become a confliction. You go to those strips and you pick out the ones that are going to be in conflict if you descend an aircraft, and you look for those on the radar and you put them on headings of whatever, you find out whether those, what those two are --which conflict with your third one. It might be all sorts of conflicts all over the place on the radar, but only two of them are going to be a problem, and they should show up on my strips."

This interview extract provides a good example of the role flight strips play in assisting information processing and its significance in planning future actions. Harper, Hughes, and Shapiro (1989) point out that "paradoxically, the 'moving' radar screen is from an interpretative point of view relatively static, while the 'fixed', 'hard copy' strip is interpretatively relatively dynamic." For ATC tactical operations, planned actions are the purview of flight progress strips, and past actions are reflected in feedback on the radar and flight strip markings (Vortac, 1991).

Hopkin (1991b) states that the paper flight strip "acts as (an) information display, notepad, memory aid, history, and record of actions." "Controllers have considerable freedom in their choice of FPS markings, motor activity is required to interact with the FPS, and their resemblance to note-taking should boost encoding processes in the expected fashion" (Vortac, 1991, p. 44). Due to its current significance, the automation of the paper flight strip has become a critical issue in the design of AAS (Ammerman & Jones, 1988; Hopkin, 1988; 1991b; Wise, 1991).

Hopkin (1991b), in summarizing work on flight strip functionality (Harper, Hughes, & Shapiro, 1989; Jackson, 1989), indicates that the actual use of the paper flight strip has exceeded its original purpose as a memory aid. He notes that "the quest for an electronic replacement for paper flight strips has revealed that (paper flight strips) are a more complex and powerful tool than was originally believed, with more flexible functionality." For example, the process of physically manipulating the paper flight strips by inserting or removing them from the strip bay facilitates the controller's awareness of the physical interrelationships between aircraft. Additional actions such as sorting the paper flight strips or cocking them on the strip board, further facilitate the controller's understanding and memory for the information displayed.

Paper flight strip markings or notations give them their note pad character. Jackson (1989) stated that "it is possible that when controllers read information from a strip in their own handwriting they do not only interpret and comprehend the content, they also remember the previous act of writing it and, perhaps more importantly, the reasons why a particular course of action had been undertaken. "Now why did I do that?", p. 5. This observation is supported by psychological research on retrieval cues (Tulving & Thomson, 1973) and recent research that demonstrated subject-generated memory aids using, for example, hand-written notes or annotation of to-be-recalled items with a self-generated icon facilitate memory retrieval (Intons-Peterson & Fournier, 1986; Lansdale, Simpson, & Stroud, 1990).

The implementation of ISSS may replace all of the paper flight strip notations with either controller-entered or system generated flight data entry notations (Ammerman & Jones, 1988). The impact of such a change on the controller's processing of flight data is unknown. While the ISSS stage of AAS is expected to reduce workload and improve some aspects of controlling air traffic, there exists the real possibility that ISSS will fundamentally alter and impair memory performance of controllers. New systems will likely require additional data entry via the keyboard in order to maintain the dynamic data bases. In a recent study of a small sample of air traffic controllers at the FAA Technical Center, Zingale, Gromelski, Ahmed and Stein (1993) used a simulation game that required controllers to enter their commands with the keyboard instead of giving instructions verbally. Controllers reported that their ability to recall aircraft call signs was poorer than it was when they actually worked live traffic. The authors speculated that the additional keyboard use may have been distracting.

Data Link services provide a further example of potential human factors consequences of new automated systems. The Data Link system, which will provide digital communications between ATC ground facilities and aircraft, may directly and/or indirectly impact the memorial processes of the controller in several ways. First, with the reduction of voice communications, the controller may not use the single most effective memory encoding process - phonetic maintenance rehearsal. By saving the voice, the controller's memorial representation of the transmitted information is potentially weakened. Second, the electronic updating of the flight strip prevents the controller from directly manipulating the information by strip markings or cocking the strips, This may further impact the memorial representation of the information. Third, automated presentation and updating of information will require perceptual processing by monitoring, rather than memorial processing, which may effect the creation and revision of the controller's mental picture.

The assumption underlying the implementation of new technologies is that, with the automation of functions which were once allocated to human control, the processing resources of the controller will be freed to deal more effectively with other required aspects of the system (Naval Air Development Center, 1990; Swedish, 1983). However, while the use of new technologies may be essential in order to deal with the ever increasing information-processing demands of the ATC system, the long-term performance implications of extended use of the new technologies on human performance are largely unknown (Endsley, 1988; Harwood, Barnett, & Wickens, 1988; Naval Air Development Center, 1990). One can safely conclude that, for the present time, paper flight strips are a valuable ATC memory aid (Stein, 1991).

There is the real possibility that new technologies, intended to reduce workload and consequently enhance memory, will influence memorial processing. There is an obvious need for human factors professionals to develop the methods for keeping the controller alert and actively involved in meaningful ways. New technologies should be designed to optimize memory load rather than reduce it. Wickens (1984) concludes, "at best (memory aids) will provide a valuable service if they are needed, and they can be perceptually filtered (or physically turned off) by the user if they are not. However, at worst, memory aids may prove unnecessary in most circumstances and either distract or disrupt the perception of more recent events" (p. 217).

4. FUTURE OPPORTUNITIES.

This review of the theory and research behind working memory demonstrates that the ATC system will only be as efficient and reliable as the controller's working memory system. A controller's memory directly or indirectly influences every aspect of his/her ability to work traffic. As ATC automation increases, more attention to the fundamental cognitive aspects of the controller's job is necessary. We need to develop cognitive performance measures so that the consequences of automation on controller performance can be effectively evaluated. Hopkin (1991c, p. 558), discussed future ATC measures of performance:

> "In previous studies, the most appropriate performance measures may not have been employed. In the future, better measurement tools will be needed to show the consequences of automation not only in terms of performance but also in terms of associated cognitive skills. Some cognitive effects are not currently measured at all, for example understanding or memory, but they may be more significant than the routinely measured effects on performance."

Throughout this report information has been presented which emphasizes the critical importance of working memory in ATC tactical operations. Much of the available research on working memory in ATC and non-ATC settings has largely gone unnoticed in ATC system design. As Hopkin noted in 1980, it is definitely time to apply existing (and new) memory research to the practical problems of ATC. While there exists considerable research on the frailties of working memory and ways to overcome them, there also exists a basic problem in making the appropriate knowledge influence the ATC system design process. Hopkin (1991c, p. 555) commented:

> "It is not sufficient to plan and conduct research if the only products are journal articles, standards, or handbooks, essential though these are. The research evidence has to be applied and integrated into the design. Nowhere does this seem to be done satisfactorily, although its necessity is acknowledged and many attempts are made. Lack of appropriate mechanisms to apply research findings to design processes appears to be the main difficulty. This problem is linked to some uncertainty about how valid and general some of the existing data and findings are. Is all the existing evidence actually worth applying to the design process? If not, how do we determine which should be applied and which should not? What criteria could serve such a purpose? What should the balance of evidence be between previous research and current and future research? What are the best measurements to gain evidence in the form of practical advice at the design stages? How can research findings be made more acceptable to designers, so that they are more willing to adapt design processes of future ATC systems to incorporate evidence from research?"

For several decades, the implicit philosophy of automation has assumed that maximum available automation is always appropriate. This philosophy has been based, in part, on the availability of increasingly sophisticated and advanced technological innovations, the need to reduce human workload, the need for increased safety of flight, and perhaps, primarily on the assumption that the human mind (especially human memory) is similar to a silicon-based system that cannot be easily overloaded. While automated systems have provided substantial benefits, several human factors consequences have arisen and incidents/accidents have occurred, calling for the aviation community to re-examine automation practices.

There is an increasing awareness of the lack of a scientifically-based philosophy of automation. This philosophy must be based on an understanding of the relative capabilities (frailties of working memory) of the controller in the system, and the circumstances under which automation should assist and augment the capabilities of the controller. Our approach to automation should be more human-centered if we intend to avoid the most adverse human factors consequences of automated systems. This would provide a better-planned progressive introduction of automated aids in step with user needs (Garland, 1991). Such a comprehensive, scientifically-based design philosophy for human-centered automation must be developed in order to avoid inevitable "one step forward and two steps backward progression."

For the time being, the human controller, despite the limitations and constraints of the working memory system, will remain an essential part of the ATC system. As ATC automation increases, the significance of the human controller in the system, and the importance of the controller's working memory system, should no longer be taken for granted.

The purpose, intent, and nature of this report are best reflected in ideas Levesley (1991, p. 539) put forth about the way he sees the ATC system in 50 years. Levesley comments:

> "What I actually predict will happen is that the lessons of the last fifty years will be repeated in the next fifty. Airlines will still prefer to spend $500 on aircraft for every $1 spent on ATC. Will the cost of potential super-systems actually prohibit their introduction, as they prove totally cost-ineffective? If I survive to the age of 93 and I fly somewhere in 2040, I suspect that there will still be a human problem solver on the ground in control of my flight, who will rejoice in the title of the controller. And I don't think that controllers will be there because they are irreplaceable, or because the public wants someone there. I think that, with the right tools to help, the controller will still be there as the most cost effective, flexible system solution to the problem of safely guiding pilots and passengers to their destination. And that is what ATC is really all about."

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☆U.S. GOVERNMENT PRINTING OFFICE: 1993 - 504-078/90170