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THE EFFECT OF ACTIVE AND PASSIVE CONTROL ON AIR TRAFFIC CONTROLLER DYNAMIC MEMORY

by

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Daniel J. Garland, Center for Aviation/Aerospace Research and Department of Humanities and Social Sciences, and has been approved by the members of his thesis committee. It was submitted to the Office of Graduate Programs and was accepted in partial fulfillment of the requirements for the degree of Master of Aeronautical Science.

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Abstract

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The purpose of this study was to investigate the effect of automated and passive control on air traffic controller dynamic memory. The study consisted of two experiments, each involving a realistic ATC scenario for radar approach control with a mix of arriving and departing traffic. In Experiment I, the subjects performed manual control of the traffic while, in Experiment II, the scenario was highly automated and the subjects were tasked with only monitoring the situation. The dynamic memory performance was measured by interrupting the scenario and having the subjects recall the traffic situation at the moment of simulation interruption. The accuracy of recall was compared between the manual and automated scenarios. It was anticipated that subjects exercising manual control would have superior recall ability and a "picture." This would have significant implications on the design of automated systems for ATC and the role of the human controller within the ATC system.

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Introduction

The air transportation system is becoming increasingly complex due to the implementation of advanced technologies. The Federal Aviation Administration (FAA) has been paying close attention to air traffic controllers' operational errors in this changing environment and has identified a number of factors contributing to controller errors (Vingelis, Schaeffer, Stringer, Gromelski, & Ahmed, 1990). An area of particular concern is controller memory lapses.

The role of the air traffic controller is undergoing significant changes due to increasing automation. One of the major concerns of automation is how to keep the human controller actively in the control "loop". Dynamic memory plays a key role in controller information processing and in the formation and maintenance of the "picture" of the situation. Consequently, understanding of how dynamic memory works is of utmost importance in the system design to keep the human element an integral part of the system.

Statement of the Problem

The purpose of this study is to investigate the effect of active and passive control of air traffic on air traffic controller dynamic memory. For the purposes of this study, dynamic memory is defined as the continuous memorial processing of random stimuli and their attributes, where responses are required for each stimulus or series of stimuli some time after they have occurred without a definite interval for recall.

Review of Related Literature

Working memory. Human memory can be thought of as consisting of three subsystems of processes: sensory storage, working memory, and long-term memory (Sanders & McCormick, 1987). Another memory model, Broadbent's (1984) "Maltese Cross", comprises five modules. The four arms of the cross represent the sensory store, the motor output store, the long-term associative store, and the abstract working memory. In the middle of the cross is the central processing system. In all models of the human memory system the working memory is probably most critical due to its central role as information processor and its severe limitations in terms of capacity.

The working memory is a conscious, attention-demanding, short-term store for information until it is used and forgotten or stored more permanently in the long-term memory. It also serves an important function between sensory inputs and long-term memory by evaluating, comparing, and encoding different mental representations (Wickens, 1992). The working memory is generally thought of consisting of an articulatory loop, holding verbal and speechlike representations, the visuo-spatial scratch pad, holding imaginal representations, and the central executive, which coordinates the functions of the other two components and directs attention (Baddeley, 1986). However, the working memory is extremely limited in capacity, both in terms of the number of items it may contain and the time these items will remain in it.

Based on several experiments using a wide variety of stimuli, including visual, auditory, and tactile stimuli, Miller (1956) concluded that the span of absolute judgment is about seven plus or minus two bits of information. To explain how people can still hold much more information, e.g., several words or entire phrases, in their immediate memory even if the number of letters in the above example far exceeds seven or nine, Miller proposed the technique of chunking. When remembering a familiar phrase, we do not remember individual letters but a phrase which forms an entity, a single meaningful item. Because the span of immediate memory is limited in terms of items, according to Miller, a considerable amount of information can be held, depending on how effectively the information is chunked, as long as the number of items does not exceed nine. In fact, there seems to be no absolute limit to the amount of information that can be held in immediate memory, as long as it is chunked to form nine or less items. This notion of the importance of chunking has significant implications in the study of the air traffic controller's memory.

Craik and Lockhart (1972) argue that retention relies heavily on the familiarity, compatibility, and meaningfulness of the information to the subject. They also recognize several levels of information processing in the working memory. Preliminary processing depends on sensory features, such as loudness, brightness, and contrast. Deeper levels of processing are concerned with pattern recognition and extraction of meaning. According to Craik and Lockhart, deeper processing implies a greater degree of semantic or cognitive analysis. This deep processing produces more elaborate and stronger memory traces that facilitate better recall. Meaningful information already compatible with existing cognitive structures will pass more rapidly through preliminary processing to deeper levels. Thus, instead of producing preliminary information to be stored, it brings about meaningful, familiar, and final products, making the whole process more rapid and expanding the capacity of working memory. While deep processing also facilitates smooth information transfer between working memory and long-term memory, the items, regardless of the depth of the processing, are still in working memory and thus subject to rapid decay when attention is diverted from them. However, the deeper the level of processing, the slower the rate of decay and the better the accessibility.

Norman and Bobrow (1975) propose a simpler approach to human information processing and memory. They concentrate on the quality of the data to determine whether the processes are data- or resource-limited. Resources, such as processing effort, memory capacity in various forms, and communication channels are always limited, but in many instances the quality of data may limit the processing performance. Understanding the allocation of resources is central to their analysis. Resource allocation also has a central role in Norman and Schallice's (1980) theory of the human information processing system. They state that attentional resources are used to add to, or decrease, the activation values of various schemas, resulting in appropriate actions. These resources, however, come to play only when the task is not sufficiently well specified or when some critical or dangerous situation is involved and autonomous, habitual processing is not possible.

Consistent with Craik and Lockhart's theory is the phenomenon Chase (1986) describes as the skilled memory effect. In the study of chess masters' information processing capabilities he concludes that chess masters possess a mental data base of up to

50,000 different configurations on the chess board and that they can recognize these patterns quickly. This familiarity of patterns reduces the time needed for processing the information and allows more effective chunking in the working memory. Also Schank's (1982) theory on dynamic memory stresses the importance of past experience in understanding new situations.

Klapp and Netick (1988) explain the better-than-expected performance of their subjects by proposing at least two systems of working memory that differ in resource composition, processing, and storage. They suggest that people performing complex tasks may be able to distribute their memory overloads across relatively independent subsystems of the working memory, thus increasing its total capacity. This capability can be attributed to both system design and training.

Vingelis, Schaeffer, Stringer, Gromelski, and Ahmed (1990) define controller tactical working memory in terms of functional requirements, contents, capacity, limitations, and organization. Functional requirements include attention and rehearsal, where rehearsal is necessary to maintain the contents of the working memory for the three to five minute tactical window. Contents include data such as aircraft callsign, altitude, airspeed, heading, type, and position as well as projected position, status, and possible conflicts. Contents also include other data about weather, navaid status, recent communications, and the like. Capacity is defined as seven plus or minus two items, following Miller's (1956) findings, and limitations are defined in terms of interference affecting the search and retrieval process between working and long-term memory. Finally, the working memory is organized hierarchically with the most important items at the top. This organization is heavily dependent on individual control techniques, procedures used, and training. Vingelis, et al. also suggest the need for some sort of chunking, based on the fact that the number of individual items in the working memory exceeds Miller's "magical" number of seven plus or minus two.

Human working memory is fairly well researched and understood, with perhaps the exception of the central executive. There is also general agreement in the literature reviewed about the functions and the structure of the working memory, as well as its limitations in terms of capacity and the rapid decay of items held in it. Working memory is well defined in the literature and it is not unusual to find block diagrams of the human memory system where working memory is depicted as an independent, separate entity located between sensory inputs and the long-term memory.

Dynamic memory. Dynamic memory, on the other hand, appears to be best defined in terms of circumstances. Situations where the flow of information is continuous, the information changes or is updated frequently, and a great number of variables are included, place considerable demands on a person's dynamic memory (Moray, 1986; Wickens, 1992). A feature of the dynamic memory is also the need for active management of the information held in it, including the prompt discarding of old and unimportant information (Hopkin, 1980).

Yntema (1963) performed a series of experiments on memory capacity under the above-mentioned circumstances. Subjects were asked to keep track of a large number of objects, each varying along certain attributes, which in turn would have a certain value. The results of these experiments suggest that the capacity of the running, or dynamic, memory is even smaller than that of the static working memory: the subjects would make mistakes while keeping track of only two or three things at once. Further, Yntema observed that performance was not improved even when the variables followed a certain regular and predictable pattern. However, performance was improved when the number of objects was reduced, even when the number of attributes remained the same.

Yntema's experiment is analogous with the tasks of air traffic controllers. In fact, the task in the experiment was modeled after an ATC situation (Yntema, 1963). However, the subjects in the actual experiment were tasked with remembering completely meaningless information, such as unrelated letters, shapes, colors, animal and food names, instead of flight data relevant to a realistic ATC situation. This may have affected the results and convey an overly pessimistic view of human capabilities.

Moray (1986) defines dynamic memory as keeping track of a great deal of information arriving in a continuous stream without a definite interval for recall. This definition also serves as an apt description of an air traffic control task. Consistent with Yntema's experiments, Moray concludes that observers viewing a time series are not capable of holding more than three items in their dynamic memory. Also, Wickens (1992) identifies running memory as memory handling random stimuli, where a different response is required for each stimulus or series of stimuli some time after they have occurred. According to Wickens, running memory is synonymous with dynamic memory. Baddeley's (1986) notion of the central executive of the working memory parallels the descriptions of dynamic memory as well. He suggests that the central executive acts as a supervisor or scheduler, controlling attention and sampling and integrating information from several different sources.

Air traffic controllers, however, seem to defy the paradigm of limited working and dynamic memory capacities. Moray (1986), although generally agreeing with Yntema's conclusion that the dynamic memory's capacity is only three items, notes that these results may have been due to the fact that the items presented to the subjects were random and meaningless to them. He had observed a significantly higher capacity of the dynamic memory among air traffic controllers and suggests that this may be due to the fact that by actively handling the flights, controllers in a sense generate the information to be kept in the dynamic memory. Based on Megaw and Richardson's (1979) experiment on visual scanning strategies, Moray also suggests viewing the gathering of information as, "a cumulative process, but whose outcome was the convolution of data acquisition function and a forgetting function" (p. 40-28).

Several authors (e.g., Broadbent, 1984; Elman, 1990; Garland and Stein 1991; Keane, 1987) emphasize the importance of the meaningfulness and contextuality of information. Air traffic controllers, for example, may be able to enhance their dynamic memory capacities simply by chunking information more effectively. Chunking is useful in two different ways: first, it helps to maintain information in the working memory longer, and second, it facilitates the transfer of information to the long-term memory for more permanent storage (Wickens, 1992). If information is meaningful, it can be encoded more effectively into larger chunks, which in turn allows more effective storage and retrieval strategies between the working and long-term memories. Dynamic memory appears to have a key role in both of these processes. Memory can also be enhanced by the intensity of the stimuli. Higher intensity and subsequently better memory trace can result from a strong emotional response to a stimulus, or from a physically intense stimulus, or if the stimulus evokes another, well established, memory with which it will be associated (Murray, 1984). Retention of boring material is possible only if it is rehearsed sufficiently.

Hopkin (1980) addresses the importance of forgetting as a part of managing the working memory. Given the highly dynamic environment of ATC and the rapid pace of information update, old information must be effectively dumped from the memory to make room for new, more critical information. This kind of active management appears to be characteristic of the dynamic memory.

In general, the available literature consistently stresses the importance of the meaningfulness of information. As Moray (1980) points out, the world is meaningful and has values for humans, and humans approach decisions with reasons, not merely responses. This implies that the dynamic memory might have a very important and central role as a facilitator of information transfer between working and long-term memories. Further, this emphasizes the importance of both experience, i.e., the knowledge base in the long-term memory, and the quality of information received (e.g., Broadbent, 1984). Quality of information in this context means that it can be rapidly and easily coded to match the information in the long-term memory (Keane, 1987).

The literature and the proposed role of the dynamic memory raise a question about the driving forces behind it. Sufficient workload and level of activity appear to have a definite effect on the performance of the dynamic memory. Also the multiple resources theory (Mane & Wickens, 1986) offers some insights in understanding the functions of the dynamic memory.

The work of Mane and Wickens concerns training situations, but their findings are applicable to performance in other tasks as well. They found that workload during learning and the difficulty of the task have significant implications on the learning performance. If the task is difficult, more resources will be allocated to its performance and it will be learned better. However, this is true only when the difficulty stems from the task to be learned. If the trainee has to perform other, secondary tasks not benefiting learning, resources will be deployed away from the learning situation, resulting in a negative impact on the learning performance. This suggests the importance of attention in the performance of the dynamic memory and maintenance of the controller's picture.

It may not be possible, however, to create a definite, modular representation of human memory, in which the dynamic memory would be separate from the long-term and working memories and the central processing system. This is clearly illustrated by Elman (1990), who points out the problems with sequential representations of memory. Further, according to Elman, "memory is neither passive nor a separate subsystem, but it is inextricably bound up with the rest of the processing mechanism where the input patterns are represented in the context of a given output function, varying from task to task" (p. 208). Also Broadbent (1984) seems to assign the functions of the dynamic memory to the abstract working memory and the central processing system of his "Maltese Cross" model of memory. Finally, Schank (1982) defines the entire human memory and information processing system as dynamic, as opposed to other, man-made, information storage and retrieval systems.

Dynamic memory is considerably harder to define than working memory. Its properties seem to be closer to those of a central executive rather than those of a temporary store of information, such as the working memory. Dynamic memory also appears to function as a highly integrated system within human memory, which would make it difficult to tap its functions through experimental designs.

The controller's picture. Memory plays a crucial role in the formation and maintenance of the internal representation, or mental model, of air traffic controllers' task. Controllers themselves refer to this internal representation as the "picture" As Elman (1990) points out, even simple models of memory networks have internal representations of many tasks, and these representations are implicit in various tasks. Moray (1986) emphasizes the importance of good mental models in controlling various systems, where the understanding of the dynamics and causality of the system leads to more efficient control. Obviously, this is essential for efficient ATC as well, where predictive behavior and open-loop control is of critical importance. Further, human behavior is goal-oriented, not merely stimulus-determined, and these are the basic qualities of mental models and human skills (Moray, 1980).

The air traffic controller's picture is fundamentally a mental model of the airspace architecture, layout of the runways at airports, rules and standard procedures regulating the conduct of flights, and positions, flight data, and performance characteristics of the aircraft operating within this system. Included in the picture are also numerous other factors relevant to the traffic situation, such as the weather, operational status of navigation aids and the ATC equipment, staffing, and sectorization within the facility, and possible irregularities within these components. The picture is highly dependent on the limitations set by the actual maneuvering space and the constraints of the airspace design. The bigger the maneuvering space, the more freedom controllers have in the choice of their strategy, and the more individual these strategies, the more varied the pictures will be. This kind of environment also requires a high degree of attention and flexibility. Consequently, with little maneuvering space the possible solutions for conflicts are more rigidly determined by the limitations of the airspace design, leaving little room for individual strategies. However, controllers can support their pictures by sets of predetermined procedures (Coeterier, 1971).

Endsley's definition (cited in Garland, Phillips, Tilden, and Wise, 1991) of situation awareness as "the perception of elements in the environment within a volume of time and space, their comprehension and meaning, and the projection of their states in the near future" (p. 5) summarizes the essence of air traffic control (ATC). In this context, the term "situation awareness" can be considered to be synonymous with the "picture." Controllers must keep track of several aircraft simultaneously, sort available information according to its importance, and prioritize their actions within constrained space and time. Furthermore, the situations change continuously, sometimes at a very rapid rate, making it difficult to judge the ultimate importance of the information.

It is important to note, however, that the bits of information controllers receive through displays and communication channels are hardly new to them. Most information is expected and it fits into the controller's mental model, or picture, immediately upon receipt, reducing processing requirements to the mere acknowledgment of the data. The secret of the sometimes astonishing mental performance of air traffic controllers lies in their picture and in the relevance of the incoming information to that picture.

Controllers seem to work on two mental levels simultaneously, with each level facilitating the functions of the other. Sperandio (1978) identifies these levels as a process of decision and a process of action. Preplanning, or the projection of aircraft trajectories into the future and subsequent decision-making, is the basis of controller performance. When the situations have been analyzed and planned ahead of time, monitoring the events actually taking place and acting upon them require little effort and attentional resources. The current situation is already familiar, freeing resources for further planning tasks.

Another important factor is the familiarity with the supporting structures, i.e., the airspace architecture, rules and standard procedures, and flight plan data. This kind of knowledge base puts the incoming information immediately in the right context, facilitating rapid processing, effective chunking, and good situation awareness. Controllers also build their own structures within the existing framework when working traffic. They create patterns that result in smooth and conflict-free traffic flows according to each situation. All this will become part of the controller's picture.

The patterns along which traffic is controlled vary extensively depending on many factors, e.g., weather and mix of traffic. These patterns are usually modified from a few relatively fixed patterns, which are determined by general directions of traffic flow, airway and navigation aid structures, and airport layouts. Experienced controllers are very familiar with these patterns, and modify them only as necessitated by a given situation. This suggests a definite skilled memory effect associated with air traffic controller performance. Garland and Stein (1991) observe that controllers do not necessarily process the information as thoroughly as would appear from their decisions. As in the case of chess masters (Chase, 1986), controllers may need very little information to recall a similar situation or pattern from their long-term memory and then use this information as a basis for their decisions. New experiences are interpreted in terms of old ones (Schank, 1982), and the importance of preexisting memory patterns in rapid information processing cannot be overemphasized.

As has been discussed before, controllers rely heavily on their experience and knowledge base in the formation of their picture. Controllers are also very conscious of their picture and understand and use mental imagery extensively in both radar and non-radar situations (Isaac, 1992). The picture, being a conscious part of the controller's mental model, exists in the working memory (Mogford, 1991), while more static models are stored in the long-term memory. The role of the dynamic memory as a manager of information flow between the working and long-term memories therefore becomes critical in the formation and maintenance of the picture.

Workload, dynamic memory, and the picture. Many pilots flying the most modern aircraft equipped with "glass cockpits" have reported deterioration of their flying skills as a result of increased automation. Increased automation of ATC may result in similar phenomena among controllers. Without direct involvement with traffic, controllers--especially younger ones--may never be able to develop the skilled data base in their long-term memories necessary for the efficiency of the working memory. Following Craik's and Lockhart's (1972) theory of levels of processing, even experienced controllers may find it difficult to exercise their dynamic memory capacities fully if the level of direct manipulation and interaction, and therefore the level of information processing, is reduced.

A significant number of incidents in ATC happen during periods of low traffic levels and limited workload. This is hardly surprising, as it is a well-known fact that human reliability deteriorates rapidly in tasks requiring continuous maintenance of attention over long periods of time without much overt action (Hopkin, 1982). This suggests an identifiable optimum workload for the best dynamic memory performance. It can be further speculated that this workload may be fairly high, resulting in concentrated attention on the task at hand and minimizing the susceptibility to external distractions.

Sperandio (1971, 1978) has observed controllers adapting to increased workload by changing their operating strategies. As the amount of traffic under their responsibility increases, controllers become selective of the information they process, and deal with only the most relevant variables associated with each individual flight. Furthermore, they begin to treat individual aircraft as links in a chain, whose characteristics remain rather stable. It can be argued that these kinds of more economical working strategies also result in better situation awareness. Controllers handling strings of aircraft rather than individual flights see the "big picture", and are able to better predict the effect of an individual flight to the traffic flow. This kind of highly structured handling of traffic also typically results in fewer conflict points to be monitored.

Krol (1971) concludes that air traffic controllers find their workload lighter when they are actively controlling an aircraft than when they merely monitor its track on radar. According to Moray (1980), this indicates the importance of prediction in reducing workload. When a controller has an aircraft under control she can predict its position and status many seconds into the future based on the commands she has issued, except for occasional aberrations. When only monitoring the flight paths of aircraft there is an element of uncertainty of the pilots' actions involved, resulting in a higher workload. This ability to predict future traffic situations and statii of the aircraft is the most critical element of the controller's picture.

There are several common control techniques that support the controllers' information processing and memory, and which result in improved situation awareness. Consistent with Sperandio's (1971, 1978) findings, controllers not only chunk information given to them, but literally chunk aircraft they must keep track of. One of the most common methods used by approach controllers is to arrange inbound aircraft on downwind, at the same altitude, at the same speed, and at sufficient distance apart in trail. Thus, instead of keeping track of many individual aircraft, the controller must keep track of a single string of aircraft, a string which behaves exactly as he has planned. When it is time to turn the aircraft on final, the controller simply takes one aircraft at a time from downwind as it approaches the turning point and gives it a heading for localizer interception and approach clearance. Anderson (1990) claims, that with these kinds of techniques, there is practically no limit to the number of aircraft a controller can handle.

Although the previous example is perhaps overly simplistic and applies to only a few situations, it nevertheless illustrates some strategies controllers have developed to counter information overloads. Indeed, Coeterier (1971) found that controllers begin to handle airplanes in groups of two or three when the number of planes to be handled exceeded six. This kind of chunking and reliance on predetermined procedures illustrates the importance of experience and dependence on patterns stored in long-term memory. The role of the controllers' dynamic memory in tapping this data base while constructing the picture in the working memory also contributes to this cognitive process.

Supervisory control vs. manual control. Increasing use of automation in the aviation industry has put more and more human operators in a position where they exercise supervisory control instead of manually controlling the processes. The extensive automation involved with the National Airspace System (NAS) Plan, for example, reserves for the human controller a role of system monitor, who is removed from tactical control decisions and active involvement with the traffic (Della Rocco, Manning, and Wing 1991; Simolunas and Bashinski, 1991). Supervisory control presents many problems as a result of fundamentally changing the role of the air traffic controller in the system as well as the controller's working methods. It is of utmost importance that the operator maintains an understanding of the underlying causal structures of the system. This will allow her to make more economical hypotheses and better predict the future status of the system (Moray, 1980). Further, keeping in direct touch with the physical process may be extremely important to the understanding of the process.

Taylor (1976) distinguishes between two explanatory models of behavior, the scientific, or cause-based explanations, and purposive, or reason-based ones. He argues that cause-based behavior is passive--things happening to people--whereas reason-based behavior refers to the actions of people, and that the latter is characteristic of human operators. Moray (1980) points out the meaningfulness and the values of the world to humans, and that world events are not simply stimuli to them but have a deeper meaning depending on their world view and value hierarchy.

Goal-oriented behavior is also the cornerstone of Schank's (1982) theory of dynamic memory (see also Kellerman, Broetzmann, Lim, and Kitao, 1982). Schank's theory utilizes Memory Organization Packets (MOPs) to explain the structures of the human memory system. MOPs are defined as "a set of scenes directed towards the achievement of a goal. A MOP always has one major scene whose goal is the essence or purpose of the events organized by the MOP" (p. 97). Another important feature of Schank's theory are Thematic Organization Points (TOPs). TOPs are the structures that represent abstract, domain-dependent, information and which enable the creation of new structures that coordinate or emphasize the abstract significance of a combination of episodes. TOPs also are goal-based. This suggests the importance of active planning for human performance in any systems control.

Wickens and Kessel (1979) also have demonstrated superior performance in error detection and corrective actions within the manual control mode, as compared to the automated mode. Wickens and Kessel's experiment consisted of a tracking task and they attribute the subjects' superior performance in the manual, or participatory, mode to the added proprioceptive information in this mode. They suggest that the inferior performance in the automatic mode can also be attributed to the loss of vigilance and wandering of focal attention. Finally, Wickens and Kessel argue that an active controller, having the opportunity to differentiate his own inputs to the system from disturbances acting upon it, will be able to construct a better internal model, resulting in better performance in a fault-detection task.

These concepts offer valuable insights into the world of air traffic controllers. The controllers' behavior is distinctively purposive and their environs, the airspace structure and the traffic situation, inarguably meaningful to them. Controllers do not merely react to aircraft appearing on their radar scopes, but they evaluate the information available to them, make hypotheses and plans, and then act upon them. "Plan your work and then work your plan" is standard advice ATC instructors worldwide give to novice controllers. Planning and prediction of outcomes also serve an important function in memory organization (Schank, 1982). Creating and following an elaborate plan to achieve some goal, people predict achieving that goal. It is important to have memories of the outcomes of these plans, including failed plans, to help predicting what will happen if the plan under consideration is used.

There is still very little information available about the optimum task allocation between controllers and automated systems. The problem with task allocation is not only related to the inherent capabilities of men and machines, but it is also related to the type of communication and interaction needed between them (Soede, Coeterier, and Stassen, 1971). In the time analysis of controllers tasks, Soede, et al. found evidence of possible bottlenecks that could be avoided by the use of automation. However, they are quick to point out that these may be typical human tasks which are not suited to computer handling.

Findings of Koriat, Ben-Zur, and Nussbaum (1990) may indicate certain advantages of manual over supervisory control. In a series of experiments Koriat, et al., were able to show that subject-performed tasks were better remembered than were their verbal instructions. Further, they found that this was heavily dependent on the encoding strategies employed by the subjects. It was apparent that when the subjects anticipated performing the instructions they encoded the information for future action, resulting in significantly better test performances. When the test mode (perform vs. recall) was different from that anticipated, the subjects' performance suffered. It is important to notice however, that if the subjects had anticipated a performance test but were given a recall test instead, the results were better than if the subjects had encoded the information for a recall test. This indicates that memory performance depends more heavily on the type of cue presented during learning than on the mode of report used in testing memory.

These results have some important implications for ATC. Controllers who actively control traffic and plan their future actions may have a superior picture of the overall situation compared to controllers who only monitor the traffic situation. This would be due to the differences in information encoding strategies as suggested by Koriat et al. (1990). Also, controllers exercising manual control may be able to better anticipate the "test mode", or the conditions under which they are required to use the information stored in their memory. After all, they have made the plan for their future actions themselves.

Koriat et al. suggest that the encoding of tasks for future performance may take advantage of the richness of the sensory and motor properties of the planned action, which enhances retention. Although controllers do not physically perform their actions but rather give verbal commands to pilots of the aircraft, it is important to note that controllers nevertheless refer to their planned actions as if they would tangibly "turn", "descend", or "slow down" an aircraft.

Conclusions. There appears to be an explicit interrelationship between the air traffic controller's picture, dynamic memory, and workload. The available literature consistently stresses the importance of the meaningfulness of information for efficient processing. This implies that dynamic memory might have a very important and central role as a facilitator of information transfer between the working and long-term memories. Further, this emphasizes the importance of both the experience, i.e., the knowledge base in the long-term memory, and the quality of information received. Quality of information implies that it can be easily and rapidly coded to match the information in the long-term memory.

Given these assumptions and the active nature of the dynamic memory, it is logical to conclude that active involvement with the task at hand is essential to support the dynamic memory. When air traffic controllers handle traffic, for example, they have an overall picture of the situation in which even the smallest bits of information are within a context, and therefore meaningful. One of the greatest dangers of automation is that the operator is removed so far from the situation that this contextuality is lost.

Purpose of the Study

Very little research has been done on human dynamic memory characteristics. Even less information is available on memory functions in operational environments. Given the pace of technological advancements in the aviation/aerospace industry and the trend towards more automation in ATC, it is of utmost importance to fully understand the characteristics and processes of controllers' dynamic memory. The system must be designed in such a way that human controllers will be able to exercise their best abilities and have a meaningful role within it. The purpose of this study is to investigate the effect of active and passive control of air traffic on air traffic controller dynamic memory. It is anticipated that active, manual control of air traffic will enhance the controller's dynamic memory performance while a passive monitoring of air traffic will have a negative effect.

Method

Subjects

The sample was selected from the population of undergraduate students at Embry-Riddle Aeronautical University in Daytona Beach, Florida, who were enrolled in the ATC minor. The subjects had successfully completed the required prerequisites, as well as the first two or three courses of the minor, and were on their third or fourth course, entitled Enroute/Terminal Air Traffic Control with Laboratory or Advanced Air Traffic Control Operations with Laboratory, respectively. Descriptions of the laboratory courses for the minor are provided in Appendix A. A total of 39 students were enrolled in these classes. The subjects participating in the actual experiment were selected from this population using a random number generator and a personal computer (PC). A total of 21 subjects participated in the experiment, the rest of the students acted as pseudo-pilots supplying air traffic data for the subjects.

Instruments

The instruments used in this study were an ATC radar simulator, two simulated scenarios, and two paper-and-pencil tests. The instruments were used in two separate experiments, with each subject participating in both.

Simulator. The radar simulator used was a Wesson International TRACON/Pro™ ATC training system. TRACON/Pro is a PC-based system featuring ATC radar workstations, pseudo-pilot stations, and a voice communication system between controllers and pseudo-pilots (dePutron and Warner, 1993). The simulated radar display includes primary aircraft returns, primary weather returns, mapping overlays, and secondary target data blocks. The operator may adjust the display by selecting the radar range, selecting and deselecting range rings, and off-centering the display. Paper flight strips were used. The functions of the simulator as well as the presentation of radar data on the display were realistic and consistent with current ATC practices.

Scenarios. The scenarios were created by the experimenter and they consisted of an airport with an overlaying airspace and a mix of departing and arriving traffic. The airspace used was replicated after Daytona Beach (DAB) airport and Airport Radar Service Area (ARSA), or class C airspace, with minor modifications. These modifications included redesigned standard instrument arrival routes (STAR) and standard instrument departures (SID) to allow highly autonomous operations of flights in the second experiment. The SIDs and STARs were designed to prevent any conflicts within the DAB ARSA. Complete descriptions of the SIDs and STARs are provided in Appendix B. All flights in the experiments were conducted according to instrument flight rules (IFR) and they included a representative sample of current commercial aircraft types.

Two scenarios were created. They involved the same number of aircraft; the aircraft types were similar with similar performance characteristics, and the runway-in-use was the same. The aircraft callsigns were changed in each scenario to prevent recall of the previous experiment. Both scenarios were about 30 minutes long and included ten departures and nine arrivals for a total of 19 aircraft. The flight plans of the aircraft involved in the scenarios are provided in Appendix C. In the first, manual scenario the subjects were tasked with vectoring the arriving aircraft for an instrument approach to DAB and directing the departing aircraft to the appropriate routes and altitudes. In the second, automated, scenario the aircraft followed the appropriate SIDs and STARs autonomously and the subjects were responsible for only monitoring the traffic for possible deviations from these routes.

Test. The subjects were tested on the retention of their mental picture of the current and future traffic situation. The test consisted of two parts, a recall and a prediction task. In the recall task the subjects were asked to plot the positions, callsigns, altitudes, cleared altitudes, airspeeds, headings, types, and routes of the aircraft on a paper copy of the radar map at the moment the simulation was interrupted. In the prediction task the subjects were asked to predict the values of the aforementioned attributes of the aircraft two minutes into the future on a paper copy of the radar map.

Design

The study consisted of two experiments, each subject participating in both. The subjects participated in the experiments in two groups. Group I participated in Experiment I (manual scenario) first and Experiment II (automated scenario) five days later; Group II participated in Experiment II first and Experiment I second.

The independent variable manipulated was the degree of manual control required in a simulated ATC scenario. The dependent variables were the accuracy of recall of the aircraft positions, callsigns, altitudes, cleared altitudes, headings, airspeeds, types, and routes. Possible extraneous variables included subject experience and level of proficiency, the traffic intensity and workload, the traffic mix and flow, and the subjects' familiarity with the scenario and degree of interference with the previous experiments.

Experiment I. The first experiment was approximately 30 minutes long and included ten departures and nine arrivals for a total of 19 aircraft. The number of aircraft was determined according to the desired duration and workload in the scenarios. The workload was to be high enough to require concentrated attention to the task, but sufficiently low to allow all the subjects to successfully complete the task with some room for unexpected events, such as missed approaches. To keep the scenarios similar, apart from the differences in working methods, the workload on the manual scenario dictated the number of aircraft in the automated scenario. The scenarios were first tried by the experimenter and another ATC instructor and then given to the ATC students as a routine simulator exercise where their performance was recorded. Based on these experiences, the necessary adjustments on the workload were made in the form of scheduling of the flights, changes in flight plans, and changes in aircraft types.

The subjects were tasked with vectoring the arriving aircraft for an instrument approach to DAB and directing the departing aircraft to the appropriate routes and altitudes. The aircraft entered the scenario in such a schedule that arriving aircraft could be vectored for approach the shortest way without need for sequencing and departing aircraft directed to their exit points in a similar manner. Descent and climb instructions as well as speed control were the controller's responsibility.

After about 20 minutes, in which time the subjects were estimated to have developed a complete picture of the traffic, the scenario was interrupted, the simulator paused, and the subjects were asked to turn their backs to the radar displays. The subjects then plotted from memory the aircraft positions at the moment of experiment interruption on a paper copy of the radar map overlay. The subjects also included all relevant attributes with the targets, such as the aircraft callsigns, altitudes, cleared altitudes, airspeeds, headings, types, and routes. After this, the subjects plotted the aircraft positions and flight data on another paper as predicted two minutes into the future from the moment of scenario interruption. The use of the first test sheet for reference in this task was allowed. The subjects were explicitly told to estimate, reason, or guess the requested information they were not able to remember, and the importance of marking all the attributes for all the targets was stressed.

Experiment II. The second experiment was similar to the first, except that the aircraft followed appropriate SIDs and STARs autonomously and the subjects were responsible for only monitoring the traffic for possible deviations from these routes. The pilots contacted the controller at the entry fix or immediately after departure and verified their STAR or SID. Climb, descent and adherence to speed restrictions as published were the pilots' responsibility and were programmed into the scenario. The aircraft were sequenced by a simulated flow control in such a manner that no conflicts would occur within the controller's area of responsibility. The subjects were only tasked with verification of a radar and radio contact upon the entry of the aircraft, issuance of an approach clearance to arriving traffic, and handoff and transfer of radio communications to the tower or center at appropriate points. The number of aircraft and the traffic mix in both experiments was the same.

Validity considerations. Subject experience and level of proficiency may have affected the data. The experimental design was validated in a pilot study using Full Performance Level (FPL) controllers from the Daytona Beach FAA facility as subjects. The data collected from this study also offered an opportunity to compare the performance of experienced, professional controllers with that of students. Subjects participating in the main experiment were on the last two courses of the ATC minor program, having successfully completed one or two laboratory courses using ATC simulators. All subjects were able to successfully control the traffic involved in the experimental scenarios.

The traffic mix and flow were such that they were realistic, provided for desired workload for the manual experiment, and enabled the use of automated sequencing in the automated experiment. For these reasons all flights were IFR and originated or terminated at the same runway at DAB. While the simulation included a total of 19 aircraft, a maximum of 10 was under the subjects' control at one time.

The subjects' familiarity with the scenarios and degree of recall of the previous experiments may have affected their performance in the experiments. To control these variables aircraft callsigns were changed in Experiment II, as well as some aircraft types. The types were changed within the same aircraft performance categories, so that the traffic flow was not affected. The two experiments were five days apart to minimize the effect of interference. To detect the possible effects of learning, familiarity with the scenarios, and the subjects' ability to predict simulation interruption and a test, the subjects participated in the experiments in two groups. Group I participated in Experiment I first and Experiment II five days later, Group II participated in Experiment II first and Experiment I second.

The experiment, although conducted in a laboratory, was highly realistic. This was due to the high fidelity of the radar simulator used and the use of real airspace and traffic mix. The naturalism of the scenarios was also validated in the pilot study.

The subjects had received an extensive amount of instruction and practice in ATC and radar procedures in the prerequisite courses of the program. The subjects had also been trained intensively in simulations involving the same airspace and similar traffic mix prior to the experiment. All subjects were able to successfully control the traffic involved.

Procedure

Subject training. The subjects were in the last two courses of a four-course ATC minor program. They had successfully completed two or three previous ATC courses, one or two of which had been laboratory courses using an ATC radar simulator. Additionally, the previous courses had utilized the same airspace and airport that were used in the experiment. Because air traffic controllers must possess detailed knowledge of the airspace/airport structure they work within to be able to successfully control traffic, the subjects had received intensive instruction before the experiment in similar conditions.

Pilot study. Prior to the experiment the design and the naturalism of the scenarios, as well as the workload in the manual experiment, were analyzed in the pilot study. The subjects in this study included the students, professional controllers from the Daytona Beach Air Traffic Control Tower (ATCT), and ATC instructors from ERAU. The four full performance level (FPL) controllers from Daytona Beach ATCT, who participated in the pilot study, generally corroborated the realism of both of the experimental scenarios and the simulator. Their only criticism concerned the design of the SIDs and STARs, which lacked some of the safeguards normally required by the FAA. Nonetheless, these imperfections did not affect the functionality of the procedures in the simulated environment. The subjects participated in one practice simulation in the automated mode to familiarize themselves with the procedures and working methods. However, at that time, they were not told about the real purpose of the simulation.

Subject briefing. The subjects received written and verbal instructions for each experiment. The subjects were not told the real purpose of the simulation nor were they told that the simulation would be interrupted and that they would be required to recall the traffic situation in a test. In the manual scenario the subjects were also not told that the traffic would enter the scenario optimally sequenced. They may, however, have been able to determine this by themselves.

In Experiment II the subjects also received a written and verbal briefing. They were told that the purpose of the simulation was to study the feasibility of a planned SID/STAR structure for DAB and that they would be required only to monitor the traffic flow to detect any deviations from these routes. The subjects were explicitly told not to intervene in the situation unless they detect a safety hazard. As in Experiment I the subjects were not told about the interruption of the simulation and the following test.

However, it was evident that during the second experiment (Experiment I for Group II and Experiment II for Group I) the subjects did expect a simulation interruption and a subsequent recall test. For this reason the two groups participated in the experiments in different order. Thus it was possible to determine whether possible active rehearsal in anticipation of the recall task had an effect on the results.

Conducting the experiment. The subjects participated in the experiments in groups. The experimenter had three assistants to oversee the experiment, interrupt the simulation, and administer the test. Two of the assistants supervised the pseudo-pilots and the experimenter and one assistant provided oversight on the subjects' performance in the experiment and administered the test. The subjects began the experiment as a normal training simulation. After about 20 minutes the simulation was paused and the subjects were asked to turn their backs to the radar displays and the flight progress strips. The subjects then were given the recall test. First, they plotted the aircraft and the relevant attributes on a paper copy of the sector at the moment the simulation was interrupted. After this, they were given another sector map and asked to predict the situation two minutes into the future. The pseudo-pilots copied the aircraft positions and their relevant attributes from their displays on a similar test sheet the subjects had for actual data.

After the subjects had completed the test, the simulation was continued for two minutes, the subjects controlling the traffic, after which the pseudo-pilots again copied the traffic situation from their displays. This procedure was identical in both experiments.

Data collection. The data were gathered using a paper-and-pencil test, in which the subjects were required to plot from memory the aircraft positions, callsigns, altitudes, cleared altitudes, airspeeds, headings, types, and routes on a paper copy of the radar map overlay. These results were then be compared to the actual situation, copied from the radar scopes by the pseudo-pilots. Deviations from the actual data were measured separately for each attribute, i.e., aircraft position, callsign, altitude, cleared altitude, heading, airspeed, type, and routing.

Results

General

Although the mean error in aircraft position was within reasonable limits (*M* = 4.2 nautical miles, *SD* = 3.7 in the manual experiment, *M* = 4.1 nautical miles, *SD* = 3.4 in the automated experiment) it was nevertheless large enough to make it difficult to match the responses on the subjects' test sheets with those on the comparison sheets from the pseudo-pilots. Matching the targets on the response sheets and determining the position error was further complicated by the fact that the recall of aircraft callsigns was very poor. Under these circumstances data was recorded following the assumption that positions and traffic patterns would be recalled better than callsigns, and in ambiguous cases the larger error was consequently marked under the callsign category. Hence, very large errors were recorded on aircraft callsigns and little data for analysis were obtained from that particular category.

The data collection was also complicated by the subjects' inability to provide the requested information they could not recall, resulting in a limited amount of data for analysis. The subjects' inability to use reasoning to determine aircraft positions or the requested attributes was evident from the fact that some subjects had marked targets well off areas of normal traffic flow and entry and exit points, as well as in areas where they should have not been. Some subjects also assigned contradictory values to the requested attributes on aircraft (e.g., a speed of 250 knots for a piston twin) which may reflect the inexperience of the subject. It was also surprising to notice that the FPL controllers, who participated in the pilot study, failed to mark many of the requested attributes for the targets recalled. Additionally, the pseudo-pilots on the pilot study failed to mark the actual aircraft headings on the key sheets and because there was no comparison data, no errors could be measured in this category. The percentage of responses for all subjects is given in Tables 1, 2, and 3.

Of the original eight attributes requested (i.e., the aircraft position, altitude, heading, airspeed, callsign, aircraft type, cleared altitude, and routing) four were deleted from the analysis. These were aircraft callsigns, aircraft types, cleared altitudes, and routes. Aircraft callsigns were dropped from the statistical analysis for reasons discussed above, i.e., too little data was obtained for analysis. The aircraft type category also yielded too little data for statistical analysis, with response percentages less than 10, and only a few correctly recalled types. Routes were dropped from analysis because the simple traffic patterns included only one destination for arriving aircraft and only two possible exit points for departing traffic. Furthermore, errors made in aircraft routes were reflected in errors in aircraft headings, i.e., an error of nearly 180 degrees in aircraft heading clearly indicated mistaken routing. Finally, cleared altitudes had to be eliminated from analysis because there was no comparison data. The pseudo-pilots failed to mark the aircraft's cleared altitudes on the control sheets representing actual situations and therefore it was not possible to determine errors made in that category.

Table 1

Mean percentage of responses for Group 1 in recall and prediction tasks by requested attributes (N = 11 on manual scenario, N = 10 on automated scenario)

Attribute	Recall task		Prediction task	
	Manual	Automated	Manual	Automated
Aircraft position	77.98 (*SD* = 24.42)	74.31 (*SD* = 16.47)	66.56 (*SD* = 20.89)	72.32 (*SD* = 25.47)
Aircraft altitude	57.55 (*SD* = 36.77)	59.94 (*SD* = 19.34)	47.18 (*SD* = 20.03)	54.52 (*SD* = 33.11)
Aircraft heading	42.54 (*SD* = 32.89)	38.89 (*SD* = 30.72)	25.63 (*SD* = 21.19)	43.38 (*SD* = 34.72)
Aircraft airspeed	45.20 (*SD* = 31.93)	55.00 (*SD* = 18.82)	22.72 (*SD* = 22.99)	45.47 (*SD* = 30.99
Aircraft callsign	71.52 (*SD* = 17.99)	63.20 (*SD* = 12.58)	- -	- -
Aircraft type	16.61 (*SD* = 21.64)	7.92 (*SD* = 13.95)	- -	- -
Aircraft route	- -	- -	- -	- -
Aircraft cleared altitude	- -	- -	- -	- -

Note. Percentages are calculated from the number of aircraft under subjects' control at the time of simulation interruption. *SD* = standard deviation.

Table 2

Mean percentage of responses for Group 2 in recall and prediction tasks by requested attributes (N = 7 on manual scenario, N = 9 on automated scenario)

Attribute	Recall task		Prediction task	
	Manual	Automated	Manual	Automated
Aircraft position	91.27 (*SD* = 8.48)	86.11 (*SD* = 11.60)	85.10 (*SD* = 13.44)	76.72 (*SD* = 17.28)
Aircraft altitude	80.55 (*SD* = 21.09)	60.49 (*SD* = 22.95)	70.14 (*SD* = 14.55)	54.76 (*SD* = 28.12)
Aircraft heading	36.51 (*SD* = 46.13)	16.05 (*SD* = 21.59)	20.88 (*SD* = 35.96)	8.16 (*SD* = 13.94)
Aircraft airspeed	50.23 (*SD* = 37.86)	25.93 (*SD* = 30.43)	30.32 (*SD* = 35.16)	17.72 (*SD* = 24.49
Aircraft callsign	70.39 (*SD* = 21.12)	52.22 (*SD* = 22.03)	- -	- -
Aircraft type	8.84 (*SD* = 15.16)	2.47 (*SD* = 4.90)	- -	- -
Aircraft route	- -	- -	- -	- -
Aircraft cleared altitude	- -	- -	- -	- -

Note. Percentages are calculated from the number of aircraft under subjects' control at the time of simulation interruption. *SD* = standard deviation.

Table 3

Mean percentage of responses for the FPL controllers in recall and prediction tasks by requested attributes (N = 4)

Attribute	Recall task		Prediction task	
	Manual	Automated	Manual	Automated
Aircraft position	75.11 (*SD* = 3.43)	69.88 (*SD* = 20.42)	66.36 (*SD* = 7.30)	59.28 (*SD* = 22.32)
Aircraft altitude	65.68 (*SD* = 13.33)	38.19 (*SD* = 27.81)	35.07 (*SD* = 25.08)	32.50 (*SD* = 27.27)
Aircraft heading	- -	- -	- -	- -
Aircraft airspeed	48.46 (*SD* = 33.26)	41.67 (*SD* = 27.78)	26.46 (*SD* = 26.25)	20.00 (*SD* = 15.15)
Aircraft callsign	67.80 (*SD* = 13.40)	52.14 (*SD* = 26.91)	- -	- -
Aircraft type	7.08 (*SD* = 9.46)	21.52 (*SD* = 20.83)	- -	- -
Aircraft route	- -	- -	- -	- -
Aircraft cleared altitude	- -	- -	- -	- -

Note. Percentages are calculated from the number of aircraft under subjects' control at the time of simulation interruption. *SD* = standard deviation.

Data Analysis

For the statistical analysis, targets which were not critical to the current traffic situation, albeit within the subjects' area of responsibility and on their radar scopes, were not included in the data analysis. These targets included departures already handed off to the next ATC unit or arrivals that had not yet been handed off to the subjects. Elimination of these targets was justified because they were not the immediate responsibility of the controllers and should have had minimal impact on picture development and immediate working memory processes. The results were consistent with this notion, with very large recall errors recorded for departures already handed off to the center and smaller recall errors recorded for targets close to the airport or in other critical phases of flight which required current tactical control. Also, those targets which had not been on the subjects' radar scopes at the time of simulation interruption, but which entered during the two-minute period the subjects were asked to predict, were eliminated from the analysis. The elimination of these targets was based on the fact that the subjects were denied the use of flight strips and other memory aids normally available to them aiding in the prediction of future situations.

The errors in aircraft position, altitude, heading, and airspeed were measured as absolute errors in nautical miles, feet, degrees, and knots, respectively. Each attribute was determined to be correct if it satisfied predetermined criteria. Recalled aircraft position was correct if it was within five nautical miles of the actual position, which is the International Civil Aviation Organization (ICAO) standard for radar separation. Aircraft altitude was determined correct if the error was within 1000 feet above or below the actual altitude, which is the ICAO standard for vertical separation. Aircraft heading recall values were correct if they were within ten degrees. Airspeed recall values were determined correct if they were within ten knots. Heading and airspeed limits were determined based on the significance of the error in the operational environment. The subjects' responses were categorized as either correct or incorrect according to these parameters for the analysis. The same criteria was used for both the recall task and the prediction task.

The categorization of responses as either correct or incorrect produced a series of percentages, i.e., per cent of correctly recalled or predicted positions, altitudes, headings, and airspeeds from the total number of aircraft under the subjects' control. Converting the dependent variable values to percentages provides uniform scoring for the different attributes which involve different units of measurement. Thus it was possible to also calculate a total, or combined, score for each subject for statistical analysis.

The data was analyzed using Statview 512+™ software. A two-factor repeated measures analysis of variance (ANOVA) was performed separately for the recall task and for the prediction tasks. Complete ANOVA tables are provided in Appendix D.

The results indicate that recall of aircraft heading was significantly better on the manual scenario ($M = 20.37$, $SD = 19.43$, $N = 18$) than on the automated scenario ($M = 9.50$, $SD = 7.69$, $N = 19$), $F(1, 15) = 8.278$, $p < .05$. The other attributes were not significantly different with respect to control condition. The combined score of all attributes revealed significantly better performance on manual mode ($M = 37.27$, $SD = 10.90$, $N = 18$) than on automated mode ($M = 31.13$, $SD = 8.25$, $N = 19$), $F(1, 15) = 5.03$,

$p < .05$. There was no significant difference between the groups, which suggests that the order in which the subjects participated on the experiments and other possible differences between the groups did not influence recall performance.

It was expected that active involvement with traffic would better facilitate planning and have a significant effect on the subjects' performance on the prediction task. It was, therefore, disappointing to find no statistically significant differences between the modes on the prediction task. The apparent difference between the groups in predicting the aircraft heading ($F(1, 15) = 10.69$, $p < .01$) is likely to be an extrinsic phenomenon and a result of the poor response rates on that attribute.

The results from the pilot study involving experienced controllers from the Daytona Beach FAA facility were analyzed separately. A repeated measures ANOVA performed on this data revealed no significant differences between the modes of the experimental scenarios. The complete ANOVA table is provided in Appendix E.

Discussion

The results of these experiments appear to raise more questions than they answer. Their interpretation is further complicated by the many unexpected events and phenomena encountered. The first, and most important, question is, however, whether the experimental design succeeded in its mission, i.e., did it measure the performance of the subjects' dynamic memory in a simulated environment?

In the test situation, every subject received a test sheet and was able to begin the task within one minute after the simulation was paused and they had turned their backs to the radar displays and flight strips. The subjects consistently marked the aircraft positions on the test sheets first, within a few seconds, and then filled out the rest of the requested attributes. After finishing the recall task the subjects completed another test sheet where they were requested to predict the situation two minutes into the future. It was not observed how much the subjects relied on their responses in the first, recall, task when doing the prediction task. All subjects were able to complete both test sheets in about ten minutes.

Based on these observations it can be argued that only the responses on target positions represent the performance of the subjects' working memories and the picture of the traffic situation, and that the memory traces and the picture on their working memories were completely lost by the time both tasks were completed. It can be further argued that the attributes for each target recalled were therefore probably retrieved from the long-term memory and do not illustrate the "goodness" of the picture in the working memory, and that the prediction task was completely based on reasoning.

However, long-term memory has an important role in supporting the picture in the working memory, and the performance of the dynamic memory must be judged by the performance of both long-term and working memories. Human memory generally functions as a highly integrated system, and it may not be possible to separate the functions and performance of the different subsystems in an experimental situation (Morris and Jones, 1990). Therefore, the time elapsed filling out the test sheets presumably was unimportant in testing the subjects' pictures.

In a pure memory test, the subjects generally should not be allowed to use any active rehearsal techniques to improve their memory unless this is part of the task. However, because air traffic controllers are aware of their picture and actively use available memory aids and mental imagery to support it (Isaac, 1992; Stein, 1989), conscious rehearsal in anticipation of a recall task would have little impact on the results. Therefore, the precautions against conscious rehearsal taken in these experiments by obscuring their real purpose from the subjects must be considered unfounded. This notion is further supported by the results, which show no significant differences between the subject groups despite the fact that the groups participated in the experiments in different order and the subjects did know about the recall task and expected it during the latter experiment.

The traffic situation in the experimental scenarios was not complex or difficult. This was confirmed also by the subjects who practiced on a similar scenario prior to the experiments and unanimously rated the workload as moderate. The traffic was scheduled in such a manner that all arriving aircraft could be vectored for an approach in the order they entered the airspace without any need for sequencing, and departures could be given direct routings to their respective exit points. In only a few cases an altitude restriction or a vector for a departing aircraft was necessary for separation. However, there was a considerable number of aircraft on the subjects' radar scopes at the time of simulation interruption (*M* = 10.2, *SD* = 1.3 in the manual scenario, *M* = 10.5, *SD* = 0.9 in the automated scenario), which, in retrospect, brought about a significant load on subjects' memories. This was probably reflected in the poor response rates.

There is evidence of a floor effect in the experiment. Even after all non-critical aircraft were excluded from the analysis, the results still show a considerable number of aircraft completely missed by the subjects (see tables 1, 2, and 3, aircraft positions). Of the aircraft recalled, the mean percentage of correctly recalled, i.e., the absolute position error was five nautical miles or less, was 57.2 (*SD* = 19.7) in the manual scenario and 58.2 (*SD* = 18.8) in the automated scenario. The floor effect becomes even more pronounced in other attribute categories, with deteriorating response rates and increasing errors in aircraft altitudes, headings, airspeeds, callsigns, and types. This phenomenon can be attributed to the heavy memory load, i.e., the number of aircraft on the subjects' radar scopes, their respective attributes, and the values of these attributes, but it can also be argued that the sheer magnitude of the task of writing all that information down on a paper had an effect on the results. A simpler test may have provided more complete responses and better data for analysis.

The poor response rates may, however, have important implications. The memories of the subjects, including the FPL controllers, clearly became overloaded in the experiment. It is also obvious that this overload was a result of the number of targets on the subjects' radar scopes, not the complexity of the situation or attentional demands, neither of which were particularly high. As the objective of automation in ATC is to maintain or decrease current staffing levels by increasing the size of sectors and enabling controllers to handle more aircraft at one time, the inevitable result of these plans seems to be the degradation of controllers' pictures.

If, then, the experiment, despite its shortcomings, did reliably measure the subjects' dynamic memory performance, were the results sufficient for a reasonable decision to accept or reject the hypothesis? The statistical analysis revealed a significantly better performance on the recall task and on the manual scenario on one attribute only, namely aircraft heading. Although there were no significant differences on performance on any other attributes, i.e., aircraft position, altitude, or airspeed when analyzed separately, analysis of the combined score again indicated significantly better performance in the manual mode. Higher expectations were placed on the prediction task, based on the assumption that the value of a good picture is in the ability it gives the controller to accurately predict future traffic situation. Therefore it was undeniably disappointing to find no significant difference in performance between the manual and automated scenarios.

Although the results inevitably hint that the original hypothesis is correct, they nevertheless provide an insufficient foundation for either acceptance or rejection of the hypothesis. This must be attributed to deficiencies in the experimental design. Several probable causes can be found for the lack of differences between the manual and automated scenarios. The substantial memory load and the subsequent floor effect may have compressed the distribution of responses in such a manner that the analysis was not able to reveal significant differences between the experimental scenarios. Also the presumably overwhelming task may have had a discouraging effect on the subjects, resulting in less than optimal performance in the task. This was observed during the experiment when several subjects would not mark the requested attributes despite repetitive prompting and encouragement by the experimenter to guess or to use reasoning in determining values for the missing attributes.

The highly dynamic terminal environment and the ATC operations within it are not innately suitable for automation. Therefore the design of the procedures and traffic patterns in the automated scenario were not genuinely representative of ATC operations in such an environment. After the practice session in the automated mode nearly all subjects reported a moderate workload during the simulation. This can be attributed to the fact that the situation was completely new to the subjects and very different from the usual classroom exercises, in which manual control is emphasized and little use is made of the existing SIDs and STARs. Thus, it can be concluded that the subjects felt high attentional demands having little confidence in the system and the scheduling of the traffic. During the pilot study it was observed that the FPL controllers had to restrain themselves from actively controlling traffic, implying distrust in the scheduling of flights and the pilots' compliance with the procedures. The controllers may have also experienced difficulties in assuming a passive role of a system monitor, which was contrary to their active working methods prevalent in their everyday work at DAB.

Given these considerations the contrast in working methods between the manual and automated scenarios may not have been as great as was planned. The potential loss of vigilance normally attributed with automated systems may not have been fully realized due to the newness of the situation to the subjects, who may have maintained their alertness in anticipation of deviations from standardized flight paths possibly resulting in conflicts. The subjects' comments on workload support these notions, the majority of them rating the workload equally high on both manual and automated scenarios.

Yet, the design appears inherently suitable for research of dynamic memory and the experiments that have been designed to tap its functions are remarkably similar to the tasks of air traffic controllers (e.g., Yntema, 1963). This is only logical, because memory is one of the primary mental tools of the air traffic controllers who have only a few, relatively simple, external aids available in their jobs to help them in ensuring the safe, orderly, and expeditious flow of air traffic. However, given the extreme complexity of air traffic controllers' working environments and the wide variety of demands placed on them, as well as the equally complex and highly integrated human memory system, it may not be possible to pinpoint the functions of any specific part of the controller's memory in a realistic experimental setting. On the other hand, experiments conducted in controlled laboratory conditions may not provide useful data for practical applications. This is lucidly illustrated by Moray (1980), who contrasts the properties of the world and the human operator with those of laboratory experiments. Research on controller memory in as realistic circumstances as possible is absolutely essential in order to determine the effects of automation on controllers' work and subsequently on the efficiency and safety of the entire ATC system.

Recommendations

Given the complexity of the controllers' picture, and the environment they work in, the experimental scenarios should be as realistic as possible. However, increasing realism also introduces a number of extraneous variables which may not be controllable in the experimental setting. The experimental design is, thus, a compromise between a realistic scenario providing for a full use of the controller's picture, and the possible effects of uncontrollable variables (e.g., variations in the traffic flow, either due to controller actions or due to external factors such as pilot performance and weather, and variability in individual working methods). This research also revealed the need for the development of research methodology and tests that tap the structures and functions of the operators' mental models in general, and air traffic controllers' pictures in particular.

It was encouraging to notice that, despite the shortcomings, the results showed at least the tendency that was initially expected. Therefore, further research must be considered and the following recommendations are offered:

1. A follow-up study should be done with a refined test for the retention of the subjects' pictures. Because the literature (e.g., Koriat, et al., 1990; Krol, 1971; Moray, 1980) consistently suggests that the value of a good picture is in the ability it gives the controller to accurately predict future traffic situations, only a prediction task appears

sufficient to test the effects of different working methods on the controllers' pictures. Eliminating the pure recall task would make the test simpler and allow the subjects to complete the task in a shorter time, which in turn would abate the effects of decay of the picture in the working memory. It also appears necessary to reduce the memory load on subjects by including fewer aircraft in the experimental scenarios and asking for prediction of fewer attributes, perhaps only four instead of eight.

2. The differences between the manual and the automated scenarios should be emphasized more than was established in these experiments. While the total number of aircraft and the traffic flow would be kept identical between the scenarios, the aircraft must not necessarily be optimally sequenced prior to entering the controller's airspace in the manual scenario. Thus a controller in the manual scenario would have to get involved in active decision-making about landing order, planning of optimal sequencing of both arriving and departing traffic, and optimal execution of the necessary actions. Contrasting the different working methods between the scenarios more explicitly would make the experimental design more realistic and presumably better reveal differences in subjects' pictures and in performance of their dynamic memories.

3. In any research, a good, valid definition of the topic must be considered essential. While there are several definitions of mental models and internal representations available, the controller's picture has not been particularly well defined. As the controllers' pictures are dependent on their specific working environments and individual working methods, it seems reasonable to expect broad individual variability in the composition and usage of the pictures. To define the controller's picture sufficiently for research purposes, a survey

should be conducted to assess how controllers themselves perceive their pictures, how do they use them in their work, and what do they think constitutes the formation and maintenance of a good picture of the traffic situation. A questionnaire appears to be a suitable tool for this. However, the questionnaire should be given to a large sample of controllers, including some outside the U.S., to determine the differences between different cultural environments, or similarities in the perception of the picture across cultural boundaries.

4. In the experimental research on operators' mental models, the tasks consistently bear remarkable similarities to those of the air traffic controllers in their everyday work. Therefore, simulation of operational ATC seems suitable for research of mental models and controllers' pictures. There may be, however, better ways of doing the actual testing for effects of various manipulations in the ATC environment on the controllers' pictures than was done in this research. Different tests need to be developed for use in different environments, i.e., for research conducted in laboratories and for research done in the operational environment. The data collected through the above-mentioned survey and the insights gained about controllers' pictures would serve as a starting point in the development of new research methodologies and testing techniques to tap the structure and functions of air traffic controllers' pictures and operator mental models in general.

5. The foundation of the air traffic controllers' pictures is their experience and the data bases in their long-term memories. Ideally, this type of research should use subject samples selected from the population of FPL controllers. It is important, however, that the experimental setting, if a laboratory, and the simulated scenario, be consistent with the

operations in the subjects' particular facility to fully exploit the skill and experience components of the picture. Given the presumably high individual variability among the subjects in their respective construct and usage of their pictures, the sample size must be sufficiently large for reliable results. The sample of four FPL controllers who participated in the pilot study of this research was too small for any explicit conclusions.

In the era of increasing automation and changing working environments, mental modeling is a ripe area for research. It is of utmost importance to fully understand the underlying determinants of human capabilities and performance in the ATC environment to make reasonable predictions on the effects of automation on the performance of the human controller and subsequently on the safety and efficiency of the entire ATC system.

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APPENDIX A

Course Descriptions of the Laboratory Courses in the Air Traffic Control Minor

AT365: Air Traffic Control Operations and Procedures

A basic course in the procedures and techniques used by air traffic controllers to ensure safe, orderly and expeditious flow of air traffic. This course will consist of both traditional classroom (lecture/discussion) work and performance-based instruction using an air traffic control radar simulator. The airspace used in the simulations will be a simple terminal airspace, represented by Daytona Beach (DAB) class C airspace.

AT462: Terminal Air Traffic Control With Laboratory

This course introduces students to air traffic control operations in a complex terminal environment. Orlando (MCO) terminal area (or class B airspace) will be used in simulated exercises. The airspace will be divided into departure, arrival, final control, and satellite airport sectors, familiarizing the students with methods of coordination and standard procedures used in busy terminal areas.

AT464: Advanced Air Traffic Control Operations With Laboratory

This course introduces students to air traffic control operations in a complex terminal and enroute environment. Orlando (MCO) terminal area (or class B airspace), Daytona Beach (DAB) class C airspace, and overlaying Jacksonville Center (ZJX) sectors will be used in simulated exercises. Students will be working a variety of positions in a realistic environment, much the same way they would in an FAA facility as operational Air Traffic Control Specialists.

APPENDIX B

Descriptions of the Standard Instrument Departures and the Standard Instrument Arrival Routes Used in the Experiment II

Standard Instrument Departure (SID) Routes

JET1N DEPARTURE (Turbojet and high-performance turboprop aircraft)
Climb on runway heading until passing 3,000 feet, then turn left, home on OMN VOR, cross OMN at or above 6,000 feet.

JET1S DEPARTURE (Turbojet and high-performance turboprop aircraft)
Climb on runway heading until passing 3,000 feet, then turn right, proceed direct to LAMMA intersection, cross LAMMA at or above 5,000 feet.

PROP1N DEPARTURE (Piston-engined aircraft)
After departure turn left, home on OMN VOR, cross OMN at or below 4,000 feet.

PROP1S DEPARTURE (Piston-engined aircraft)
After departure turn right, proceed direct to LAMMA intersection, cross LAMMA at or below 3,000 feet.

Standard Instrument Arrival (STAR) Routes

JETSO1 ARRIVAL (Turbojet and high-performance turboprop aircraft)
From JETSO intersection follow OMN VOR radial 360 inbound to OMN, cross COKES intersection (16 DME) at 10,000 feet, cross OMN at 5,000 feet. After passing OMN descend to 2,000 feet, reduce speed to 210 KTS IAS. Follow OMN radial 220 until 16 DME, then turn left to intercept LLZ DAB RWY 7L. Cross TOMOK at 1,600 ft at 170 KTS IAS.

SMYRA1 ARRIVAL
Cross SMYRA intersection at 4,000 feet. After passing SMYRA turn left, follow 16 DME arc from OMN VOR, descend to 2,000 feet and reduce speed to 210 KTS IAS. After crossing radial 210 from OMN turn right to intercept LLZ DAB RWY 7L. Cross TOMOK at 1,600 ft at 170 KTS IAS.

WORMS1 ARRIVAL
Cross WORMS intersection at 4,000 feet and at 210 KTS IAS. After crossing radial 215 from OMN VOR turn right to intercept LLZ DAB RWY 7L. Cross TOMOK at 1,600 ft at 170 KTS IAS.

APPENDIX C

Flight Plans of the Aircraft Involved in the Experimental Scenarios

Flight Plans: Experiment I (Manual Scenario)

Arriving Traffic

Entry time	*Callsign*	*Type*	*Route*
01:00	USA5211	B737	JETSO COKES OMN DAB
06:20	AAL1132	MD80	JETSO COKES OMN DAB
06:00	N721GD	C425	KIZER WORMS DAB
10:00	ASH7331	BA31	JETSO COKES OMN DAB
14:00	DAL3852	MD80	JETSO COKES OMN DAB
11:35	COM5542	SW3	KIZER WORMS DAB
16:05	COM4233	SW4	JETSO COKES OMN DAB
17:00	N744BS	PA42	KIZER WORMS DAB
19:30	N16GT	LR24	OAKIE SMYRA DAB

Departing Traffic

Entry time	*Callsign*	*Type*	*Route*
00:30	N428VR	LR24	LAMMA BITHO
03:00	DAL7311	B727	OMN ROYES MATEO
06:00	AAL4295	MD80	OMN ROYES MATEO
08:00	N527GL	C550	LAMMA BITHO
10:00	COA2321	DC9	OMN ROYES MATEO
12:00	N373EP	PA34	LAMMA BITHO
15:00	COM2344	E120	LAMMA BITHO
17:00	N772AP	PA31	OMN ROYES MATEO
19:00	AAL1125	MD80	OMN ROYES MATEO
23:00	N713LA	BE56	OMN CARRA

Flight Plans: Experiment II (Automated Scenario)

Arriving Traffic

Entry time	*Callsign*	*Type*	*Route*
01:00	COA4821	DC9	STAR JETSO1 DAB
06:20	USA821	B737	STAR JETSO1 DAB
06:00	N662PY	PA42	STAR WORMS1 DAB
10:00	COM5542	SF34	STAR JETSO1 DAB
14:00	AAL1211	MD80	STAR JETSO1 DAB
11:35	USE7521	E120	STAR WORMS1 DAB
16:05	COM5562	SW3	STAR JETSO1 DAB
17:00	N886TU	BE20	STAR WORMS1 DAB
20:30	N16GT	LR24	STAR SMYRA1 DAB

Departing Traffic

Entry time	*Callsign*	*Type*	*Route*
00:30	N562CC	C550	SID JET1S LAMMA BITHO
03:00	AAL1263	B757	SID JET1N ROYES MATEO
06:00	DAL1055	MD80	SID JET1N ROYES MATEO
08:00	N522PW	BE40	SID JET1S LAMMA BITHO
10:00	USA321	B737	SID JET1N ROYES MATEO
12:00	N336KP	PA34	SID PROP1S LAMMA BITHO
15:00	N995BA	LR24	SID JET1S LAMMA BITHO
17:00	N77261	PA31	SID PROP1N ROYES MATEO
19:00	DAL1155	B727	SID JET1N ROYES MATEO
23:00	N713LA	BE56	SID PROP1N CARRA

APPENDIX D

ANOVA Tables for Differences Between the Modes and the Groups

ANOVA table for a two-factor repeated measures ANOVA for difference between the modes and the groups: recall of the current traffic situation

Attribute	*F*-ratio		*p*	
	Mode	Group	Mode	Group
Aircraft position:	0.004	2.861	0.948	0.111
Aircraft altitude:	3.150	2.203	0.096	0.158
Aircraft heading:	8.278	0.454	0.011	0.511
Aircraft airspeed:	0.031	0.681	0.862	0.422
Total score:	4.602	1.158	0.049	0.299

ANOVA table for a two-factor repeated measures ANOVA for difference between the modes and the groups: predicted traffic situation

Attribute	*F*-ratio		*p*	
	Mode	Group	Mode	Group
Aircraft position:	0.031	2.041	0.862	0.174
Aircraft altitude:	0.110	0.456	0.746	0.510
Aircraft heading:	1.022	10.691	0.332	0.007
Aircraft airspeed:	0.123	0.072	0.731	0.792
Total score:	0.107	0.011	0.748	0.919

APPENDIX E

ANOVA Table for Difference Between the Modes in the Pilot Study

ANOVA table for a repeated measures ANOVA for differences between the modes on recalled and predicted traffic situation: the pilot study

Attribute	Recall task		Prediction task	
	F-ratio	*p*	*F*-ratio	*p*
Aircraft position:	0.001	0.984	0.129	0.754
Aircraft altitude:	0.220	0.685	2.231	0.267
Aircraft airspeed:	0.271	0.655	0.006	0.947
Total score:	0.485	0.558	0.116	0.765