technical note

The Complexity Construct in Air Traffic Control: A Review and Synthesis of the Literature

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16. Abstract

Air traffic control (ATC) operations are the primary activity of the National Airspace System. This report summarizes the literature on ATC operations which has identified factors related to ATC complexity. ATC complexity has two components: sector complexity and traffic complexity. A model is proposed to explain the relationship between ATC complexity factors and controller workload. This review summarizes ATC complexity factors identified in the literature and methods used to measure them. In addition, the literature on information display, controller cognitive strategies, and individual differences is addressed with respect to ATC complexity. Metrics used to assess complexity are described. Airspace factors that correlate with controller performance and workload are presented. Controller information processing strategies that change in response to workload are reviewed. It is concluded that further research should emphasize how to apply these factors to improve sector design techniques and manage controller workload.

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EXECUTIVE SUMMARY

The purpose of this review is to summarize the literature on air traffic control (ATC) complexity in U.S. National Airspace System operations. Literature was obtained through searches of the Psychological Literature, National Technical Information Service databases, Federal Aviation Administration Technical Center Library, Drexel University Library, and Psychological Information Library Service.

The first section of the report discusses ATC complexity and states that complexity accounts for a large proportion of controller workload. ATC complexity is defined as a multidimensional construct that includes static sector characteristics (sector complexity) and dynamic traffic patterns (traffic complexity). A model is proposed that relates ATC complexity to controller workload through a set of mediating factors, including equipment quality, individual differences, and cognitive strategies.

The report reviews papers concerning the definition and measurement of ATC complexity, both in the terminal and en route environments. A number of studies have demonstrated a link between ATC complexity and a criterion measure, such as controller workload.

The literature shows that a large number of sector and traffic characteristics can influence the controller's workload and task performance. Human performance variables which correlate with ATC complexity include control task duration, the number of operational errors, and the amount of controller communication.

The report considers literature focusing on the relationships between information display, human information processing, and ATC complexity. The way information is presented to the controller may affect how complexity is perceived. There is evidence that the processing of air traffic information changes as ATC complexity increases. With increased complexity, controllers use more economical control procedures to regulate their workload. Finally, literature relating to individual differences (such as age and skill level) and their relationships to ATC performance and sector complexity are reviewed. The findings are summarized in a series of tables at the end of each section.

It is concluded that considerable research has been conducted to identify a useful set of ATC complexity factors. While work to identify additional factors would be useful, it is recommended that the next phase of research in this area be focused on the determination of how these factors affect ATC complexity and controller workload. This work, in turn, could allow the creation of guidelines that will improve control over sector configuration and traffic flow, leading to more manageable sectors. Finally, research on the effects of complexity could help direct work on automation tools and procedures to reduce controller workload.

1. INTRODUCTION.

Air traffic control (ATC) operations are the primary activity of the National Airspace System (NAS). NAS facilities exist to support commercial, private, and military use of aircraft in the United States. The goals of the NAS are safety of flight, expeditious movement of aircraft, and efficient operation (Holmes, 1982).

Safety of flight is of paramount concern. Studies that have examined potential future scenarios for the ATC system stated that if present day practices continued through the next two decades, system performance and safety will degrade (Wesson, Solomon, Steeb, Thorndyke, & Wescourt, 1981). There are a number of sources of potential problems including controller and pilot errors and equipment malfunction. Controller errors can be the result of inadequate coordination between sectors, poor communication, and mistakes in controller judgment (Wesson, et al., 1981). It is expected that the number of errors will increase with the higher air traffic load projected for the late 1990's and thereafter.

Hearings before the Committee on Public Works and Transportation indicated that sector configuration is a major contributor to controller workload (General Accounting Office [GAO], 1986). The results of a GAO report concerning "Serious Problems in the Air Traffic Control Work Force" indicated that 45 percent of Air Route Traffic Control Center (ARTCC) supervisors and 33 percent of Terminal Radar Approach Control (TRACON) supervisors reported that sector configuration was a major reason why controllers were handling more traffic than they should.

There is considerable agreement among aviation experts about the continued growth of civil aviation and the increased demand for ATC services. One method presently used to accommodate growth in the system is to redesign sectors to become smaller, thereby reducing the amount of traffic in each sector (Holmes, 1982). This practice is not very cost effective as it requires additional controllers to handle the sectors, more equipment to display sector information, and an increased amount of coordination between aircraft and ATC. Adding to the number of sectors also increases the requirements for coordination between controllers. The strategy of creating smaller sectors to reduce traffic volume becomes self-defeating when the coordination workload exceeds the reduction in workload of other kinds (Hopkin, 1982).

Given the present situation and the projected increase in traffic flow over the next ten years, a comprehensive understanding of the factors that create complexity in ATC is needed. Improvements in sector design could yield substantial cost savings since more than 50 percent of recurring system cost is directly related to the number of operating sectors (Arad, 1964). Any reduction in the number of sectors will reduce the total amount of sector-related equipment, yield better frequency management, reduce the amount of communication between controllers, and reduce cockpit workload.

1.1 PURPOSE.

The purpose of this review is to define the concept of complexity in ATC and summarize the literature, focusing on specific studies that identify the factors contributing to ATC complexity. Particular attention is given to the measurement of complexity and its affect on controller workload.

1.2 METHOD.

References were found through searches of government and non-government databases, the Psychological Literature (PSYCHLIT) database, and the National Technical Information Service (NTIS) database. Literature was obtained from the Federal Aviation Administration (FAA) Technical Center Library, Drexel University Library, and from the Psychological Information (PsychINFO) Library service. Emphasis was placed on obtaining the most recent literature directly related to ATC. Both the PSYCHLIT and NTIS searches were conducted on articles published between 1985 and 1992. A large number of articles published before 1985 was available from previous literature reviews completed by CTA. Article summaries are presented at a level of detail consistent with the goals of this report.

The research material reviewed here primarily refers to the en route ATC environment. However, a few authors focused on terminal operations when considering factors related to ATC complexity or workload. In addition, the papers cover a wide time span during which significant technological changes were made in ATC automation. The reader should be aware that the context (in terms of both airspace and time period) in which the original research was accomplished, will have a bearing on the type and weighting of identified ATC complexity factors. Nevertheless, the reviewers have included this range of sources in order to provide a thorough review of potential complexity factors. It is suggested that the reader interprets the material presented here according to the application at hand. The factors and variables listed are not meant to be a definitive or prescriptive list, but a range of possible concepts that could be used to study ATC issues. In this sense, it was felt that it would be more beneficial to include a variety of sources as opposed to restricting the survey to specific environments or technologies.

2. DEFINITIONS OF ATC AND SECTOR COMPLEXITY.

There exists some vagueness in the use of the terms complexity, sector complexity, and traffic complexity when discussing ATC. The terms are sometimes used interchangeably, resulting in confusion when attempting to review literature in this field and when undertaking new research projects. An example of this problem with terminology is found in how the FAA defines sector complexity. It is the number of arrivals, departures, en route aircraft, emergencies, special flights, and coordination associated with a sector (FAA, 1984). This definition includes both sector and traffic features.

Grossberg (1989) made a useful distinction between the attributes of a sector and their effect on the controller. He defined complexity as a construct that has both dynamic and static characteristics that affect the rate at which controller workload increases. Controller workload is the activities, both mental and physical, which result from handling air traffic.

A construct is a process which is not directly observable, but gives rise to measurable phenomena (Reber, 1985). This approach emphasizes that, although there may be objective, measurable features of sectors and aircraft, the concept of ATC complexity is subjectively defined by the controller. It is developed from the controller's perception of and interaction with the sector and the air traffic within it.

Based on the literature reviewed, ATC complexity is defined as a construct that is composed of a number of sector and traffic complexity dimensions or factors. These factors can be physical aspects of the sector, such as size or airway configuration, or factors relating to the movement of air traffic through the airspace, such as number of climbing and descending flights. Some factors cover both sector and traffic issues, such as required procedures and functions (Mogford, Murphy, Yastrop, Guttman, and Roske-Hofstrand, 1993).

In this review, the term ATC complexity will refer to the effect on the controller of the complexity of the airspace <u>and</u> the air traffic flying within it. In theory, the structure of a sector is separate from the characteristics of the air traffic. However, when considering ATC complexity, it is not useful to separate these concepts and consider them in isolation.

A certain constellation of sector features might be easy to handle with low traffic volume or certain types of flight plans. More or different traffic might completely change this picture. When there is no traffic in the sector, there is no complexity. (At least, there is no effect on the controller.)

On the other hand, a given level of traffic density and aircraft characteristics may create more or less complexity depending on the structure of the sector. Traffic density alone does not define ATC complexity, but it is one of the variables that influences complexity and so is a component of complexity. Its contribution to ATC complexity partially depends on the features of the sector. Sector and traffic complexity interact to produce ATC complexity.

ATC complexity generates controller workload. Studies have defined several complexity factors that are positively correlated with controller workload or operational errors (Grossberg, 1989; Schmidt, 1976; Hurst & Rose, 1978; Stein, 1985; Stager, Hameluck, and Jubis, 1989).

Schmidt (1976) defined workload or control difficulty as related to the frequency of occurrence of events which require decisions to be made and actions to be taken by the controller team (p. 531). Jolitz (1965) (discussing work by Arad, 1963) used the term Dynamic Element of Load (DEL) to describe "the load imposed by one standard aircraft over-flying the sector area in a straight and level flight for one hour" (p. 2).

Jolitz (1965) divided load into three categories: background, routine, and airspace. Background load is the load associated with basic monitoring of the radar screen whether or not there is traffic in the sector. Routine load is the work of controlling a "standard aircraft following a straight and level over-flight when no interaction with other aircraft is considered. Finally, airspace load is the work of keeping aircraft separated in accordance with the separation standards.

It is the thesis of this review that controller workload is also a construct and is influenced by four factors. The primary element consists of a constellation of ATC complexity factors. Secondary components (acting as mediating factors) include the cognitive strategies the controller uses to process air traffic information, the quality of the equipment (including the computer-human interface), and individual differences (such as age and amount of experience). Figure 1 illustrates a proposed model of controller workload.

As indicated in the figure, controller workload originates from the sector and the aircraft within it. The procedures required in the sector, flight plans of the aircraft, traffic load, weather, and other variables form the basis for the tasks the controller must complete. This discussion employs the term "ATC complexity" to describe these elements.

The amount of workload experienced by the controller also may be modulated by the information processing strategies adopted to accomplish required tasks. Such techniques may have been learned in developmental training or evolved on-the-job and may vary in effectiveness. The influence of a complex ATC environment on workload can be ameliorated through the use of strategies that will maintain safety through, for example, simpler or more precise actions.

Also relevant to ATC is the effect of equipment on workload. The controller's job may be made easier if a good user interface and useful automation tools are available. This will ensure that adequate and accurate information is presented to the controller to allow for effective task completion.

Workload can also be influenced by personal variables, such as age, proneness to anxiety, and amount of experience. Variations in skill between controllers can be quite pronounced. These factors can have a strong effect on the workload experienced by a given controller in response to a specific array of ATC complexity factors.

3. ATC COMPLEXITY FACTORS AND MEASUREMENT.

The FAA described a method for calculating complexity workload in FAA Order 7210.46, "Establishment and Validation of En Route Sectors." The purpose of this order is to provide standardized criteria for the purpose of establishing and validating en route sectors for ARTCCs. Complexity workload is measured in terms of a formula consisting of counts of number of arrivals, departures, en route aircraft (requiring control function), emergencies, special flights, en route aircraft (not requiring control function), and coordination.

Counts are made for the peak traffic hour for the 90th percentile busiest day for the sector of interest. The count for each item during the peak traffic hour is multiplied by a weighting factor. The weighted sum of the counts is totaled to arrive at a complexity score for the particular sector. (A form used for computation of the complexity workload formula is found in the appendix.)

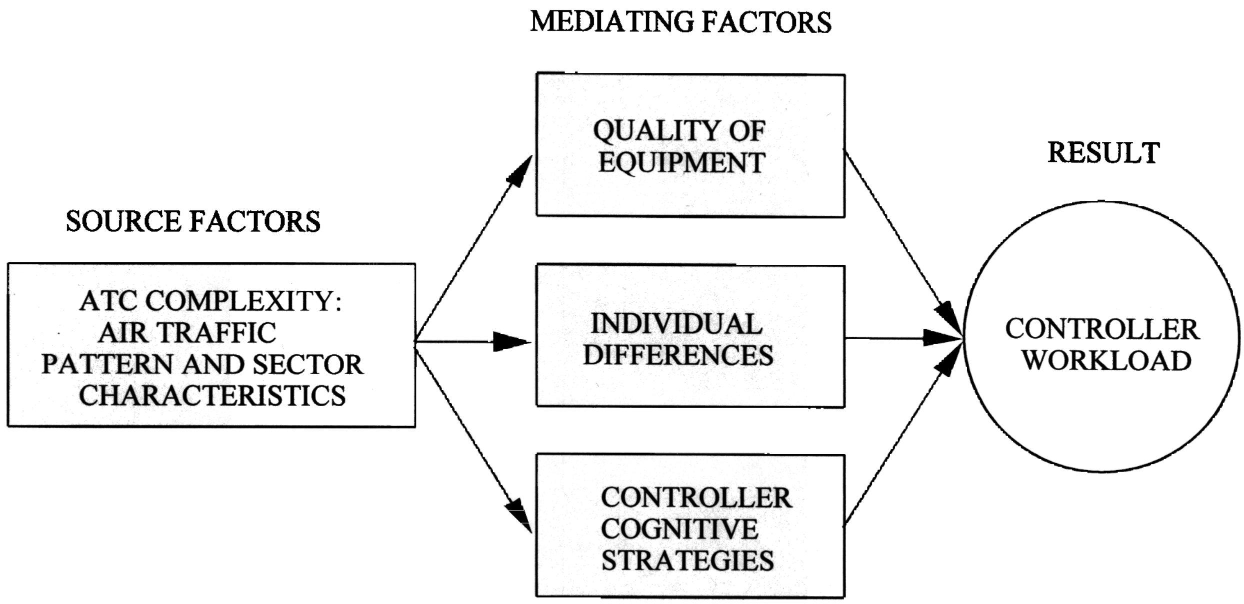

FIGURE FACTORS AFFECTING CONTROLLER WORKLOAD

A measure of traffic density is also calculated separately for each sector. Other factors such as requirements for multiple control functions in order to maintain separation, limitations of radar and radio coverage, and military activities are mentioned as considerations in validating a sector. However, they are not included in the computation of complexity workload, perhaps due to the difficulty in measuring the workload associated with these variables in a standardized fashion.

A number of studies have been completed which examined the effects of ATC complexity variables on controller workload, performance, and operational errors (Davis, Danaher, and Fischl, 1963; Kuhar, Gavel, and Moreland, 1976; Buckley, DeBaryshe, Hitchner, and Kohn (1983); Arad, 1964; Arad, Golden, Grambart, Mayfield, and Van Saun, 1963; Jolitz, 1965; Soede, Coeterier, and Stassen, 1971; Schmidt, 1976; Stein, 1985; Hurst and Rose, 1978; Grossberg, 1989; Mogford, et al., 1993). These studies vary widely in the approaches used to assess complexity, the factors associated with ATC complexity, and measurement techniques. The goal of this section of the report is to document the factors reported by these authors and compare the methods used to measure and assess complexity.

Davis, et al. (1963) examined three factors thought to be related to ATC complexity for approach control. Two radar controllers shared a 22-inch radar display which presented two simulated approach control sectors. The independent variables included traffic density, traffic mixture (arriving and departing versus overflying traffic), and number of airport terminals.
Traffic density was varied at four levels (50, 65, 85, or 100 percent) ranging from very light to near saturation. Traffic densities were based on the actual densities of the approach control sectors being simulated (Great Falls ARTCC). Complexity with respect to the proportion of arriving and departing to overflying traffic was varied at three levels (30, 50 and 70 percent). The last variable was number of airport terminals; one and two terminal configurations were used.

Davis, et al. (1963) found that the total time the controller spent in control activities, manual operations, and communication time increased as a function of traffic density. The results showed that controller communication and the amount of routine relay information was significantly higher in the 70 percent versus the 30 percent arriving and departing traffic condition. Workload (amount of time the controller was active, time spent in communication activities, and amount of time spent in manual operations), was not affected by the number of airport terminals.

Kuhar, et al. (1976) identified 25 measurable workload indicators used to assess the impact of the Automated Radar Terminal System (ARTS) III upon ATC system productivity and capacity. Some of the indicators were: average sector flight time, control type messages, coordination and flight data activity, other communications (i.e., direct oral and visual coordination requirements), flight strip activity, equipment adjustment type activity, and keypad activity. In addition to the workload indicators, other relevant information, including traffic volume and distribution, staffing, weather conditions, airport and equipment operational status, and pace ratings (a qualitative assessment of the controller's amount of activity) were also recorded.

The analyses of the workload data showed an increase in productivity and capacity due to the implementation of the ARTS III. The air traffic controllers handled a greater number of aircraft at the same work pace in the ARTS III environment than in the pre-ARTS system.

Buckley, et al. (1983) performed two experiments to assess the feasibility of using dynamic real-time simulation procedures for ATC systems. The purpose of the work was "to determine the quality of measurement of system performance and statistical treatment that is possible and appropriate in dynamic simulation of air traffic control systems" (p. 1). The studies identified the important basic dimensions for measuring ATC functions in real time dynamic simulations. Of interest to the topic of ATC complexity is that Buckley, et al. (1983) addressed the issue of the interaction of sector geometry and traffic density on various performance measures.

The first experiment examined the effects on system performance measurements of two en route sector geometries and three traffic levels ranging from very light to very heavy. Data were collected from two 1-hour runs for each of 31 controllers. The results of this experiment led the researchers to conduct a much less complex experiment using only one of the possible six combinations of conditions of sector and geometry. This second experiment examined the effects of replication and provided a sufficient amount of data to enable the completion of a factor analysis. Twelve 1-hour runs were conducted using the same sector with the same traffic level for each of 39 controllers.

One of the results of the first experiment was a statistically significant effect of sector geometry and traffic density on almost all of the ten performance measures. There was also a significant interaction effect between geometry and density. The authors suggest that "Sector [geometry] and [traffic] density are, as expected, important factors in determining the results which will occur in a given experiment, but they interact in a complex way. The nature and extent of this interaction depend upon the measures involved" (p. 73).

This finding supports the assumption discussed earlier that static sector characteristics and traffic patterns cannot be considered independently when examining ATC complexity. They interact to produce complexity and workload.

The data resulting from Buckley, et al.'s (1983) first experiment were cross-validated with the factor analysis derived from the second experiment. This yielded four operationally meaningful factors or measures: confliction, occupancy, communication, and delay. The confliction factor included measures of three-, four-, and five-mile conflicts. The occupancy factor included measures of the time an aircraft was under control, distance flown under control, fuel consumption under control, and time within boundary. The communications factor included path changes, number of ground-to-air communications, and the duration of ground-to-air communications. The delay factor included total number of delays and total delay times. Two auxiliary measures, number of aircraft handled and fuel consumption, were also relevant.

The cross-validation of the repeatability and dependability of the measurements proved to be reasonably successful. Buckley, et al. (1983) advised that the smaller set of data used in the second experiment could be used without a major loss in measurement accuracy and with a corresponding increase in the interpretability of the results. This set of measurements provided a statistically adequate, equivalent set of variables for all of the sector geometry and traffic density combinations used in the first experiment.

Arad (1964) conducted an analytical and empirical study of workload in relation to sector design. As defined previously, Arad divided controller workload into three categories: the background load of the controller, the routine load of controlling a standard aircraft, and the airspace load imposed by separation criteria.

Measurement of load was accomplished by calculating DEL. This was defined by the amount of work generated in one hour by a standard aircraft over-flying a sector when no interaction with other aircraft was considered.

Since all aircraft and controller interactions with aircraft are not standard, Arad conducted field studies in 13 ARTCCs to derive traffic features and measure their difficulty. These factors included: aircraft that had to be handed-off vertically, aircraft that had to be handed off to a terminal area, climbing and descending aircraft, and pop-up aircraft that required impromptu admission to the Instrument Flight Rules (IFR) system.

Airspace load took into account the constraints of the separation rules under which the controller had to work. Arad defined an equation for airspace load which incorporated the rules of separation in terms of nautical miles per aircraft (a), the average speed of the air traffic (V), the number of aircraft under control (N), the size of the sector (S), and the flow organization (g).

$$\text{Airspace Load} = 2aVN^2 / gS$$

Theoretically, this equation predicts the number of conflicts in the sector. Examination of the equation leads to the conclusion that increases in separation standards, speeds, or number of aircraft would increase the number of conflicts. Likewise, a smaller sector or tighter flow organization would also increase the number of conflicts.

This mathematical model did not specify any limits to the load equation. However, Arad, et al. (1963) considered the treatment of very low traffic activity to be irrelevant since the loads imposed were below sensitivity levels. On the other hand, they suggested that very high traffic activity generated additional and very complex load components not accounted for by the load equation. Therefore, the researchers' interests were within prescribed limits of traffic activity that were considered practical for each sector.

Jolitz (1965) reported a study where he investigated the relationship between the predictions of a mathematical model that calculated DEL (the sum of routine and airspace load) and controllers' judgment of workload. He was also interested in evaluating the routine load, and the number of aircraft handled per hour as predictors of workload. Using data from 16 sectors from 5 ARTCCs, he concluded that the mathematical model was not a good predictor of controllers' judgment about workload. Jolitz (1965) stated, "The mathematical model predicts the mean of controllers' judgment of load less accurately than an equivalent of the number of aircraft handled per hour, but more accurately than the routine load component of the mathematical model" (p. 63).

Soede, et al. (1971) conducted a correlational study where they analyzed the types of tasks required of approach controllers and their relationship with ATC parameters. For 134 flights, the performance of an approach controller was recorded by measuring the times for selected task components. These times were correlated with counts of airspace parameters. The ATC tasks included: time between receiving a flight strip and the first call to an aircraft, duration of the first call to an aircraft, duration of transfer of communication to the tower frequency, tasks associated with a conflict situation, and number of communications.

The airspace parameters were: the number of communications with other aircraft, the number of communications with other sectors, the number of path changes in inbound traffic (arrivals), the number of path changes in outbound traffic (departures), and the speed of aircraft recorded in the airway.

The results indicated that the greater the number of communications with aircraft, the longer it took the controller to transfer an aircraft to the tower frequency. Secondly, the presence of conflicts in a sector was related to the number of internal communications with other sectors. Lastly, the number of path changes in arrivals was related to the time between the receipt of an aircraft flight strip and the first call to that aircraft. Communication, conflicts, and path changes could be considered complexity factors based on their positive correlation with variables related to controller task loading.

Schmidt (1976) described a sector workload model intended to aid in the design and evaluation of airspace. The author defined ATC workload as the frequency of events which required decisions to be made, the actions taken by the controller or controller team, and the time required to accomplish the tasks associated with these events. Event categories included: potential conflicts between aircraft at air route intersections, potential aircraft-overtaking conflicts along air routes, and routine procedural events.

The technique Schmidt used to measure complexity was called the Control Difficulty Index (CDI). This index was calculated by multiplying a weighting factor (based on the task execution time) by the expected number of events occurring per hour. The CDI is expressed as:

$$CDI = \sum_{i} W_i E_i$$

where:

CDI = control difficulty index;

W_i = the weighting for event i (based on task execution time); and

E_i = the expected number of type i events per hour.

Schmidt (1976) conducted field surveys to determine the relative difficulty of processing the events used in the calculation of the CDI. Examples of events included controller hand-offs, coordination between controllers, and pilot requests. Schmidt conducted structured interviews and video tape recordings, and made direct measurement of factors, when feasible, to calculate the weighting factors. Some of the types of events (in order of difficulty) included:

a. preventing a crossing conflict;
b. preventing an overtake conflict;
c. handoff;
d. pointout;
e. coordination with other controllers;
f. pilot requests; and
g. traffic structuring.

Stein (1985) conducted a simulation to determine the relationship between a number of airspace factors and controller workload. Workload was measured by the Air Traffic Workload Input Technique (ATWIT) in which the controller pressed 1 of 10 buttons on a console with 1 representing low workload and 10 representing high workload.

Ten air traffic controllers participated in a series of one-hour simulations. Subjects experienced a low, moderate, or high task load as defined by the number of aircraft in a sector and the clustering of aircraft in a small amount of sector airspace. Controller input to the ATWIT was performed once per minute. Stepwise regressions were done using ATWIT scores as a criterion measure. Four airspace variables produced a multiple correlation of $R = .85$ with the workload measure. These were (in order of entrance into the stepwise regression equation) clustering of aircraft in a small amount of sector airspace, number of hand-offs outbound, total number of flights handled, and number of hand-offs inbound.

The study demonstrated a strong relationship between controller workload and a subset of airspace variables. In addition, controllers were able to provide real-time workload estimates using the ATWIT without any noticeable decrement in performance. Workload was best predicted through a multivariate combination of airspace variables.

Hurst and Rose (1978) studied sector workload and job difficulty in both the New York and Boston ARTCCs. Controllers were rated according to their behavioral response via pace ratings. Pace ratings involved experts rating the pace or degree of activity and behavioral arousal of 47 controllers working radar sectors (Kuhar et al. 1976). Modified control load factors based on Arad's (1964) work were also calculated for each sector for a one-hour period (the hypothesis being that control load factors would act as behavioral stressors). In addition, traffic counts, communication times, and other objective parameters were measured for each sector. It was found that pace ratings were positively correlated with hourly traffic ($r = .49$) and peak traffic counts ($r = .70$). The study failed to show any relationship between Arad's control factors and pace ratings.

Grossberg (1989) found a statistically significant relationship between sector complexity, as defined by FAA Order 7210.46, and operational errors at the Chicago ARTCC. Operational errors occur when two or more controlled aircraft violate the separation standard and the cause is attributed to ATC. The relationship was statistically reliable, but was low in magnitude. This provided impetus for obtaining more information on factors that affect sector complexity.

Ninety-seven controllers rated the degree to which 12 factors contributed to the difficulty or complexity of operations in their particular sector or area of specialization. The complexity factors most frequently cited in the Chicago ARTCC included: control adjustments involved in merging and spacing aircraft, climbing and descending aircraft flight paths, mixture of aircraft types, frequent coordination, and heavy traffic.

Grossberg combined the factors with the four highest ratings to form a complexity index. He found that this index was correlated with the number of operational errors found in sectors in the Chicago ARTCC. Data were collected for 21 months in 1987 and 1988. The complexity index was highly correlated ($r = .74$) with operational errors. Correlations between the standard FAA formula and the same operational error database correlations were not as high ($r = .44$). The results of this study implied that a better predictive measure of controller error could be developed than the standard measure currently being used to evaluate sector complexity.

Mogford et al. (1993) conducted a study to examine the cognitive processes associated with ATC. Controllers from the five specialization areas in Jacksonville ARTCC participated. The purpose of the research was to identify complexity factors associated with ATC and compare the use of direct (questionnaire and interview) versus indirect (statistical) methods for factor identification.

Direct methods involved asking controllers to suggest and then rate complexity factors in terms of how they made sectors more or less difficult to control. Indirect methods involved having controllers make paired comparisons with respect to complexity between maps of sectors in five specialization areas. Multidimensional scaling (MDS) was used to formulate complexity factors by determining whether the arrangement of sectors along each MDS axis corresponded to the increase or decrease in some variable or factor related to complexity.

Thirteen of the 19 total complexity factors were produced by both methods showing a close correspondence between direct and indirect techniques for determining ATC complexity factors. The 19 variables were regressed over an overall complexity criterion formed by ratings of 5 traffic management unit staff members who were familiar with all sectors in the ARTCC. The factors of complex aircraft routings, spacing and sequencing for departures and arrivals, and frequency congestion during peak periods formed a significant multiple correlation ($R = .85$) with the overall complexity criterion.

Table 1 provides a complete list of ATC complexity factors and the method of their measurement from the above studies. A common theme among complexity studies is the attempt to define a relationship between airspace factors and controller performance or judgments. While nearly all of the studies discussed found statistically significant relationships, not all airspace factors were related to the same controller measures. In addition, there is a problem with comparing the results from different studies because of a wide variety of measures used to assess complexity.

However, table 1 provides a useful listing of the ATC complexity factors identified in FAA Order 7210.46 and a number of scientific studies. Given the range of different approaches taken, this table should represent a fairly comprehensive catalog of complexity factors affecting controller workload.

There are two potential applications for table 1. One is to help orient researchers interested in assessing the benefits of new ATC systems or procedures. In order to be effective, such innovations should in some way address the sources of controller workload found in table 1. Secondly, researchers working in the area of ATC complexity should refer to the factors and sources found in table 1 as a starting point for additional investigations.

4. RELATIONSHIP OF INFORMATION DISPLAY AND HUMAN INFORMATION PROCESSING TO ATC COMPLEXITY.

Considerable research has been done on the information display and processing factors which make ATC tasks more or less difficult or complex. The references cited below focus on how information display issues and the manner in which the controller processes ATC information can affect how the controller copes with ATC complexity.

Hopkin (1982) stated that complexity (defined as a failure in task performance) in ATC could result from a mismatch between system requirements and human information processing capabilities. Crucial information includes:

a. Physical distance between tracks on the radar display;
b. The scale of the radar display;

TABLE ATC COMPLEXITY FACTORS AND METHODS OF MEASUREMENT

Source	Complexity Factors	Approach	Results
FAA Order 7210.46	Number of departures. Number of arrivals. Emergencies. Special flights. En-route aircraft requiring control function. En-route aircraft requiring no control function. Coordination.	Complexity workload formula.	Weighted sum of complexity factors for peak hour of the 90th percentile busy day used to validate sector.
Davis (1963)	Traffic density. Traffic mixture (arriving/departing vs. overflying aircraft). Number of airport terminals.	Experiment examining the effect of sector characteristics on controller activities.	Statistical relationship between complexity factors and controller activities.
Kuhar et al. (1976)	Traffic volume. Traffic distribution. Staffing. Weather conditions. Equipment status.	Assessment of ARTS III system.	ARTS III supported increased productivity and capacity.
Buckley et al. (1983)	Sector geometry. Traffic density.	Two simulation experiments.	Sector geometry and traffic density interacted in their effect on ten performance measures.
Arad (1964)	Background load. Routine load. Airspace load.	Samples from 13 ARTCCs to derive difficulty factors.	Derive airspace load formula.
Jolitz (1965)	DEL. Routine load. Traffic density.	Attempted to validate load model developed by Arad (1964).	Mathematical model not a good predictor of workload; density better.

TABLE 1. ATC COMPLEXITY FACTORS AND METHODS OF MEASUREMENT (continued)

Source	Complexity Factors	Approach	Results
Soede, et al. (1971)	Communications with aircraft. Presence of conflicts. Number of path changes.	Correlated factors with ATC task times.	Airspace variables were correlated with the duration of ATC task components.
Schmidt (1976)	Preventing a crossing conflict. Preventing an overtaking conflict. Hand-offs. Pointouts. Coordination with other controllers. Handling pilot requests. Traffic structuring.	Conducted field surveys to determine event difficulties.	Developed CDI. (Sum of expected number of ATC events per hour multiplied by a weighting factor.)
Stein (1985)	Clustering of aircraft in a small amount of airspace. Number of handoffs outbound. Total number of flights handled. Number of handoffs inbound.	Correlated airspace factors with ATWIT scores.	Statistical relationship between airspace factors and controller workload.
Grossberg (1989)	Control adjustments involved in merging and spacing aircraft. Climbing and descending aircraft flight paths. Mixture of aircraft types. Frequent coordination with other controllers. Traffic density.	Developed complexity index based upon factors and correlated with operational errors.	Found statistically significant correlation between complexity index and operational errors.

TABLE 1. ATC COMPLEXITY FACTORS AND METHODS OF MEASUREMENT (continued)

Source	Complexity Factors	Approach	Results
Mogford et al. (1993)	Amount of climbing or descending traffic. Aircraft mix. Number of intersecting flight paths. Multiple functions. Number of required procedures. Number of military flights. Amount of coordination. Airline hubbing. Weather. Complex aircraft routings. Restricted areas, warning areas, and Military Operating Areas. Sector size. Requirements for longitudinal sequencing and spacing. Adequacy of radio and radar coverage. Radio frequency congestion.	Questionnaire rating scales. Multidimensional scaling of paired comparison of complexity judgments. Correlation of complexity ratings with overall complexity criterion.	Final list of 15 complexity factors developed. Subset of these factors correlated with controller judgments of complexity.

c. The relative and absolute speeds of aircraft;
d. The aircraft headings and angles of approach;
e. The time until two aircraft conflict;
f. The aircraft altitudes;
g. The aircraft types and maneuverability;
h. The ease of contacting an aircraft;
i. The known intentions and destinations of an aircraft;

The known quality or reliability of the data on the radar display;
k. The separation standards and/or other instructions in force; and
The amount and behavior of other aircraft under the control of the same controller.

Hopkin (1982) asserted that any variance between the information required by the controller (items a-l) and presentation of that data would increase the complexity of the controller's job. He also stated that the information presented to the controller should be at a level of detail which allows task performance. Too much or too little detail would make the controller's job more complex. Another common problem is that ATC is a team activity, yet many forms of computer assistance are oriented toward individual controllers.

Hart (1982) also found that information display is an important variable in ATC workload. Hart conducted an experiment involving a Cockpit Display of Air Traffic Information (CDTI) which provided the aircrew with information about their position relative to other aircraft. Professional pilots and controllers participated in a simulated ATC task in which flight simulators were equipped with CDTIs. The results showed that verbal workload was stable for pilots using CDTIs compared to those using radio procedures only, but lower for air traffic controllers when CDTIs were used. In addition, spacing between aircraft was less variable when the CDTIs were used. This study suggested that the current mode of information display (radio) can be optimized through the use of cockpit visual displays depicting air traffic.

Krol (1971) found that air traffic controllers tended to report less workload when they controlled an aircraft on a radar screen versus monitoring a track on a radar screen. He explained the effect by assuming that when a controller issues commands to an aircraft, it is possible to predict its position for many seconds after the command is issued. Krol stated that when a controller is merely observing the flight path of a radar track, there is more uncertainty as to what the pilot will be doing and therefore more workload compared to the control task. Thus, the perception of being in control of the system (which can also be influenced by human-machine interface design) can affect workload.

Coeterier (1971) conducted a study examining the effect of the amount of maneuvering involved in controlling airspace and traffic density on the flexibility of strategies used by approach controllers. The experimental variables included the number of arrivals (4, 5, 6, or 7 aircraft) to each of two simulated runways. One runway was in an area of restricted airspace due to three military airfields in the vicinity. The second runway had a greater amount of maneuvering space for sequencing aircraft. The controller's task was to establish a landing sequence for the aircraft in each experimental condition.

The results showed that controller strategies were more uniform for the runway with restricted airspace at all levels of traffic density, and were more uniform for both runways as traffic density increased. The type of information requested by aircraft was also more consistent as traffic density increased. The results were explained in terms of flexibility of controller strategy. When traffic density is high and/or if there is little airspace available for maneuvering, few possible solutions are available. To prevent conflictions, planning has to be done at an earlier stage. However, when traffic density is low and there is ample maneuvering space, there are more options available for sequencing aircraft and less formalized, more improvisational strategies can be used. The study suggested that flexibility in operating procedures is related to the complexity of the sector and density of traffic flow.

Sperandio (1971) found that en route air traffic controllers modified their strategies to regulate their workload as traffic density increased. Controllers processed increasingly fewer traffic variables in order to regulate their mental workload. For example, in a low traffic situation controllers took into account aircraft performance data, geographical data, and flight levels of aircraft. However, as the traffic level increased, controllers looked at only the most critical data (i.e., flight levels of aircraft) in order to regulate their workload. In a later review of field studies among air traffic controllers, Sperandio (1978) found evidence that controllers selected operating procedures based on economy. That is, certain operating procedures were less costly than others in terms of the workload they generated. He found that as air traffic density increased, the controllers used less costly procedures to avoid an abrupt onset of overload. In addition, he repeatedly found that as traffic density increased controllers sacrificed secondary objectives in order to maintain their principal objectives.

It is clear from such studies that flexible controller strategies can ameliorate workload. Table 2 lists the information processing variables related to ATC complexity. In general, the studies fall into two groups. Hopkin (1982) and Hart (1982) looked at the input or perceptual aspects of information processing. They considered the effect that the display of information can have on controller workload. Thus, impact of complexity on the controller may be ameliorated or worsened by the quality of information display. If the "lens" between the user and the domain is good, the controller will experience few restrictions on the amount and quality of required information. However, if the medium is poor, workload will increase.

This first group of studies is concerned with "data limited" information processing as defined by Norman and Bobrow (1975). They noted that some types of decision-making are encumbered by a lack of information while others are limited by a lack of internal (cognitive) resources. The following authors are more concerned with this latter, "resource limited" problem.

Sperandio (1971), Krol (1971), and Coeterier (1971) focused on the cognitive aspects of ATC, finding that the choice of strategy can affect workload. Their research suggests that as traffic complexity (defined as traffic density) increases, the processing of ATC information changes. Specifically, controllers use more economical control procedures and more standard strategies to control air traffic at higher traffic densities. In addition, there is some evidence that this shift in controller strategy is an attempt to regulate workload. Controllers appear to be flexible in their response to ATC complexity and can adapt their information processing and decision-making strategies to suit a given situation. In this way, they conserve their cognitive resources available for the task.

The insight to be gained from studies in this section is that ATC complexity is not a "given." It is not a static set of elements that are directly perceived and interpreted in the same way by all controllers in every situation. The quality of the system transmitting the information about the sector and the aircraft within it effects the adequacy of the information reaching the controller's

TABLE 2. RELATIONSHIP OF INFORMATION PROCESSING VARIABLES WITH ATC COMPLEXITY.

Source	Factor	Results
Hopkin (1982)	Mismatch between system requirements and human information processing requirements.	Workload increased when information missing or not accessible.
Hart (1982)	Method of displaying ATC information to aircrews.	Reduced controller workload with the use of a CDTI.
Krol (1971)	Controlling versus monitoring aircraft on a radar screen.	Reduced controller workload associated with controlling versus monitoring aircraft.
Coeterier (1971)	Flexibility of controller strategies.	Increased uniformity of strategies and less improvisation with increased traffic density and restricted airspace.
Sperandio (1971, 1978)	Use of economical control procedures.	Used to regulate workload as traffic density increases.

senses. Once this information has been perceived and classified, the cognitive tactics used to identify problems and make decisions will also influence workload. Therefore, when dealing with the issue of ATC complexity and its effect on the controller, information display and cognitive mediators must be considered in order to assess the ultimate effect of complexity.

5. INFLUENCE OF INDIVIDUAL DIFFERENCES ON ATC WORKLOAD.

Although individual differences do not directly cause ATC complexity, they have been shown to affect controller performance (Cobb, 1967, Cobb, Nelson, and Mathews, 1973; Buckley, O'Connor and Beebe, 1969; Collins, Schroeder, and Nye, 1991). Knowledge of the individual difference factors which affect workload and related measures is important for conducting accurate ATC complexity research. Age, skill, anxiety level, and other factors may play a major role in determining the amount of workload experienced by a controller in response to a given level of ATC complexity.

Cobb (1967) investigated the relationships between controller age and years of experience with ATC performance. He distributed three experimentally derived field questionnaires of job performance to over 500 ARTCC journeymen radar controllers. The subjects in the sample ranged in age from 26 to 51 years. About half of the sample had 10 or more years of experience and over 90 percent of the sample had greater than 6 years of experience. He found low ($r = -.14$ to $-.18$), but statistically significant negative correlations between controller age and performance. There was no statistically significant relationship between controller experience and job performance ratings.

Cobb et al. (1973) conducted a similar study of several hundred journeymen radar controllers who worked at one of 17 high traffic density TRACON facilities. Experimentally derived rating scales were developed to allow the collection of performance evaluation data from supervisors and peers. The sample ranged from 27 to 60 years of age with over 56 percent of the respondents falling between the ages of 31 and 37. Significant negative correlations (r = -.36 to -.44) were found between controller age and performance.

Significant negative correlations were also found (r = -.23 to -.29) between ATC experience and performance. However, when the variance associated with age was removed, controller experience was only negligibly correlated with performance. These two studies demonstrated that age might be a significant factor affecting ATC performance. In addition, when the sample of controllers was taken from high traffic density environments (i.e., busy terminal approach areas), the correlations between age and performance were stronger compared to samples from the en route environment. However, data were based on subjective ratings which may have included an element of age bias.

Collins et al. (1991) assessed the relationship between anxiety, as measured by the State Trait Personality Inventory, and success of post-strike air traffic controller specialist trainees at the FAA Academy and during field training. The sample was comprised of trainees in an en route facility curriculum. Both state (the current level of anxiety when measured) and trait (proneness to anxiety) were measured. Trainees who had relatively high scores on a combined index of state and trait measures exhibited a higher percentage of Academy failures, higher percentage of option switches in the field, and had a higher percentage of overall attrition than did trainees with low combined scores. It was also found that, overall, trainees had lower anxiety scores than college students or military recruits. The results supported the notion that a low anxiety characteristic is important for ATC job success.

Buckley et al. (1969) conducted a simulation study to examine the relationship between measures of controller performance and ATC system measures. The study also examined the relationship between traffic density and controller performance, personality, and age. The study was done using a simulated sector from the Los Angeles ARTCC. The results challenged the assumption that all controllers perform about equally. There was evidence of a considerable range in controller skill that became more pronounced in problems with higher air traffic densities. Controller performance (as measured by supervisory and peer ratings) was moderately correlated (r = -.23 to -.31) with measures of system performance and included: the number of conflictions, the number of delays, the delay time, and the aircraft time in the system.

Moderate correlations (r = .50) were found between controller personality variables as measured by a personality test and system performance measures. The superior performing controller tended to be free from depression, lacking in timidity, relatively free from anxiety, and somewhat non-conformist.

The relationship between traffic density and controller age yielded similar results to Cobb's (1967) study. Low but statistically significant negative correlations were found between age and some of the proficiency rating data. Some positive correlations were found between experience and some of the field criteria. Low positive correlations were found between the age and experience variables and some simulation performance measures. However, most of these were not statistically significant. There was a trend (significant at the $p < .10$) for more delays as age increased.

Buckley et al. (1969) concluded that chronological age was not a good predictor of proficiency (based on field ratings) or of simulation performance. However, they found that there were qualitative effects of age on performance. Aging tended to correspond with greater caution and safety with an accompanying tendency to delay traffic. Personality factors (as measured by a personality test) were correlated with controller performance. He also found large differences in the degree of skill evidenced by controllers as they handled identical traffic problems in simulated ATC exercises.

Table 3 summarizes the relationships of individual differences among controllers that may affect workload. The research reviewed in this section demonstrates that chronological age may play some role in controller performance although years of experience may not be a factor. Some personality variables such as general anxiety level, depression, assertiveness, and conformity seem also to be connected to performance in some way. Most evident from this research is that controller skill levels vary widely and may even eclipse the effects of ATC complexity on workload.

6. CONCLUSIONS.

The growth of civil aviation and the concomitant demand for air traffic control (ATC) services place considerable pressure on the National Airspace System to improve services while maintaining safety. An understanding of the task environment of the air traffic controller is necessary to monitor and control workload as traffic density increases. Specifically, an analysis of the characteristics of ATC complexity is needed to determine how these factors affect controller workload.

The definition of ATC complexity adopted for this review is that it is a construct composed of a number of complexity dimensions or factors. These factors are the physical aspects of the sector (sector complexity) or are related to the movement and characteristics of the air traffic (traffic complexity) occupying the airspace. ATC complexity generates controller workload. The transformation of ATC complexity into controller workload is mediated by the quality of information display, information processing strategies, and personal variables. This is depicted in a workload model, as shown in figure 1.

Many studies have been conducted to identify and evaluate the factors or processes underlying ATC complexity. Much useful work has been done to isolate potential causes of complexity and controller workload. In many cases, it has been possible to find simple or multiple correlations between complexity factors and system measures (such as number of conflicts) or subjective workload. Although this has tempted some authors (such as Arad, 1964) to take a more aggressive approach to quantifying and formalizing these relationships, theoretically-based mathematical models have not proven to be very successful in accounting for controller judgments of workload. A simple measure of number of aircraft per hour has been more effective (Jolitz, 1965).

TABLE 3. RELATIONSHIP BETWEEN INDIVIDUAL CONTROLLER DIFFERENCES AND PERFORMANCE.

Source	Factor	Results
Cobb (1967) Cobb et al. (1973)	Controller age and experience.	Low negative correlations between age and performance; experience not a factor.
Collins (1991)	State and trait anxiety.	ATC trainees with high anxiety scores failed in school more frequently.
Buckley, et al. (1969)	Controller personality and age.	Correlations found between performance and personality factors and age and proficiency.

An analysis of information display issues, controller cognitive strategies, and personal factors has shown that ATC complexity is not experienced and handled the same in all situations. The effect of sector structure and traffic flow patterns on workload is filtered by the quality of the computer-human interface and communication system, as well as by the perceptual and cognitive processing style adopted by the user. Age and skill level have also been shown to influence how the task environment is experienced.

Further studies on ATC complexity should not necessarily emphasize the identification of additional complexity factors (although efforts should be made to update the knowledge base as new ATC technologies are introduced). A significant amount of work has been done (as expressed in table 1) to generate a long list of items. Many have been linked, in some way or another, to relevant criterion measures to indicate that they have meaning in the ATC environment. It would be more beneficial to focus further investigation on ATC complexity on refining our understanding of the complexity factors so that intelligent sector design and traffic flow management strategies become feasible. It should be possible to discover how much weighting each salient complexity factor has in determining overall complexity and controller workload. In this way, ATC environments could be created that have predicable effects on the controller.

Given that there will always be some level of ATC complexity with which the controller must cope, it will also be important to discover how complexity factors, display and communication systems, perceptual and decision-making strategies, and personal variables can be adjusted to ameliorate the resulting workload. Such efforts should also help to identify the critical information that should be displayed to the controller and suggest automation tools to improve the controller's ability to cope with complexity. Training in procedures adapted to complexity could help modify information processing styles and reduce workload. Lastly, information on controller characteristics that interact positively with sector complexity could help channel the right people into the best fitting task environments.

DEFINITIONS

Task Load	The number of tasks or frequency of task occurrence associated with a specific job description.
Workload	The total effect on the worker of all physical, sensory, and mental activities required to perform tasks required of a specific job description.
Traffic Density	The number of aircraft under the control of an air traffic controller responsible for a given sector of airspace.
Sector	A volume of airspace defined by vertical and lateral boundaries.
ATC Complexity	Sector and traffic characteristics that cumulatively add to create a complex set of rules, requirements, and tasks for the air traffic controller when controlling aircraft in the sector. ATC complexity is composed of sector and traffic complexity factors.
Performance	An activity or set of responses that has an effect on the environment (Reber, 1985).
Work	Expenditure of energy or application of effort to achieve some purpose.

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APPENDIX A
SECTOR COMPLEXITY WORKLOAD WORKSHEET

Sector ____________________

SFT Peak Hourly Count

	Number of Functions	Point Value	Total Points	
A. DEPARTURES		5		
B. ARRIVALS		4		
C. RADAR VECTORED ARRIVALS		2		
D. EN ROUTE (requiring control functions)		4		
E. EN ROUTE (no control functions)		2		
F. EMERGENCY		4		
G. SPECIAL FLIGHTS (7110.65. CHAPTER 7)		3		
H. COORDINATION (additional points when above functions require coordination)		1		
				TOTALS

COMPLEXITY WORKLOAD FORMULA

1.	FUNCTIONS	POINTS
(aa)	Departures	5
(bb)	Arrivals	4
(cc)	En Route requiring control function	4
(dd)	Emergency	4
(ee)	Special flights	3
(ff)	En Route (no control function)	2
(gg)	Coordination (additional point/s when above function/s require coordination)	1

2 An en route aircraft is classified as an aircraft that originates outside and passes through the sector without landing.

3 An en route aircraft operating at an altitude which will transit approach control airspace and is handed-off to the approach control, then back to the same sector, is counted as an en route (2 points) and a coordination (1 point) factor.

4 A "pop-up" (airfile) en route is counted as a departure (5 points) and 1 point for each coordination function necessary.

5 A "pop-up" or special VFR arrival is counted as an arrival (4 points) and 1 point for each coordination function necessary.

6 Special flights (7110.65, Chapter 7) are counted as an additional 3 points, e.g., departure complexity points plus special flight points and 1 point for each coordination function necessary.

7 Arrivals that are radar vectored to final approach add an additional **(2 points).**

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