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Relationship of Complexity Factor Ratings With Operational Errors

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16. Abstract

This study is an examination of the extent to which objective static sector characteristics and controller ratings of static and dynamic sector complexity factors contributed to the occurrence of operational errors (OEs) at the Indianapolis air route traffic control center (ZID). A multiple regression model of the relationship between a combination of static sector characteristics (sector altitude strata and sector size) resulted in a modest prediction of the variance in OE incidence ($R = .70$, $R^2 = .49$). Sector size was negatively related to OEs, indicating that smaller sectors were associated with more OEs. Sector strata were positively related to OEs, indicating that higher altitude sectors were associated with more OEs. Principal Components Analysis (PCA) of the complexity ratings produced four components with eigenvalues >1.00, accounting for 62% of the variance in the data. Components were used as predictors in a multiple regression analysis of the number of OEs in the ZID sectors. Only Component 1 (climbing and descending aircraft in the vicinity of major airports) and Component 2 (services provided to non-towered airports) contributed significantly to the total proportion of variance explained by the model ($R = .78$, $R^2 = .61$). Component 2 shared an inverse relationship with the number of OEs, indicating that the complexity related to providing services to non-towered airports is associated with fewer OEs. These results will be used to guide the choice of objective measures for further analysis of the influence of static and dynamic sector characteristics in the occurrence of OEs.

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EXECUTIVE SUMMARY

Extensive research has focused on the behavioral and organizational aspects of operational error (OE) occurrence. While recognizing that the human component of OEs is extremely important, it is equally important to examine contextual and environmental factors. In this study, we analyzed the extent to which controller ratings of static and dynamic sector complexity factors related to the occurrence of OEs at the Indianapolis air route traffic control center (ZID). OE information was derived from final reports for 247 errors that occurred between 1/15/2001 and 5/28/2005. Thirty-six ZID volunteers (32 controllers and 4 operational supervisors) rated the importance of 22 static and dynamic complexity factors for each sector on which they were certified.

Principal Components Analysis (PCA) of sector complexity ratings produced four components that accounted for approximately 62% of the variance in the dataset. The basic theory behind PCA is that variables cluster together into "components" that reflect underlying dimensions in the data. In this PCA, the pattern of variables associated with Component 1 described climbing and descending aircraft in the vicinity of major airports. Component 2 variables involved ATC services provided to non-towered airports. Component 3 comprised variables associated with military operations and special use airspace. Component 4 described the effects of inclement weather on ATC operations. These results were comparable in many ways to the PCA of sector complexity factors at the Atlanta ARTCC conducted by Rodgers, Mogford, and Mogford (1998). Specifically, Components 1 (major airports) and 3 (military activity and Special Use Areas [SUAs]) of the two analyses were strikingly similar, suggesting that these dimensions may be common to more than one facility.

A multiple regression analysis was conducted to examine the relationship between the four dimensions revealed by the PCA and the number of OEs. Only Component 1 (major airports) and Component 2 (non-towered airports) explained a significant amount of the variance in OEs in the ZID sectors (R = .78, R2 = .61). Component 1 was positively associated with the number of OEs (i.e., higher scores were related to a higher number of OEs), whereas Component 2 had a negative relationship (higher scores were related to fewer OEs). The relationship between Component 2 and the incidence of OEs reminds us that sector complexity does not always produce a negative outcome. Indeed, a certain degree or type of complexity may actually be associated with a reduction in the number of OEs. The fact that Component 3 failed to contribute significantly to the prediction of OEs in this analysis does not mean that military airspace or SUAs do not make a sector more difficult to work or increase the likelihood of an OE. It simply means that subjective ratings of these factors failed to predict OEs. Similarly, the inability of Component 4 to contribute significantly to the regression model may reflect the intermittent nature of this dynamic event, or it may simply be an artifact of the way the variable was measured. In other words, the presence of inclement weather might be highly correlated with the occurrence of OEs but the component scores based on subjective ratings of variables associated with inclement weather were not.

We believe it is imprudent to make strong recommendations based on the results of analysis of subjective ratings. Practical prediction models must be calculated from objective measures because the actual characteristics of the sectors must be addressed when developing strategies to reduce OEs. However, these results represent a necessary and important step toward understanding how static and dynamic sector characteristics combine to create sector complexity, and how that complexity relates to the occurrence of OEs. Subjective information about the importance of complexity factors will guide our choice of objective measures in future analyses and may also be used to weight their importance, thus enabling us to make recommendations for reasonable, effective changes to the current system.

RELATIONSHIP OF COMPLEXITY FACTOR RATINGS WITH OPERATIONAL ERRORS

The Federal Aviation Administration (FAA) is currently implementing strategic safety initiatives aimed at reducing operational error rates (FAA, 2005). Toward that goal, a considerable amount of research has focused on behavioral and organizational aspects of operational error (OE) occurrence. While recognizing that the human component of OEs is extremely important, it is also important to remember that air traffic controllers do not operate in a void. Logic dictates that environmental and contextual factors contribute to the development of at least a portion of these errors. Otherwise, the frequency of OEs would be relatively equal in all sectors. This simply is not the case. Some sectors are more prone to OEs than others.

The idea that sector characteristics might contribute to the occurrence of OEs is not new. Environmental and contextual factors affecting controller workload and performance – often referred to as sector complexity – have been the focus of numerous studies (e.g., Arad, 1964; Arad, Golden, Grambart, Mayfield, & Van Saun, 1963; Buckley, O'Connor, & Beebe, 1969; Davis, Danaher, & Fischl, 1963; Grossberg, 1989; Hurst & Rose, 1978; Kirwan, Scaife, & Kennedy, 2001; Kopardekar & Magyarits, 2003; Laudeman, Shelden, Branstrom, & Brasil, 1998; Masalonis, Callaham, & Wanke, 2003; Mogford, Murphy & Guttman, 1994; Rodgers, Mogford, & Mogford, 1998; Schmidt, 1976; Stager, Hameluck, & Jubis, 1989; Stein, 1985). Even so, a single set of reliable general complexity factors has remained elusive. This may be partially due to the complicated interaction between static and dynamic sector characteristics. Static sector characteristics are usually related to airspace design and change infrequently or not at all. Dynamic sector characteristics are those that fluctuate, such as traffic volume or weather. Mogford, Guttman, Morrow, and Kopardekar (1995) observed that "a given level of traffic density and aircraft characteristics may create more or less complexity depending on the structure of the sector" (p. 3). Buckley, DeBarysche, Hitchner, and Kohn (1983) concluded that traffic characteristics and sector geometry were "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 depends upon the measures involved" (p. 73).

Perhaps one of the greatest challenges to the study of environmental factors in the development of OEs is that sectors are almost as unique as the people who work them. For example, Grossberg (1989) found that the highest-rated complexity factors in the Chicago air route traffic control center (ARTCC) were control adjustments involved in merging and spacing aircraft, climbing and descending aircraft, mix of aircraft types, frequent coordination, and amount of traffic. An index based on these factors was significantly correlated with the number of OEs. In the Jacksonville airspace, Mogford and coworkers (1994) found complex routings, spacing and sequencing for departures and arrivals, and frequency congestion to be most predictive of a subjective complexity index. Comparing their results with Grossberg's, they concluded that complexity factors that were salient in one facility might not be applicable to another. Although this observation may be valid, another interpretation is that different complexity factors were found to be predictive because the two studies used different criteria. In other words, numbers of OEs and the value of a subjective complexity index may not be comparable criterion measures.

This brings us to an important point: It is extremely difficult to compare the results of the studies cited because of the variety of methods and measures used to assess complexity. Some of the studies compared sector complexity factors with OEs, some with subjective workload measures, and some with subjective complexity ratings. On the basis of a comprehensive review of the literature that spanned more than 40 years of research and identified in excess of 100 complexity factors, Hilburn (2004) concluded that "despite the breadth and depth of previous work done into identifying ATC complexity factors, a good deal of work remains. Nobody, it seems, has yet managed to construct a valid and reliable model of ATC complexity that [1] moves substantially beyond the predictive value of simple traffic density alone, and [2] is sufficiently context-free" (p. vi). In his conclusions, Hilburn makes an excellent case for the use of non-linear models of complexity to circumvent the context-specific shortcomings of linear models. The only drawback to this argument is that it fails to recognize that sometimes the context is the factor of interest. This is not to imply that Hilburn was ignoring the importance of context or the inevitability of contextual influences in airspace complexity. Rather, it emphasizes the fact that development of a "context-free" model is not always a desirable goal in research.

In spite of the "embarrassment of riches" represented by the literature, one precept is evident: It is extremely important to compare complexity factors in as many environments as possible. The Sector Characteristics and Operational Errors (SCOpE) project is an extension of a study conducted by Rodgers, Mogford, and Mogford (1998) that examined the relationship between sector complexity factors and the occurrence of OEs at the Atlanta ARTCC (ZTL). Specifically, the SCOpE project was initiated to compare and contrast the results of selected analyses from the 1998 study with similar analyses conducted using data from the Indianapolis ARTCC (ZID). The methodology of developing a regression model at one facility and applying the derived regression weights to another facility has met with limited success (e.g., Laudeman et al., 1998; Masalonis et al., 2003). The advantage of the SCOpE paradigm is that it employs discrete models, thus enabling us to collect a set of general factors (i.e., factors that may reliably predict OEs at more than one facility) while documenting differences between facilities. After all, facility differences often represent important environmental and contextual elements as well.

The first phase of this project (Goldman, Manning, & Pfleiderer, 2006) compared a set of ZID static sector characteristics with those identified by Rodgers et al. (1998) at ZTL. With some exceptions, many of the static environmental and contextual factors that predicted OEs at ZTL also predicted the occurrence of OEs at ZID. In both studies, sector altitude strata, sector size, and number of major airports explained a significant proportion of the variance in the number of OEs per sector. However, some factors that were significantly correlated with OEs at ZTL failed to predict them in the ZID sample.

The second phase of the SCOpE project considers the relationship between a set of subjective static and dynamic complexity factor ratings and ZID OEs. In their analysis of sector characteristics and OEs, Rodgers et al. (1998) collected subjective complexity ratings and combined them with objective static sector characteristics in a Principal Components Analysis (PCA) to identify and describe the dimensions represented by these different types of variables. In the present study, subjective complexity ratings provided by ZID controllers will be examined in a series of discrete analyses to evaluate their relationship with OEs at ZID.

Method

Participants

Participants were 37 volunteers from ZID. Of these, 32 were Certified Professional Controllers (CPCs), 4 were operations supervisors, and 1 was a developmental controller who had completed Radar Associate training on all sectors in his area of specialization but was not yet certified on the corresponding radar positions. To guarantee that all participants were treated fairly and ethically, the experimental protocol and materials were cleared through the FAA's institutional review board. Treatment of participants also met with guidelines established by the American Psychological Association. Volunteers were assured complete anonymity and reminded of their right to terminate participation at any time.

The mean age of the volunteer participants was 42 years (SD = 6 years). Participants had been certified to control traffic for an average of 15 years (SD = 7 years), had been working at an ARTCC facility for a mean of 17 years (SD = 7 years), and had been working at their current facility for an average of 16 years (SD = 8 years). Four had previous experience in the Terminal Radar Approach Control (TRACON) environment, and six had previously worked at an Airport Traffic Control Tower (ATCT). ZID is divided into seven areas of specialization, each comprising either five or six sectors. All areas were reasonably well represented by the sample of volunteer controllers and supervisors.

Materials

Complexity Factor Questionnaire (Complexity-Q). "Complexity-Q" refers to an automated experimental protocol software program and the questionnaire it was designed to administer. The Complexity-Q program is divided into four sections (i.e., Work Experience, Tutorial, Demonstration, and Questionnaire). Each section is described separately in the following paragraphs.

The Work Experience section recorded biographical data about participants' work experience, collected information about the sectors on which they were certified, and generated a random-ordered list of sectors to be included in the questionnaire (based on input from the participant). It also randomized the presentation order of the complexity factor list and recorded the order of both lists in the output.

The Tutorial section consisted of a Microsoft PowerPoint slide presentation (automatically opened by the Complexity-Q program) that explained the purpose of the study, provided participants with an operational definition of sector complexity (i.e., "the static and dynamic characteristics that increase the level of difficulty involved in working traffic in a sector"), familiarized them with the basic structure of the questionnaire, and provided instructions about the functionality of interface elements (e.g., buttons, sliders, and bars). The Demonstration section was an extension of the Tutorial that provided participants with an opportunity to practice using the elements described therein.

The Complexity Factor Questionnaire followed the same basic structure for each sector on which the participants were certified. They were asked to provide a general "Complexity Rating" for a sector using a slider object with an underlying scale ranging from 0 to 100. The end points of the slider were labeled "Low" and "High" with visual anchors set at 10-point intervals. However, the slider was not restricted to these anchors, thus affording raters maximum response flexibility.

Once the participants entered an overall complexity rating, they were presented sequentially with a series of 22 complexity factors and asked to indicate the level of influence each factor had on the complexity of the sector. The "Factor Rating" was made using the same slider and scale as the general complexity rating. If the participants were unsure about the meaning of the factor, a detailed description could be obtained by moving the mouse over the "Complexity Factor" label. The list of factors and their descriptions was initially derived from the 19 complexity factors identified by Mogford et al. (1994). Subject Matter Experts (SMEs) from the facility and the FAA Academy provided additional factors prior to data collection. The Complexity-Q factors and their descriptions are provided in Table 1. Note that only two extra factors were added by the SMEs, yet there are 22 factors in the list. The "mix of aircraft with different performance characteristics" and "VFR versus IFR traffic" factors were combined in the original list but were separated into two distinct factors for this study.

After participants entered factor ratings for all 22 factors, they were given the opportunity to enter any complexity factors they believed were not included in the list. If a participant added a complexity factor, the new factor was added to that particular participant's list for all subsequent sectors. Thus, whenever participants entered a new complexity factor to the list, they had to rate that factor for all remaining sectors.

Procedure

Testing took place from 6/13/2005 to 6/17/2005 in a classroom at ZID. The Complexity-Q automated protocol was administered on laptop computers arranged around a large table to provide participants with as much privacy as possible. Participants were first given informed consent forms to read and sign. Once their written consent was obtained, they were shown the basic structure of the Complexity-Q interface, and the "Work Experience" section was brought up on the screen. Participants were requested to complete this section and then move through all subsequent sections in the order they appeared on the main interface (i.e., Tutorial, Demonstration, and Questionnaire). They were encouraged to ask questions about the interface or content of the Complexity-Q at any time during the automated protocol. Most participants completed the protocol in 40 minutes.

Measures

In addition to subjective Complexity-Q factor ratings provided by controllers, OE and sector characteristics information were collected from data provided by facility management. The following sections describe these variables and their sources.

Operational Error (OE) Data. The OE database consisted of information extracted from electronic records of the Final Operational Error/Deviation Report (FAA Form 7210-3) for 247 OEs occurring in ZID airspace from 1/15/2001 through 5/28/2005. Variables obtained from the final OE reports included the date and time of the OE and the number of controlled aircraft in the sector at the time the OE occurred. OEs were tallied for each sector in the ZID airspace.

Sector Characteristics Data. Sector altitude strata (super high-, high-, intermediate high-, intermediate-, or low-altitude) were obtained from the facility's Adaptation Control Environmental System (ACES) sector description file and verified with sector maps. The number of associated airports and the number of airports for which the sector provided approach services were derived from sector descriptions included in the center's Standard Operational Procedures (SOPs). Staff from the facility's airspace office clarified and augmented this information.

Results and Discussion

Descriptive Statistics

The sample consisted of 181 complexity ratings provided by CPCs (n = 169) and operations supervisors (n = 12). Prior to the analysis, sector-by-sector comparisons were made between the mean ratings provided by CPCs and those provided by supervisors to determine whether the two sets of observations were comparable. On the average, supervisors' ratings were less than two standard deviations from those of controllers, indicating that supervisor and CPC ratings were similar enough to constitute a homogenous sample. Conversely, data from the single developmental controller were excluded from the analysis. Supervisors and CPCs had experience working both the Radar Associate and Radar positions, whereas the developmental controller did not. This difference in experience gave rise to a discernable pattern of rating differences, suggesting that the developmental was sampled from a different population. Table 2 lists descriptive statistics for the Complexity-Q ratings. Though many of the distributions approximated normality, there were some notable exceptions. The distribution of the VFR versus IFR traffic, Shelves/Tunnels, Foreign aircraft/pilots, and

Table 1. *Complexity-Q Complexity Factors and Descriptions**

Complexity Factor	Description
Climbing and descending traffic	Climbing and descending aircraft are those that are transitioning altitudes, including departure and arrival traffic, aircraft that require different altitudes to alleviate conflictions due to crossing traffic or other problems, and aircraft requesting altitude changes due to turbulence, pilot preference, etc.
Mix of aircraft with different performance characteristics	Extent to which the mix of props, turboprops, and jets impacts the controller.
VFR versus IFR traffic	Extent to which differences in controlling VFR and IFR traffic, or VFR pilots encountering IFR conditions impacts controller workload.
Number of intersecting aircraft flight paths	The number of converging flight paths due to airways, arrival routes, frequent requests for direct routings; number of airways coming into same NAVAID; number of routes converging on a STAR, etc.
Number of multiple functions controller must perform	Set of related tasks or services required in this sector (e.g., approach control, terminal feeder, en route, and in-trail spacing).
Traffic volume	Extent to which the number of aircraft relative to the amount of available airspace impacts the controller.
Amount of military or other special traffic	Number of special missions (e.g., military, NASA, flight inspection, Lifeguard).
Number of required procedures that must be performed (i.e., crossing restrictions in LOAs)	A group of tasks, or a specific task, required by regulation or direction. A procedure mandates controller actions and must be performed regardless of other required tasks.
Amount of coordination/ interfacing required	Coordination with adjacent sectors, approach control, other en route centers, military facilities, etc.
Major airports (inside and outside sector boundaries) that might influence the number of procedures used, etc.	Extent to which the controller's work is affected by the concentration of flights into one area due to the orientation of the sector relative to one or more major airports.
Extent operations are affected by weather	Presence of weather conditions that necessitate requests for deviations, route changes, etc.
Relative frequency of complex routings	Frequency of aircraft that are not on a published route structure, such as vectors or direct routings, etc.
Special Use Areas (Restricted areas, warning areas, and military operating areas) and their associated activities	Extent to which SUA reduces the amount of airspace for non-participating aircraft, create obstructions to flight routes, increase the likelihood of conflictions due to reroutes, create situations requiring special handling and monitoring, etc.
Size of sector airspace	The volume of airspace contained within the lateral and horizontal boundaries of the sector and the extent to which it impacts the controllers' ability to handle traffic volume, deal with special conditions (e.g., weather), and conflict resolution.
Requirement for longitudinal spacing/ sequencing	Combining aircraft from several streams into one stream.
Adequacy of radio/radar coverage	Radio: Extent to which insufficient radio coverage results in the use of alternate communication techniques, such as pilot-to-pilot relays. Radar: Extent to which lack of radar results in use of non-radar procedures.
Amount of radio frequency congestion	Extent to which radio frequency congestion limits the controller's ability to utilize the frequency for issuing instructions to aircraft.
Traffic Management Initiatives	Extent to which Traffic Management Initiatives impact operations (e.g., miles that must be made up, vectoring required to meet initiatives).
Terrain/Obstructions	Extent to which the terrain/obstructions (e.g., mountainous areas) adds complexity.
Shelves/Tunnels	Extent to which shelves and/or tunnels add to complexity of the sector (e.g., are the lateral boundaries of the sectors above or below aligned or are they different?).
◊Foreign aircraft/pilots with English as a second language	Extent to which communications with foreign aircraft/pilots with English as a second language increases the difficulty of communications.
◊Non-towered airports	Extent to which providing service to non-towered airports increases the complexity of the sector.

* Complexity factors and descriptions adapted from Mogford et al. (1994) except where indicated (◊)

Table 2. ***Complexity-Q Descriptive Statistics*** (*N* = 181)

Variable	Mean	*SD*	Skew.[1]	Kurtosis[2]
Climbing and descending traffic	77.71	20.94	-0.86	0.00
Mix of aircraft types	63.75	22.22	-0.62	0.30
VFR versus IFR traffic	17.75	28.15	1.28	0.08
Number of intersecting flight paths	70.94	23.26	-0.79	-0.02
Number of multiple functions	68.92	21.18	-0.64	0.05
Traffic volume	73.38	21.14	-0.82	0.29
Amount of military or other special traffic	35.66	25.59	0.49	-0.73
Number of required procedures	69.67	22.43	-0.71	0.11
Coordination/ interfacing required	68.75	21.82	-0.61	-0.08
Number of major airports	68.19	26.53	-0.84	-0.17
Extent operations are affected by weather	75.52	22.71	-0.90	0.10
Relative frequency of complex routings	48.75	27.15	-0.04	-1.04
Special Use Areas	48.06	29.09	0.06	-1.15
Size of sector airspace	52.20	27.17	-0.11	-0.87
Longitudinal spacing/ sequencing	72.20	25.44	-1.02	0.37
Adequacy of radio/radar coverage	34.03	32.49	0.56	-1.01
Amount of radio frequency congestion	60.50	25.99	-0.55	-0.51
Traffic Management Initiatives	70.56	27.40	-0.90	-0.08
Terrain/Obstructions	11.85	23.98	1.97	2.54
Shelves/Tunnels	24.68	30.84	1.06	-0.11
Foreign aircraft/pilots	18.22	19.93	1.46	1.43
Non-towered airports	16.66	29.24	1.55	0.86

[1] SE Skew. = .181 [2] SE Kurt. = .359

Non-towered airports complexity ratings all had extreme positive skews. The distribution of Terrain/Obstructions ratings was both positively skewed and leptokurtotic. Such deviations are understandable, considering that these complexity factors only apply to some sectors (e.g., low-altitude sectors, sectors with shelves or tunnels). On the other hand, the Extent operations are affected by weather and Requirements for longitudinal spacing/sequencing were given high ratings in almost every sector. Consequently, the distributions of these variables were significantly negatively skewed.

Given the scale of some of the deviations, it is comforting to know that assumptions regarding normality are not required when PCA is used descriptively. However, it is important to remember that PCA is sensitive to the magnitudes of correlations. To the extent that normality fails, the solution may be degraded (Tabachnick & Fidell, 1989). Table 3 contains a Pearson's correlation matrix of all the Complexity-Q factors. Note that variables with non-normal distributions achieved a significant degree of association with several others in the dataset, suggesting that the deviations were not severe enough to prevent a satisfactory PCA solution.

Principal Components Analysis

PCA is a statistical technique often used to describe relationships between complex sets of variables. Components extracted by PCA contribute to our understanding of a phenomenon by consolidating variables into parsimonious groups. In orthogonal rotation, loadings represent the correlations between a variable and a component. Variables with stronger loadings are generally considered to be more representative of a component's underlying processes. Thus, we can use PCA not only to identify the number and nature of unique dimensions described by the Complexity-Q factors but also to what extent each variable relates to them. More importantly, we can use component scores output from the PCA to analyze the relationship between the complexity factors and the number of OEs in each sector.

For the Complexity-Q analyses, the number of sectors was reduced from 40 to 37 due to the combination of some sectors deemed appropriate by ZID personnel. With only 37 sectors in the sample and 22 complexity factors, the case-to-predictor ratio is unacceptable for most multivariate analyses. Component scores (computed by weighting variable scores using regression-like coefficients)

Table 3. ***Correlation Matrix of Complexity-Q Factors*** (*N* = 181)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1 Climbing/descending																					
2 Mix of aircraft types	.56**																				
3 VFR versus IFR traffic	.02	.27**																			
4 Intersecting flight paths	.51**	.34**	-.35**																		
5 Multiple functions	.56**	.46**	.01	.40**																	
6 Traffic volume	.54**	.24**	-.31**	.53**	.42**																
7 Military/Special traffic	.26**	.32**	.20**	.08	.30**	.05															
8 Required procedures	.48**	.39**	-.14	.48**	.58**	.42**	.19*														
9 Coordination	.55**	.46**	.10	.40**	.65**	.42**	.31**	.55**													
10 Major airports	.57**	.38**	-.16*	.46**	.50**	.50**	.16*	.64**	.46**												
11 Weather	.27**	.14	-.14	.34-**	.34**	.39**	.22**	.45**	.20**	.33**											
12 Complex routings	.23**	.17*	-.32**	.39**	.30**	.36**	.31**	.42**	.35**	.33**	.34**										
13 Special Use Areas	.37**	.35**	.14	.11	.33**	.15*	.62**	.24**	.35**	.24**	.30**	.22**									
14 Size of sector airspace	.35**	.43**	-.08	.44**	.37**	.21**	.31**	.40**	.39**	.40**	.22**	.32**	.34**								
15 Spacing/ sequencing	.36**	.16*	-.35**	.43**	.30**	.61**	.14	.43**	.28**	.53**	.38**	.39**	.12	.24**							
16 Radio/radar coverage	.12	.32**	.47**	-.07	.22**	-.14	.42**	.14	.30**	.13	.13	-.01	.29**	.24**	-.12						
17 Radio freq. congestion	.37**	.49**	.10	.27**	.57**	.38**	.29**	.38**	.52**	.38**	.20**	.24**	.42**	.40**	.28**	.30**					
18 TMI	.31**	.09	-.48**	.42**	.33**	.57**	.08	.47**	.19*	.48**	.44**	.47**	.16*	.23**	.59**	-.15*	.34**				
19 Terrain/Obstructions	-.03	.20**	.81**	-.29**	-.03	-.34**	.19*	-.08	.06	-.14	-.10	-.22**	.11	-.02	-.32**	.51**	.05	-.41**			
20 Shelves/Tunnels	.24**	.30**	.24**	.05	.18*	-.11	.31**	.19*	.16*	.21**	.12	.07	.28**	.34**	.08	.31**	.17*	.05	.21**		
21 Foreign aircraft/pilots	.18*	.21**	-.10	.26**	.25**	.24**	.40**	.28**	.23**	.32**	.39**	.33**	.44**	.33**	.23**	.21**	.29**	.33**	-.07	.17*	
22 Non-towered airports	.03	.25**	.80**	-.31**	.03	-.31**	.15*	-.12	.11	-.11	-.15*	-.32**	.04	-.07	-.31**	.50**	.02	-.49**	.83**	.23**	-.10

**p < .01; *p <. .05

can be substituted for individual Complexity-Q ratings, thereby reducing the number of predictors without losing information about their interrelationships.

Prior to the analysis, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was examined to test whether partial correlations among the variables were small. KMO values of .6 and above are required for a good solution. A KMO of .87 was produced by the set of variables selected. A PCA with Varimax rotation converged in nine iterations and produced four components with eigenvalues > 1. These components accounted for approximately 62% of the variance in the dataset. As shown in the rotated component matrix in Table 4, all but one of the variables had a loading of .50 or greater with at least one of the components. Only Relative frequency of complex routings failed to demonstrate a strong relationship with any one dimension, with respective loadings of .26, -.35, .35, and .39 on the four extracted components.

Component 1 had an eigenvalue of 4.93 and accounted for approximately 22% of the variance in the dataset. The variables with high loadings on this component seem to describe activity related to climbing and descending aircraft in the vicinity of major airports. When considering these kinds of flights, it is easy to see how the variables that describe this component relate to one another. For example, arrival and departure traffic associated with Major airports (.68) would tend to increase the Number of climbing and descending aircraft (.79). Airspace around major airports tends to have more Intersecting flight paths (.63). Traffic volume (.59) also tends to be higher proximal to major airports. Increased traffic directly impacts the Amount of radio frequency congestion (.58) and in some sectors would increase the Mix of aircraft types (.69). The Amount of coordination required (.74), Number of multiple functions (.73), and Number of required procedures (.66) represent tasks the controller must perform in complex airspace that often surrounds larger airports and would become more exigent in conjunction with the other factors. Perhaps the association of the Size of sector airspace (.51) represents a relationship between the size of the sector and the impact of these activities. In other words, their effects may be mediated by the amount of time available for resolution or completion.

Component 2 had an eigenvalue of 3.67 and accounted for approximately 17% of the variance. This component comprises complexity issues associated with low-altitude sectors that provide approach services into Non-towered airports (.91), the variable with the highest loading on this component. In the Indianapolis airspace, 11 sectors

Table 4. *Principal Components Analysis Rotated Component Matrix*

	Component			
Variable	**1**	**2**	**3**	**4**
Climbing and descending traffic	.79			
Mix of aircraft types	.69			
VFR versus IFR traffic		.90		
Number of intersecting flight paths	.63			
Number of multiple functions	.73			
Traffic volume	.59			.51
Amount of military or other special traffic			.76	
Number of required procedures	.66			
Coordination/ interfacing required	.74			
Number of major airports	.68			
Extent operations are affected by weather				.74
Relative frequency of complex routings				
Special Use Areas			.72	
Size of sector airspace	.51		.56	
Longitudinal spacing/ sequencing				.54
Adequacy of radio/radar coverage		.60		
Amount of radio frequency congestion	.58			
Traffic Management Initiatives				.59
Terrain/Obstructions		.88		
Shelves/Tunnels			.53	
Foreign aircraft/pilots			.60	
Non-towered airports		.91		

* Component loadings < .50 not shown.

provide approach services to airports without towers. Radar coverage does not always reach to the ground, so a loading of .60 for the Adequacy of radio/radar coverage may reflect difficulties associated with this factor. Aircraft flying VFR would also be present in these low-altitude sectors, thus increasing the ratio of VFR versus IFR traffic (.90), the second-highest loaded variable. The complexity factor Terrain and other obstructions (.88) is exclusively low-altitude and is relevant in sectors that provide approach services. In contrast, sectors with non-towered airports do not have a high mix of aircraft types (as most aircraft have lower performance characteristics), have low traffic volume, and limited frequency congestion. Moreover, these sectors have limited multiple functions, coordination, procedures, complex routings, spacing and sequencing, traffic management initiatives, and shelves/tunnels. Thus, it makes sense that complexity ratings for those factors did not load on Component 2.

Component 3 had an eigenvalue of 2.78 and accounted for approximately 13% of the variance in the dataset. Variables associated with this component are primarily related to Military operations (.76) and other Special Use Area (SUA) restrictions (.72). In the ZID airspace, tunnels are associated with military operations. This might account for the relationship of Shelves/Tunnels (.53) with this dimension. Restrictions due to military operations would reduce the amount of usable airspace. Thus, a .56 loading of Size of sector airspace on this dimension makes sense. However, it is unclear why Foreign aircraft/pilots would be associated with this component to such a high degree (.60). Perhaps the unifying theme of this dimension is that each of these factors warrants special consideration or attention, and Foreign aircraft/pilots fall into this category.

Component 4 had an eigenvalue of 2.35 and accounted for approximately 11% of the variance. The variables most strongly associated with this component relate to difficulties associated with inclement weather, as evidenced by the two highest-loaded variables, Extent operations are affected by weather (.74) and Traffic Management Initiatives (.59). Requirements for longitudinal spacing/sequencing (.54) and problems associated with Traffic volume (.51) are also magnified by inclement weather.

The test for a successful PCA is simple: A good PCA makes sense. That certainly appears to be true of the components extracted from the Complexity-Q ratings. In this particular application, the component scores can be used to empirically test some of the assumptions made during component interpretation. For example, if Component 2 really addresses complexity factors endemic to low-altitude sectors that provide services to uncontrolled airports, then Component 2 scores should be significantly higher in those sectors. If Component 3 relates to problems associated with military airspace and SUAs, then factor scores should be higher in sectors that have this kind of airspace.

To gain a clearer understanding of how the components relate to sectors in different altitude strata, a one-way analysis of variance was conducted for each of the components, using mean component scores as the dependent variable. The results demonstrated that mean component scores were significantly different between at least two of the sector groups for Component 1 [$F(2,34) = 7.85, p < .01$], Component 2 [$F(2,34) = 27.87, p < .01$], and Component 4 [$F(2,34) = 6.57, p < .01$].

When viewing the results from post hoc comparisons (Tables 5-7), keep in mind that component scores are composite variables calculated from individual responses weighted by the component loadings. Consequently, the means no longer resemble the original 100-point scale ratings. Post hoc tests revealed that high-altitude sectors had significantly greater mean Component 1 scores than super high-altitude sectors (see Table 5). Although mean Component 1 scores appeared to be greater for high-altitude vs. low-altitude sectors, this difference was not statistically significant.

As anticipated, low-altitude sectors had significantly higher mean Component 2 scores than other types of sectors (Table 6). The mean of Component 2 scores for all low-altitude sectors was .93. However, the complexity factors most closely associated with Component 2 better describe low-altitude sectors that provide services to

Table 5. ***Component Score Descriptive Statistics and*** **Post hoc** ***Comparisons***[†]**:**
Component 1 by Sector Altitude Strata

Strata	**Low**	**High**	**Mean**	***SD***
Low			-.08	.61
High	*p* =.05		.46	.51
Super High	*p* =.21	*p* =.00	-.50	.62

[†] Tukey HSD

Table 6. ***Component Score Descriptive Statistics and*** **Post hoc** ***Comparisons***†***:***
Component 2 by Sector Altitude Strata

Strata	Low	High	Mean	*SD*
Low			.93	.93
High	*p* =.00		-.54	.23
Super High	*p* =.00	*p* =.93	-.62	.15

† Tukey HSD

Table 7. ***Component Score Descriptive Statistics and Post hoc Comparisons***†***:***
Component 4 by Sector Altitude Strata

Strata	Low	High	Mean	*SD*
Low			-.54	.80
High	*p* =.02		.11	.50
Super High	*p* =.01	*p* =.81	.27	.32

† Tukey HSD

non-towered airports. Mean Component 2 scores in these sectors (1.41) were considerably higher than mean Component 2 scores in low-altitude sectors that do not provide such services (-.21). Low-altitude sectors had significantly lower Component 4 scores than high- and super high-altitude sectors. This suggests that difficulties related to inclement weather were rated lower in low-altitude sectors than in the higher altitudes. As with Component 2, there were no significant differences between high- and super high-altitude sectors for Component 4 scores (Table 7).

Component 3 scores did not vary significantly between sectors with different altitude stratum. This is not surprising, because the variables most strongly associated with this component (e.g., special routes, restricted areas) are found at all altitudes. On the other hand, Component 3 scores should be higher in sectors subject to these kinds of restrictions. Based on information derived from sector descriptions in the SOPs, sectors with restricted areas, military training routes, aerial refueling routes, and/or MOAs were grouped for comparison with other sectors. Of the 37 sectors sampled, 26 met one of more of these criteria. Mean Component 3 scores were slightly higher in these sectors (.02) than in others (-.09), but this difference was not significant; $t(35) = -6.12$, $p = .55$.

Comparison of PCA Results with Rodgers, Mogford, and Mogford (1998)

Although differences in measures and methodologies between the present study and Rodgers et al. (1998) render direct comparisons problematic, there were similarities between some of the components that are worthy of note. Table 8 contains loadings for the first and third extracted components from both studies. The correspondence between these components is readily apparent, particularly with regard to Component 1. Rodgers and coworkers named their first extracted component Traffic Activity because the variables associated with it "appeared to be related to traffic volume and activities associated with managing aircraft" (p. 13). For the same reason, the name might accurately describe our Component 1.

Size of sector airspace was positively associated with both Component 1 and Component 3 in our model but had only a small negative loading on Component 1 and a small positive loading on Component 3 in Rodgers et al. (1998). In their analysis, Size of sector airspace was strongly associated with Component 2 (not shown). This is hardly surprising as their Component 2 was named "Size" and consisted almost entirely of static sector characteristics excluded from our analysis. By the same token, none of the components extracted in the Rodgers et al. analysis could have corresponded with our "Non-towered airport" Component 2 because they did not analyze Non-towered airports, VFR versus IFR traffic, or Terrain and other obstructions as complexity factors.

The third extracted component in both analyses was related to Military operations and other Special Use Area restrictions. In the Rodgers et al. (1998) study, Radio and radar coverage had a prominent negative loading, which was inconsistent with our findings. While recognizing that this variable "did not seem to be directly related to military functions," they suggested that it might have been "conceptually associated with military airspace [because] areas that have poor radio and radar coverage, or are

Table 8. ***Comparative Component 1 and Component 3 Loadings***

Variable	Component 1		Component 3	
	Current study	Rodgers et al. (1998)	Current study	Rodgers et al. (1998)
Climbing and descending traffic	**.79**	**.84**	.11	-.10
Mix of aircraft types	**.69**	.18	.31	.07
VFR versus IFR traffic	.01	NA	.09	NA
Number of intersecting flight paths	**.63**	**.45**	.08	.34
Number of multiple functions	**.73**	**.83**	.18	.30
Traffic volume	**.59**	**.63**	-.15	-.14
Amount of military or other special traffic	.11	.13	**.76**	**.68**
Number of required procedures	**.66**	**.85**	.14	.17
Coordination/ interfacing required	**.74**	**.48**	.20	.33
Number of major airports (Hubbing)	**.68**	**.55**	.11	-.38
Extent operations are affected by weather	.18	**.66**	.21	.11
Relative frequency of complex routings	.26	**.55**	.35	.06
Special Use Areas	.20	.10	**.72**	**.48**
Size of sector airspace	**.51**	-.29	**.56**	.24
Longitudinal spacing/ sequencing	**.43**	**.57**	-.02	-.32
Adequacy of radio/radar coverage	.14	.12	**.45**	**-.59**
Amount of radio frequency congestion	**.58**	**.62**	.32	-.09
Traffic Management Initiatives	.33	NA	.08	NA
Terrain/Obstructions	-.02	NA	.11	NA
Shelves/Tunnels	.21	.09	**.53**	**.44**
Foreign aircraft/pilots	.08	NA	**.60**	NA
Non-towered airports	.04	NA	.02	NA

controlled by the military, are relatively inaccessible to FAA ATC" (p. 13). This explanation could just as easily apply to our positive loading of .45.

In our analysis, Relative frequency of complex routings was not associated with any one component, but in the Rodgers et al. (1998) study, it had a definitive Component 1 loading (.55). This probably reflects disparate sample characteristics. The only discernable divergence between ratings provided by supervisors and controllers in our sample was that supervisors consistently rated the Relative frequency of complex routings higher than controllers did. Unfortunately, we cannot make any inferences about the comparative influence of the Relative frequency of complex routings in ZID and ZTL because of these sample differences.

In spite of the dissimilarities noted, it is the similarities that are most striking. Considering statistical differences (i.e., rotated vs. un-rotated matrix, four vs. six extracted components), sample differences (i.e., ratings provided predominantly by controllers vs. ratings only provided by supervisors), variable set differences (i.e., 22 complexity factors vs. 16 complexity factors with variables derived from other sources), and airspace differences (i.e., ZID vs. ZTL), the obvious parallels between Components 1 and 3 and the dimensions they describe are remarkable.

Multiple Regression Analysis of Complexity Factor Scores With Operational Errors

As previously mentioned, one of the primary benefits of using PCA in this application is consolidation of the individual complexity factors into a reduced number of components. The method used to compute component scores (i.e., weighting individual responses according to that variable's relationship with the dimension) tends to produce variables with normal distributions. Moreover, orthogonal rotation methods make it virtually impossible for the components, as a predictor set, to suffer from multicollinearity. Therefore, there is little question as to their appropriateness for multiple regression analysis. In this sample, the distribution of the number of OEs per sector had a mean of 6.68, with a standard deviation of 4.23 (Skewness = .61, SE Skewness = .388; Kurtosis = -.67, SE Kurtosis = .759). This was less than two standard deviations from normal in skewness and less than one standard deviation from normal in kurtosis. Consequently, both the predictors (the component scores) and the criterion (the number of OEs) met assumptions

Table 9. ***Multiple Regression Analysis: Complexity Component Scores on Number of Operational Errors* (*N* = 37)**

Variable	*B*	*SE B*	*t*	*β*
Component 1	4.62	.69	6.67	.75**
Component 2	-1.18	.51	-2.33	-.26*
Component 3	1.54	.95	1.62	.19
Component 4	-.33	.73	-.45	-.05

** p = <.01; * p = <.05

of normality. No univariate or multivariate outliers were detected. Studentized[1] residuals plotted against predicted values were randomly distributed in a horizontal band around zero, indicating that the assumption of linearity and the assumption of equality of variance were met. Visual examinations of the cumulative probability plot of the observed distribution of residuals against that expected of a normal distribution demonstrated that the assumption of normally distributed errors was also met.

Standard multiple regression of the extracted complexity components on the number of OEs per sector produced a multiple $R = .78$ ($R^2 = .61$) that was significantly different from zero, $F(4,32) = 12.72, p < .01$. Note that in this analysis the number of ZID sectors has been reduced from 40 to 37 due to sector combinations that were recommended by ZID personnel to facilitate the administration of the Complexity-Q questionnaire. As shown in Table 9, Components 1 and 2 contributed a significant amount of unique information to the model, whereas Components 3 and 4 did not.

Conclusions

The present study is the second phase of a multi-year project (called SCOpE) to better understand the contribution of sector complexity measures to the occurrence of OEs in en route air traffic control. To do this, we plan to measure complexity by examining both static and dynamic measures as well as subjective and objective measures. The static/dynamic distinction involves relatively unchanging characteristics of the sector (such as size, strata, length of jet ways and airways, number of airports, required procedures, number of shelves) and more transitory aspects of the traffic situation (such as amount of traffic, weather, aircraft mix, climbing and descending aircraft). The subjective/objective method incorporates both controllers' opinions about the importance of complexity factors and impartial information extracted from environmental data.

Because limited data were available during the first year of the project and because of the lengthy processing time required to produce the objective dynamic data obtained during the second year, we have not yet been able to evaluate the effectiveness of the two measurement methods. In this study, we looked at subjective ratings for a set of combined static and dynamic sector characteristics. Next year, we will complete the project by adding objective dynamic sector information to the analysis.

In the first two years of the SCOpE project, we progressively analyzed the relationship between objectively measured static sector characteristics and OE occurrence in isolation. This does not mean that we believe they function in isolation. As Buckley et al. (1983) concluded, traffic density and sector geometry "interact in a complex way" (p. 73). The modest prediction (43%) of OE occurrence produced by the static variables sector size, sector strata, and number of major airports in the Goldman et al. (2006) study was to be expected because the corresponding objective dynamic variables with which they interact were missing from the equation. However, the analyses of static characteristics provided us with a baseline by which to evaluate the objective dynamic measures.

The controllers' subjective ratings provided a perspective about the importance of complexity factors not available from the objective data. Furthermore, the PCA of subjective complexity ratings was extremely beneficial because the extracted components provided a complexity "profile" of the ZID sectors as perceived by the controllers who rated them. Four components were extracted that described different dimensions of complexity common to ZID sectors.

We interpreted the meaning of the components based on the loadings of the individual complexity factors. By examining the relationship between objective measures and the subjectively derived component scores, we were able to discern at least one dimension that was reliably associated with a particular type of sector (i.e., Component 2, that described sectors providing services to non-towered airports). Thus, we identified specific complexity factors that are particularly relevant in these sectors.

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[1] Studentized residual: The residual divided by an estimate of its standard deviation that varies from case to case, depending on the distance between the case value of the independent variable and the mean of the independent variable (Norušis, 1990).

Other complexity components were more difficult to describe. Component 1 appeared to be related to activities associated with the control of climbing and descending aircraft in the vicinity of major airports, and Component 3 seemed to be related to military operations and special use airspace. However, we were unable to verify our interpretations by comparing the component scores with external objective measures. Nevertheless, the concordance of our Components 1 and 3 with the first and third components in Rodgers et al. (1998) suggests that these dimensions, though difficult to describe, may be common to more than one facility. The number of possible predictors in the scientific literature and the lack of concordance between studies make the discovery of two potentially stable dimensions a major finding.

We then conducted a multiple regression analysis that used the four complexity components to predict OE occurrence. Only Component 1 (major airports) and Component 2 (non-towered airports) explained a significant amount of the variance in OEs in the ZID sectors ($R = .78$, $R^2 = .61$). Component 1 was positively associated with the number of OEs (i.e., higher scores were related to a higher number of OEs), whereas Component 2 had a negative relationship (higher scores were related to fewer OEs). Considering that the component scores were based on subjective ratings of sector complexity factors and did not include any variables explicitly describing individual behavioral or organizational aspects associated with OEs, 61% explained variance is impressive. However, components were constructed from "human-weighted" complexity factors, and so it is possible that the human element was not entirely missing from the equation. The relationship between Component 2 and the incidence of OEs reminds us that sector complexity does not always produce a negative outcome. Indeed, a certain degree or type of complexity may be related to a reduction in OEs.

The insight gained by analysis of the subjective ratings provided by ZID personnel (i.e., the identification of complexity dimensions and the variables most closely associated with them) will guide our efforts as we move on to the next phase of this project. Certainly complexity characteristics associated with Components 1 and 2 will be the subject of close scrutiny. Of course, complexity factors associated with the other dimensions will also be of interest. The fact that Component 3 failed to contribute significantly to the prediction of OEs in this analysis does not mean that military airspace or SUAs don't make a sector more difficult to work or increase the likelihood of an OE. It simply means that subjective ratings of these factors failed to predict OEs. Similarly, the inability of Component 4 to contribute significantly to the regression model may reflect the intermittent nature of this dynamic event, or it may simply be an artifact of the way the variable was measured. In other words, the presence of inclement weather might be highly correlated with the occurrence of OEs but the component scores based on subjective ratings of variables associated with inclement weather were not.

The next phase of the SCOpE project involves analyzing objective measures that correspond to the subjective ratings of dynamic complexity factors examined in the present study. While static complexity factors (measured both objectively and subjectively) have so far had limited value in providing useful information about OE occurrence, objective dynamic measures should be much more descriptive and relevant.

Practical prediction models (linear or otherwise) must eventually be calculated from objective measures because the actual characteristics of the sectors must be addressed when developing strategies to reduce OEs. Nevertheless, subjective information about the importance of complexity factors can guide the choice of objective measures for analysis and may also be used to weight their importance. A potential application for the information gained from this study is a tool that could be used by airspace designers to evaluate the potential OE risk associated with different design concepts.

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APPENDIX A

Principal Components Rotated Component Matrix

	Component			
Variable	**1**	**2**	**3**	**4**
Climbing and descending traffic	.79	.02	.11	.11
Mix of aircraft types	.69	.22	.31	-.13
VFR versus IFR traffic	.01	.90	.09	-.17
Number of intersecting flight paths	.63	-.40	.08	.14
Number of multiple functions	.73	.07	.18	.22
Traffic volume	.59	-.28	-.15	.51
Amount of military or other special traffic	.11	.19	.76	.19
Number of required procedures	.66	-.08	.14	.37
Coordination/ interfacing required	.74	.13	.20	.12
Number of major airports	.68	-.12	.11	.32
Extent operations are affected by weather	.18	-.03	.21	.74
Relative frequency of complex routings	.26	-.35	.35	.39
Special Use Areas	.20	.10	.72	.20
Size of sector airspace	.51	-.20	.56	-.15
Longitudinal spacing/ sequencing	.43	-.32	-.02	.54
Adequacy of radio/radar coverage	.14	.60	.45	.06
Amount of radio frequency congestion	.58	.08	.32	.15
Traffic Management Initiatives	.33	-.47	.08	.59
Terrain/Obstructions	-.02	.88	.11	-.09
Shelves/Tunnels	.21	.16	.53	-.16
Foreign aircraft/pilots	.08	-.10	.60	.45
Non-towered airports	.04	.91	.02	-.16