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STUDY ON THE INTEGRATION OF HUMAN PERFORMANCE AND ACCIDENT RISK ASSESSMENT MODELS: AIR-MIDAS & TOPAZ

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A computational model of human performance (Air Man-machine Integration Design and Analysis System, Air MIDAS) and an accident risk assessment methodology (Traffic Organization and Perturbation AnalyZer, TOPAZ) were integrated in order to learn about the similarities and differences of their models, to demonstrate the feasibility of such integration, and the integration impact on accident risk assessment.

Introduction

In the analysis and design of advanced operations in complex, dynamic, human-machine systems, accident risk assessment is a critical component of effective system engineering. Probability Risk Assessment (PRA) techniques typically model such complex system by assigning conditional probabilities of the success, or failure for system operations into fault and event trees (e.g. Kumamoto and Henley, 1996). Subsequently, an assessment of risk is undertaken by evaluating the combined effects of the conditional probabilities in these fault and event trees. The role and contribution of the human operator has proven to be a significant element to both accident risk (Hollnagel, 1993), and to system safety and effectiveness (Dekker 2001).

The development of models that represent the contribution of the human operator to risk has been explored for some 30 years (Swain & Guttman 1983). The function of the human operator was either assigned a probability of success or failure, as would be provided for any system component, and the "integration" was the inclusion of those probabilities in the overall system success failure assessment. A serious limitation of fault and event tree based PRA is its inability to evaluate the effects of concurrent and dynamic behavior on accident risk. The remedy is to exploit stochastic dynamical modeling and Monte Carlo simulation of the concurrent and dynamic processes for accident risk assessment (e.g. Labeau et al., 2000) and to include explicit representation of human performance in individual and on teams (e.g.,. Cacciabue, 1998 or Corker, 2000)

In order to apply this approach to air traffic management, multiple human operators and their interactions with each other and with aircraft and ground systems have to be modeled and simulated.
Both with the human performance model Air-MIDAS (Corker, 2000) and with the accident risk assessment methodology TOPAZ (Blom et al., 2001, 2003; Stroeve et al., 2003), significant and complementary headway has been made. We report here on the integration of Air-MIDAS and TOPAZ in aviation safety assessment.

The objective of this integration is to combine the significant advances established in individual human performance representation and human performance factors (human factors in general and human cognitive behavior in particular) through large-scale simulations for accident risk assessment. As an objective test for the success of this integration we hypothesize that this combination allows Air-MIDAS to provide simulation results for individual human operators which improves the accident risk assessment.

The aviation community continues to be concerned with accident risk and runway operations and several technologies have been under development to mitigate this risk. Given the relevance of these operations to both safety risk and human performance, an integrated simulation of the baseline conditions for runway incursion avoidance was undertaken by Air-MIDAS and TOPAZ simulation toolset TAXIR for this operation.

Integration of human modeling approaches

Because of the complementary objectives and separate developments of Air-MIDAS and TOPAZ their human performance modeling approaches show similarities and differences. Their potentially complimentary functions form the reason why this integration is so useful and challenging at the same time. In the course of the integration study the complementary human performance modeling details of both approaches have become clear. A short explanation of this is given next, including an overview in Table 1.

Table 1 *Human performance modeling in Air-MIDAS and TOPAZ*

		Air-MIDAS	TOPAZ
A	Management modes	Max-load or Even-load	None
	Control Modes	Matching with Rasmussen's SRK (Skill, Rule, Knowledge)	Matching with Hollnagel's tactical and opportunistic control modes
	Switching between modes	Fixed thresholds	Thresholds with hysteresis
B	Task Scheduling	Goal oriented subtask scheduling	Priority rules for aggregated tasks
	Resources model	Multiple: Visual, Auditory, Cognitive, Psychomotor	Aggregation on the basis of time-critical tasks/resources combinations
	Memory model	Procedural (with decay) Declarative (with decay) Knowledge (no decay)	Aggregated (no decay)
C	SA model	SA of one human only	Multi Agent SA and interactions
D	Human error	Is result of detailed modelling	Amalberti's error recovery model is added
E	Behaviour of Non-human entities	Nominal	Nominal & Non-Nominal
F	Specification language	Air-MIDAS specific, based on LISP	Dynamically Coloured Petri Nets (DCPN)

Integration of these approaches ensures that the simulation scenario under examination is jointly represented in the two modeling systems. This allows identification of values for specific parameters of human performance in the TOPAZ simulation model to be supplied by the Air MIDAS simulation. These parameter values are generated in Monte Carlo runs of the human performance model and subsequently supplied as input to improving TOPAZ simulations. In so far as the modeling paradigms allow similar representation, this parameter exchange is straightforward. For example, simulation of pilot reaction time to recognition of an incursion by the taxiing aircraft is represented in both modeling processes, hence reaction time is a straight forward parameter value to exchange.

Application context

The following operational concept for crossing of an active runway is being considered. A simplified representation of the runway configuration is used, as shown in Figure 1. It consists of one runway with a crossing at a length y_3^b from the runway start threshold. The crossing has remotely controlled stopbars on both sides of the runway. The runway is being used for taking off aircraft. The traffic crossing over the runway accounts for traffic between apron(s) and a second runway. The involved human operators include the start-up controller, the ground controller, per runway a runway controller, the departure controller, and the pilots flying and pilots not flying of taking-off aircraft and crossing aircraft.

Communication between controllers and aircraft crews is via standard VHF R/T. Communication between controllers is supported by telephone lines. Monitoring by the controllers can be by direct visual observation and is supported by radar track plots. Monitoring by the aircraft crews is by visual observation and is supported by the VHF R/T party-line effect.

In the runway crossing operation considered, the control over the crossing aircraft is transferred from the ground controller to the controller of the runway to be crossed. If the runway controller is aware that its runway is not used for a take-off, the crew of an aircraft intending to cross is cleared to do so. The pilot not flying of the crossing aircraft acknowledges the clearance and then the pilot flying initiates the runway crossing. As soon as the crossing aircraft has vacated the runway, then the pilot not flying reports this to the controller of that runway. Next the control over the aircraft is transferred from this runway controller to either another runway controller or to the ground controller.

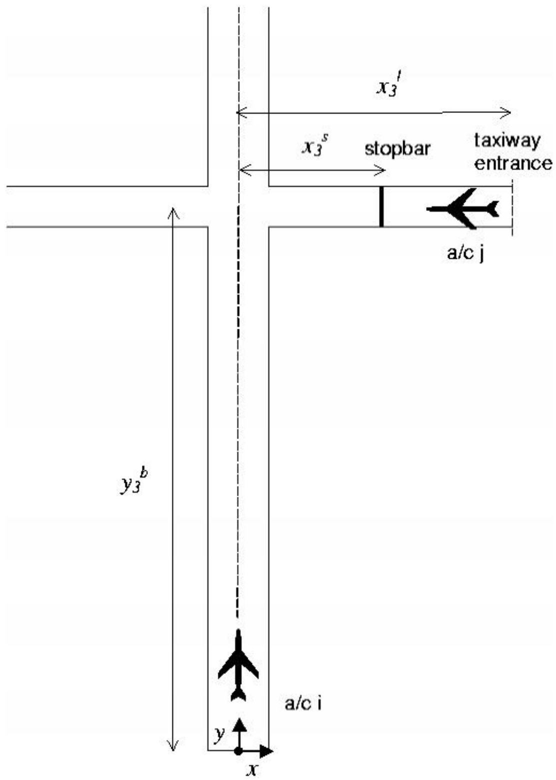

Figure 1: ***Configuration of active runway crossing operation considered. Aircraft i and j respectively take off from a position at the runway start and taxi along a taxiway leading to a runway crossing at a given distance from the runway start.***

Joint model for integrated simulations

The TOPAZ and Air-MIDAS simulation models consider the following human agents: pilots flying for both the taxi aircraft and the taking off aircraft, and the runway controller. The most important elements of these human and other entities are shortly described below.

Initially, the pilot flying (PF) of the taking-off aircraft has the situation awareness (SA) that take-off is allowed and initiates a take-off. During the take-off the PF visually monitors the traffic situation on the runway. During a monitoring action the PF may not observe the crossing aircraft, because of a limited gaze angle or the distance with the crossing aircraft exceeds a viewing threshold, or occasional heads-down time for engine parameter sampling. The monitoring process includes distance dependent error components. Furthermore, the PF monitors the VHF communication channel. The PF of the taking-off aircraft starts a collision avoiding braking action if (s)he observes the crossing aircraft within a critical distance of the runway centre-line or in reaction to a controller clearance, and (s)he decides that braking will stop the aircraft in front of the crossing aircraft.

Initially, the PF of the taxiing aircraft has the SA that either (s)he is taxiing on a regular taxiway, which does not cross a runway or (s)he is taxiing on a taxiway approaching the runway crossing. In the latter case the PF may have the SA that crossing is allowed. Both in the case that the PF has the SA that (s)he is taxiing on a regular taxiway and in the case that the PF is aware that a runway crossing is allowed, the PF proceeds on the runway crossing. During taxiing the PF visually monitors the traffic situation. The characteristics of the monitoring process depend on the SA of the PF concerning the next airport waypoint (either runway crossing or taxiway). After passage of the stopbar the PF may receive a hold clearance by the runway controller. There is a probability that the controller message is not properly understood by the PF. In response to a hold clearance or an observed conflict the PF initiates braking of the aircraft, unless the cockpit of the crossing aircraft is estimated to be already within a critical distance of the runway centre-line.

The runway controller visually monitors the traffic situation on the runway. There is a probability that during monitoring an aircraft is not observed. In response to an alert, the controller directly monitors the traffic situation and the TOPAZ controller model updates the SA. If the controller is aware that the crossing aircraft has passed the stopbar then (s)he specifies a hold clearance to both the crossing and the taking-off aircraft.

Parameters jointly represented

As noted, the representations that the two simulation modeling systems provide are in some ways similar and in others different. Upon examination of the similarities and differences of the models used for the surface operation considered by Air MIDAS and by the TOPZ-TAXIR toolset, a list of model parameters to be affected by the joint runs was identified. These parameters are grouped and provided as follows:

- braking initiation times of pilots flying;
- inter-monitoring time of pilot flying of taxiing aircraft;
- duration of visual observation of pilots flying.

Braking initiation time of PF's This parameter group includes the braking initiation times of pilots flying of taking-off or taxiing aircraft in either tactical of opportunistic mode, when they have become aware of a conflict with the other aircraft. In an overview is provided of the probability density functions (PDF's) and related parameter values for Air-MIDAS and the original and the modified TOPAZ-TAXIR. In all three models equal PDF types and parameter values for the braking initiation times are chosen for the pilots flying of the taking-off and taxiing aircraft, regardless of their cognitive control modes.

It was observed that in comparison to Air-MIDAS, the original TOPAZ-TAXIR has a smaller mean braking initiation time, and a larger tail (probability of more than 5 s initiation time). In order to improve on these aspects, for the modified TOPAZ-TAXIR model the Rayleigh PDF has been selected. The improvements are:

- its shape better fits to the Air-MIDAS data,
- it supports positive values only,
- has a more realistic tail than Gaussian PDF

The parameter value of the Rayleigh PDF has been chosen such that its standard deviation equals the standard deviation of the PDF chosen in Air-MIDAS.

Inter-monitoring time of PF of taxiing aircraft

It is assumed in TOPAZ-TAXIR that the inter-monitoring time of the pilot flying of the taxiing aircraft is independent from the cognitive control mode of the pilot. In the original model this time was represented by an exponential probability density function. Simulations of Air-MIDAS resulted in a data-set of 536 inter-monitoring times of the taxiing pilot flying. These data were well represented by an exponential PDF. Therefore, in the modified model the inter-monitoring times of the taxiing PF are also chosen from an exponential PDF with a mean equal to the estimated mean of the Air-MIDAS data.

Duration of visual observation of PF's

This parameter group includes the visual observation times of pilots flying for the taking-off or taxiing aircraft in either tactical of opportunistic mode. The PDF's of these times in the original model are exponential PDF's with a mean that is smaller in the opportunistic mode than in the tactical mode.
Air-MIDAS simulations provided data on the duration of the tasks:

- 'Monitor Out The Window' for the PF of the taking-off aircraft, and
- 'Decide Action - Decide Take-off Spotted' for the PF of the taxiing aircraft.

These tasks were found to be in good agreement with the visual observation tasks of the pilots flying of the taking-off and taxiing aircraft, respectively. These data were provided for the three control modes used in Air-MIDAS.

Integration Impact on Collision Risk Model

In Table 2 the collision risk results of both versions of TOPAZ-TAXIR are shown for three values of the distance of the runway crossing with respect to the runway start threshold. It follows from these results that the collision risks as evaluated by the modified model are smaller than those evaluated by the original model and that the relative differences in collision risk tend to get larger for larger crossing distances. In all cases, the difference between the results is within a factor two.

Table 2: *Collision risks evaluated by the original and modified TOPAZ-TAXIR models for three crossing distances.*

Crossing distance	**Original Collision Risk** (occurrence per take-off)	**Modified Collision Risk** (occurrence per take-off)
500 m	$1.3\ 10^{-8}$	$1.2\ 10^{-8}$
1000 m	$1.1\ 10^{-8}$	$7.1\ 10^{-9}$
2000 m	$8.0\ 10^{-9}$	$4.4\ 10^{-9}$

The collision risk value that result from the TOPAZ-TAXIR simulations is composed of risk contributions from combinatorially many event sequences (Stroeve et al., 2003). In particular, the event sequence classes include the status of technical systems, such as alerting systems and communication systems, aircraft types, and human operator situation awareness. Since the adaptations of TOPAZ-TAXIR in the integration process with Air-MIDAS all consider assumptions regarding the behaviour of pilots flying, it is interesting to compare the risk decomposition for a pilot flying in the original and modified models. In particular, in Figure 2, collision risk results are shown for the situations that

- the pilot flying of the taxiing aircraft believes to be on a regular taxiway, or
- The pilot flying of the taxiing aircraft believes that runway crossing is allowed.

In the first case the pilot is lost, in the second case the situation awareness corresponds well with the actual position of the aircraft. It can be observed in Figure 2 that in both the original and the modified model, the risk contribution for the situation that the pilot is aware to be on a regular taxiway exceeds the risk contribution for the situation that the pilot is aware to be on a runway crossing. However, the difference between those risk contributions is smaller in the modified model than in the original model.

On the one hand, the reduced difference in the risk contributions between the model versions is due to an increase in the risk contribution for the situation that the pilot flying is aware to be on a runway crossing in the modified model. The model modifications that may effect this risk increase concern the braking initiation times by the pilots flying of both aircraft, and the duration of the visual observation tasks of the pilots flying of both aircraft.

For a further evaluation of the effects of these modifications a sensitivity analysis is required. As a preliminary finding, the risk increase is especially due to the increase in mean braking initiation times and may be to a smaller extent due to the increase in mean visual observation time in the opportunistic mode.

On the other hand, the reduced difference in the risk contributions between the model versions is due to a decrease in the risk contribution for the situation that the pilot flying is aware to be on a regular taxiway in the modified model. The risk decrease in this situation is effected by all model modifications. The combined effect of the changes in the braking initiation times and the visual observation times is a risk increase. The decrease in the mean inter-monitoring time of the pilot flying of the taxiing aircraft leads to a risk decrease because it causes the pilot to monitors for conflicting traffic more often. The combined effect turns out to decrease risk.

Conclusions

The results showed that the Air-MIDAS based adaptation did lead up to a factor two reduction in assessed collision risk level. This result alone demonstrates that it is feasible and useful to couple Air-MIDAS and TOPAZ. More importantly this means that we have now running two human performance simulations for more or less the same situation. This gave us the unique chance to make further comparisons between the two simulation approaches.
We examined the change in collision risk assessment resultant from the integration of these two models. In the scenario examined, the actions of the flight crew and ATC are largely perceptual-motor response to runway incursion. The impact assessment reported reflects the change in those characteristics. More complex decision making or coordinated action among agents and safety augmentation technologies would require full representation of the models of those more complex interactions.
In order to recognize the logical pattern in these differences, one should be aware that both are aimed to assess quite different top-level metrics. Air-MIDAS top-level metric is the behavioral pattern of human operators; while TOPAZ top-level metric is collision risk. The implied focal attention in TOPAZ is on performance, error making and error propagation among multiple agents versus memory and task scheduling and performance in Air-MIDAS. For error mechanisms the error recovery model of Amalberti & Wioland (1997) has been reported for two types of stress levels. This is reflected by the two control modes of TOPAZ and avoids the need to model a lot of memory and task performance characteristics. In Air-MIDAS the adoption of the Skill Rule Knowledge (SRK) model of Rasmussen for task performance leads to three control modes, and with this the need to model memory and task scheduling and performance in detail. The complementarity of TOPAZ and Air-MIDAS makes it so interesting to compare simulation results obtained by both approaches.

From a validation perspective both approaches have much in common: they produce results on basis of carrying out simulations with a mathematical/computational model and by its very nature, a mathematical/computational model differs from reality. In order to validate a mathematical/computational model in a systematic way, the following activities should be performed:

- Identification of the differences between the mathematical model and the reality, and
- Assessment of the effect of these differences on the value of the output metric(s).

This validation process termed bias and uncertainty assessment is scheduled to be undertaken for the integrated simulations of Air-MIDAS and TOPAZ-TAXIR for the runway operation considered.

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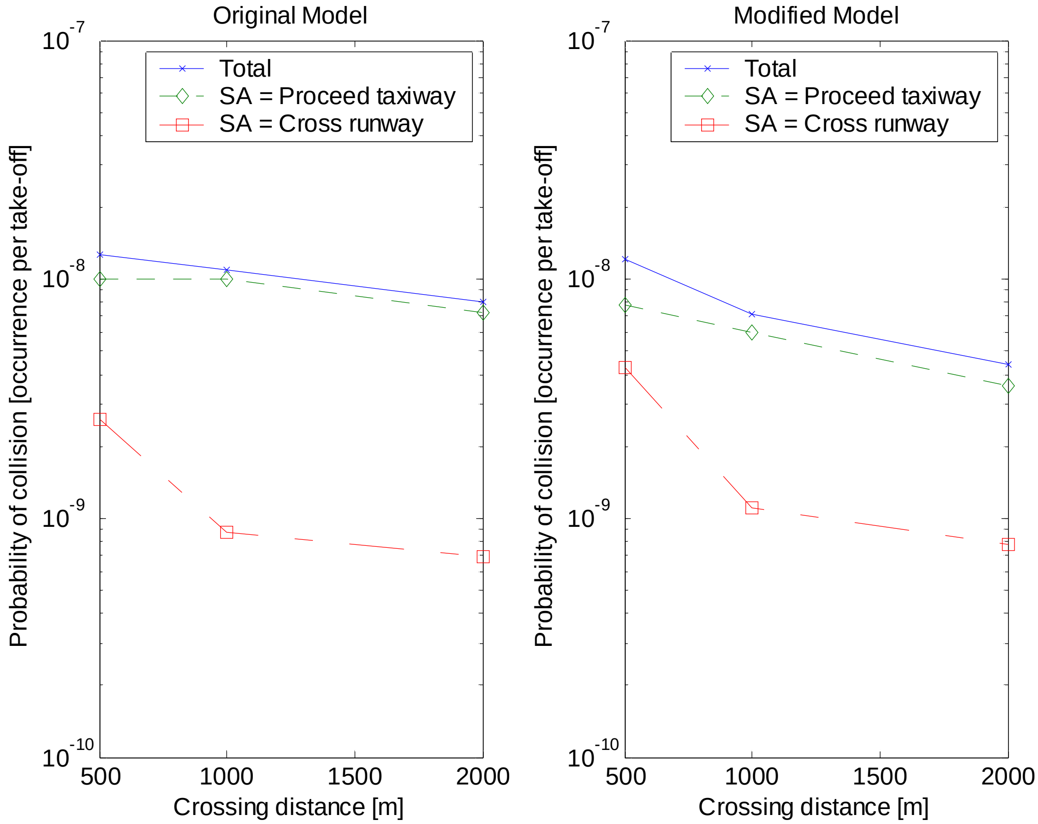

Figure 2: *Total risk per take-off aircraft to collide with a crossing aircraft and contributions to this by correct and incorrect SA by the PF of the crossing aircraft; left for the original, right for the modified TOPAZ-TAXIR model.*

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AB INITIO TRAINING IN THE GLASS COCKPIT ERA: NEW TECHNOLOGY MEETS NEW PILOLTS
A Preliminary Descriptive Analysis

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The Aerospace Department at Middle Tennessee State University and the NASA Langley Research Center entered into a cooperative agreement in 2003. The project is named the SATS Aerospace Flight Education Research (SAFER) and is part of NASA's Small Aircraft Transportation System (SATS) initiative. The SATS project envisions a future flight environment that employs small aircraft to transport people and cargo from point to point using smaller, under utilized airports instead of major gridlocked airports. The aircraft used in the SATS vision would take advantage of a range of emerging technologies including glass cockpits, new structures, and new engines. But with the understanding that the best aircraft and the best systems are still only as good as its operator, MTSU Aerospace set out to explore how pilot training might be different in the SATS environment. The SAFER project therefore takes beginner pilots and completes their initial Visual Flight (VFR) and Instrument Flight (IFR) flight training in technically advanced aircraft to determine how best to educate the next generation of pilots in the next generation of aircraft.

Introduction

Once the use of "glass cockpit" technology was reserved for airline and military flight crews. Today this technology can be purchased off-the-shelf from several general aviation aircraft manufacturers. Placing a general aviation pilot directly into such a sophisticated cockpit has many worried. The General Aviation Technically Advanced Aircraft (TAA)– Safety Study (2003) has already identified several accidents attributed to the fact that the pilots were not familiar with the technology available to them in their aircraft. Several studies are underway to aid pilots as they transition from round-dial airplanes to computerized flight displays – but that is not the emphasis of the study at MTSU. The SAFER project brings in potential pilots with little or no previous experience and teaches them to fly from the beginning with TAA.

The Students

All the students of the SAFER project are college students majoring in Aerospace at Middle Tennessee State University. To become eligible for the SAFER project students had to meet two criteria. First, they must have already been accepted into the program's flight laboratory, which requires a 2.5 cumulative college GPA, or a 2.8 high school GPA for incoming freshman students. Second, the students must have had less than five flight hours of experience with a flight instructor. Fifteen students formed the first cohort of SAFER students. The training began in September 2004 as the fall semester started. The second cohort began in January 2005 as the spring semester started.

The Training Syllabus

The features of the Garmin G-1000 system make it possible to blend the world of visual flight and the world of instrument flight – but that is not the traditional way that students are taught today. Students are taught visual flying first and pass a series of tests to obtain the Private Pilot Certificate. The Private Pilot then takes on additional training and testing to become Instrument Rated and this allows the pilot to fly in and through the clouds. The Primary Flight Display of the G-1000 provides a representation of the horizon that is far advanced from basic attitude gyro indications. The system, in effect, turns a dark night into daylight, and clouds into clear weather. The researchers wanted to take advantage of this capability and sought to teach the new students both the visual and instrument skills all at once.

Part of the cooperative agreement with NASA called for the SAFER project to work in conjunction with the FAA Industry Training Standards (FITS) initiative. The FITS group had previously developed a generic flight training syllabus that combined the training for both Private Pilot and the Instrument Rating into one. The SAFER team took the generic FITS combination syllabus and rewrote it for specific use at MTSU. In time, the syllabus was approved by the FAA under Part 141 and added to

MTSU's existing Air Agency Certificate. The MTSU version of the FITS syllabus (2004) became the first combination Private and Instrument Course for Technically Advanced Aircraft ever approved by the FAA.

The syllabus was unique in two other important ways. First, the entire combination Private and Instrument course is scenario based. Traditionally, pilots are trained using a series of maneuvers that the student masters with drill and practice. The SAFER syllabus still teaches basic skills, sometimes referred to as "stick and rudder" skills, but instead of drill and practice, the maneuver is incorporated into an overall scenario lesson. The very first lesson of the SAFER syllabus is a flight to another airport – a mission, rather than a set of maneuvers. The second unique feature of the SAFER syllabus is that it has no minimum flight time requirements. Traditionally trained students must meet several minimum flight time requirements to move from one step to another and to receive FAA pilot certification. It would be possible for a pilot to have achieved an acceptable performance level in a particular area of training, but still be required to take additional training just to reach the minimum flight time number. Students in the SAFER project are judged by performance only not flight time. When students complete each lesson of the SAFER syllabus they are recommended for testing regardless of how many or how few flight hours they have accrued.

The FAA Exemption

A major problem for the SAFER students is that they are training in a time of transition. The syllabus that they use and the airplane that they use are all new, but the FAA testing is old. Today, the Code of Federal Regulations 14, Part 61.65(a)(1) (2005) requires that an applicant for the Instrument Rating, already be the holder of the Private Pilot Certificate. But the SAFER syllabus bypasses the Private Pilot test when students would otherwise be eligible to take it. Instead, the SAFER students remain as student pilots until the day that they take the combination test and become Private Pilots and Instrument Pilots all at once. So the SAFER syllabus, is in fact, in violation of the Federal Aviation Regulations. To remedy this incongruency, the SAFER researchers petitioned the FAA for relief from 61.65(a)(1) and on December 10, 2004, the FAA granted an exception to this rule for the SAFER project. FAA exemption number 8456 (2004) allows the SAFER students to take a single practical test to gain both Private Pilot and Instrument Pilot privileges. The exemption came with a new Practical Test Standard (PTS) that is to be used by a pilot examiner when administering the combination test. The exemption has only been granted to MTSU and the SAFER project and extends until December 1, 2006.

The exemption has not eliminated all "old versus new" roadblocks to the training. The SAFER students still are required to take two knowledge tests that are administered via computer. The two tests contain questions that are not applicable to technically advanced aircraft. The new PTS that came along with the exemption is better than two separate tests, but still requires many drill-and-practice type maneuvers that do not match well with the SAFER scenario based syllabus. This forces the SAFER students to step out of the role of the scenario and occasionally revert back to pure maneuver practice simply to meet the requirements of the test. Using the old form of testing with the new form of training has become a very real impediment to the students that lengthens the time of training and pushes instructors to "teach to the test" rather than "teach for the real world" as the SAFER project intends to do.

The Methodology

The researchers of the SAFER project are in the preliminary stages of the data collection. The project is on going and the final report of findings will come at the conclusion of the project. The researcher are gathering data to help answer some of the basic research questions: If you teach people to fly from the very beginning using glass cockpits, are there any topics and/or skills that have been taught traditionally that are now no longer necessary? Will glass cockpits create new challenges for beginners that have not been contemplated previously? Can pilots learn essential skills faster and more completely using TAA? To help find some answers, the researchers started a comparison between the SAFER students and the performance of past students that were taught in traditional ways.

The Airplanes

In 2003, the Aerospace Department was able to purchase 25 new airplanes for their professional pilot degree program. Of these, eleven were

Diamond DA40s. As a part of the NASA cooperative agreement, five of the DA40s came to MTSU with the Garmin G-1000 glass cockpit system installed. These five airplanes were taken out of the traditional flight training fleet and are used exclusively within the SAFER project.

Early Findings

The researchers first looked backward to evaluate traditional flight training from the first flight until a person became an Instrument Rated Pilot. The pilot training records of past students served as archival data of traditional flight training. Nineteen past student training records were used in the study. Researchers took the training records of students who had taken both their Private Pilot and Instrument Pilot training all at MTSU and all used the traditional FAA approved syllabus. The traditional syllabus adopted by MTSU and approved by the FAA is the Jeppesen Private Pilot Syllabus (2002) and the instrument portion of the Jeppesen Instrument and Commercial Syllabus (2003). The two publications are commercially available and widely used as an industry standard throughout civilian flight training. The traditional path from first flights to Instrument Rated pilot goes first through the Private Pilot curriculum and testing, then through a series of visual flights to other airports (cross country), and finally to the specific training that leads to testing for the Instrument Rating.

Bottlenecks

Using the archival data provided by the FAA training records, the researchers examined the process of traditional training. What was discovered was a pattern of predictable bottlenecks throughout the training. A bottleneck, for this purpose, is defined as a lesson or area of training that requires the student to receive additional instruction, beyond that which is prescribed in the FAA syllabus, to reach mastery of that lesson or area. These bottlenecks represent areas that are more difficult for students, in that it requires more training to achieve the completion standards. One of the basic research questions is: Do the SAFER students experience the same bottlenecks in their training as traditional students do? Would SAFER students have less problems, or different problems than their counterparts who received the type of training that is available nationwide to the general public and to other college students? In order to answer this question the researchers first identified the traditional bottlenecks in the three phases of the training: Private Pilot, Cross Country, and Instrument.

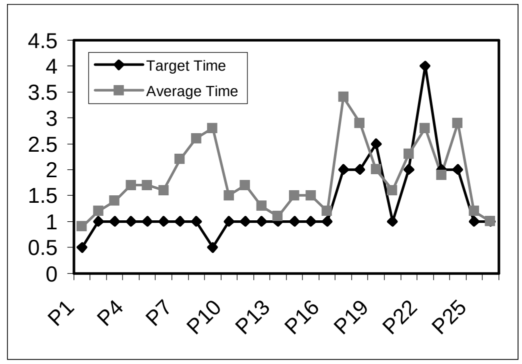

Figure 1. *Private Pilot Bottleneck. Flight Hours versus Lesson Numbers.*

Figure 1 illustrates the bottlenecks faced by traditional students during their Private Pilot training. The Target Time or recommended number of flight hours that should allow mastery in the topics and maneuvers contained in the lesson. The Target Time comes from the Jeppesen Private Pilot syllabus. The Average Time is the actual average hours it took for the traditional students to achieve mastery. It is clear that there are two predictable bottlenecks in this curriculum: Lessons 7 - 9, and Lessons 17 – 18. Lessons 7, 8, and 9 occur just prior to the students first solo flight. Lessons 17 and 18 cover cross-country navigation planning.

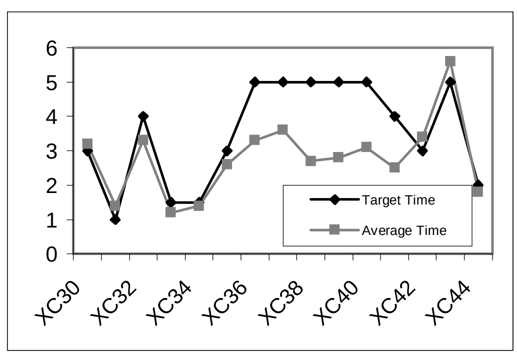

Figure 2. *Cross Country Bottlenecks. Flight Hours versus Lesson Numbers.*

Figure 2 illustrates the relationship between the target flight hours and the actual average time students needed in the cross-county phase. As Figure 2 indicates, students have few bottlenecks in this part of the curriculum. In fact, from Lessons 36 – 42, the students are actually flying less than prescribed. These lessons each require a flight to another airport with varying distances, but all greater than 50 nautical miles. One possible reason for the fact that average flight time is less than prescribed time in Lessons 39 through 42 is so students can make up for time overruns during the Private Pilot phase of training. If a student passes the Private Pilot tests with above average total flight time, this could be made up by undercutting the prescribed cross-country flight time.

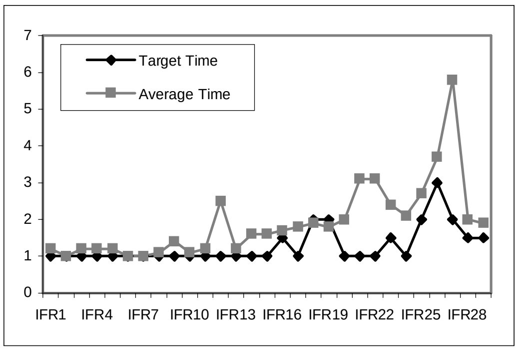

Figure 3. *Instrument Rating Bottleneck. Flight Hours versus Lesson Numbers.*

Figure 3 illustrates that last portion of the path to the Instrument Rating – the actual instrument training. Three bottlenecks are evident in the Jeppesen syllabus for instrument lessons: Lesson 12, Lessons 20 and 21, and Lesson 27. Lesson 12 contains the skill of VOR tracking and radial intercepting as well as partial panel tracking. Lessons 20 and 21 contain the ILS instrument approach, including the partial panel ILS. Lesson 27 is an instrument cross-country review flight.

Setbacks

Figures 1, 2, and 3 all illustrate the average number of flight hours that was required by students to reach mastery on that lesson. The researchers also observed the number of "setbacks" that a student experienced. A setback, in this case, is the need for a student to repeat a lesson that was previously flown. Among the archival data retrieved from the traditional student's training records, 449 setbacks were discovered. Of these, 77 setbacks took place just prior to the first solo flight – an area identified as a bottleneck in Figure 1. This number is 17.1% of all the setbacks experienced by traditional students. Setbacks continued for the traditional students throughout the remainder of the curriculum: 37.6% of the setbacks occurred during the Private Pilot and Cross Country phases of training past the first solo, and 45.2% of the setbacks took place within the instrument phase of the training. This tends to indicate that traditional students run into difficult lessons throughout the entire curriculum in all phases of Private, Cross Country and Instrument – there is never a time when it becomes "easier" for them.

First SAFER Student Data

Since the SAFER syllabus does not have minimum flight times for the course or for each lesson, there is no target flight time number to compare with actual flight time averages, as was the case with the traditional students' data. This makes a direct comparison between Traditional and SAFER student performance more difficult. Also, the Traditional students and the SAFER students do not come across the same topics in the same order, so a lesson-by-lesson comparison is also not direct. However, over the course of the SAFER syllabus, the same set of mastery skills are required, so an evaluation of student setbacks among the groups is possible.

The SAFER students within the first cohort experienced a total of 97 setbacks. Again, a setback is a repeated lesson. Lessons from both traditional and SAFER syllabi require a mastery of the subject matter before the student moves on to the next lesson, so a repeated lesson indicates that the student had difficulty with the subject matter contained in the lesson. Of the 97 setbacks, 59 took place among the SAFER students in the first nine, pre-solo lessons. This represents 60.8% of the total setbacks. The traditional students only had 17.1% of their setbacks occur during this portion of the curriculum.

	Traditional	SAFER
Pre Solo	77 of 449 17.1%	59 of 97 60.8%
Pvt & X-C	169 of 449 37.6%	15 of 97 15.4%
Instrument	203 of 449 45.2%	23 of 97 23.7%

Table 1. *Setback Percentages*

Table 1 presents the comparison of setbacks among the two pilot groups. The traditional students had far fewer setbacks in the early, pre-solo training, but their setbacks increase as they progress through the syllabus. The SAFER students had the greatest difficulty early on, but their setbacks diminished as they continued through the SAFER syllabus.

Skills Comparison

The lessons in the traditional curriculum produced student bottlenecks at Private Pilot lessons 7, 8, 9, and 17, and in the Instrument syllabus at lessons 12, 20, 21, 24, and 27. These lessons each contain many maneuvers and procedures embedded within each lesson, but there is a main area of lesson emphasis in each case. A bottleneck is an area in which students experience difficulty, so the main area of that lesson's emphasis would therefore be the source of that difficulty. Takeoff, landing, and emergency procedures present a significant challenge to all beginning flight students – especially landings. Evidence of this fact is shown by the bottleneck present with traditional students at lessons 7, 8, and 9, and by the disproportionately large number of setbacks at Lesson 9 for the SAFER students. This is the phase of flight where Traditional students out performed the SAFER students – see Table 1 where just prior to solo is where 60% of all SAFER setbacks took place and where only 17% of Traditional students setback took place. Beyond this phase of flight training however, the SAFER students reduced their number of setbacks precisely in areas where Traditional student hit bottlenecks.

On Lesson 17, Traditional students hit a bottleneck – see Figure 1. This area of emphasis is Cross Country Flight Planning. This lesson requires the student to obtain and assess weather information that is pertinent to a proposed visual flight. The student must plan a course of flight allowing for wind drift. The student must calculate time, speed, and fuel consumption for the flight and become extremely familiar with aeronautical charts that depict the terrain features that the flight will traverse. Many traditional students experience a setback at this point, requiring repeat lessons and often multiple repeated lessons. Among the Traditional students there was 0.75 setbacks per student on Lesson 17. In the SAFER syllabus, Lesson 11 is the first lesson in which Cross Country Flight Planning becomes the complete responsibility of the student. Note that SAFER students start conducting mission-oriented flights to other airports from Lesson 1, so at this point they have already been exposed to the elements of Cross Country Planning. SAFER students experienced very few setbacks – an average of only 0.18 setbacks per student on Lesson 11.

Holding patterns prove to be difficult for students when learning the basics of instrument flying. Figure 3 indicates a gap between the target flight time and the actual flight time required to master Holding Patterns at Lessons 14, 15, and 16. Traditional students had 1.06 setbacks per student through these lessons. SAFER students also had difficulty with Holding Patterns. SAFER Lessons 24 and 25 cover Holding Patterns and students on these two lessons had an average of 0.85 setbacks per student.

One of the two largest bottlenecks that faced the Traditional students in the Instrument phase of training took place at Lesson 20 – 22. Lessons 20, 21 and 22 require the student to meet completion standards in the skills of Instrument Landing System (ILS) approaches and Partial Panel Approaches. The ILS requires excellent finesse of the airplane and Partial Panel work requires excellent situational awareness. Eleven percent of all Traditional student setbacks occurred in these three lessons alone, producing an average of 3.2 setbacks per student. At Lesson 22 of the SAFER syllabus, students have been tracking the ILS localizer for several lessons, but Lesson 22 is where full ILS and Partial Panel approaches are among the completion standards. SAFER students had no setbacks on Lesson 22.

The final test of an instrument pilot's readiness is IFR Flight Planning. This requires the instrument pilot to plan and assess the weather, and the weather minimums. The pilot must calculate speed, time, and fuel consumption, but also plan on a flight to an alternate airport if the weather is unsuitable at the intended destination. The pilot must be able to file and later receive an IFR clearance and be able to expertly communicate with air traffic controllers all through the flight. Traditional students had a setback at this lesson with an average of 1.18 setbacks per student. The recommended amount of flight time to complete this lesson is 2.0 flight hours. Traditional students however took 5.8 hours, on average, to meet the completion standards of the lesson. In the SAFER syllabus, the IFR Flight Planning review lesson is number 26. No SAFER students had a setback on Lesson 26.

A comparison of average student setbacks across the entire curriculum reveals that SAFER students have more setbacks in the pre-solo phase than do the Traditional students. But Traditional students continue to have setbacks in rising numbers throughout, while SAFER students have a reduction in setbacks. Figure 4 illustrates the average number of setbacks among student for the Pre-solo lesson, the remainder of the Private and Cross Country training, and the Instrument Rating instruction.

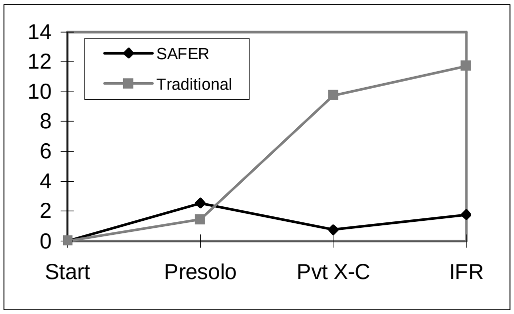

Figure 4. *Setbacks per student. Traditional students versus SAFER students.*

Conclusions

The researchers understand that we are dealing with small groups and that much more data must be taken before any claims can be made. But at this point the SAFER students have a greater number of setbacks in the lesson just prior to the first solo flight than do traditional students. The flight instructors that teach in the SAFER project say that the SAFER syllabus is very "front end loaded." This means that SAFER students are being taught cross-country flight planning, navigation, and instrument flight principles all before the first solo. The evidence, including Figure 4, seems to suggest that SAFER students pay a penalty for this expanded curriculum at the very start of the course. Traditional students are not taught cross country planning, navigation, and instrument principles before solo, and spend their time practicing takeoffs and landings in anticipation of the first solo. This focused attention on solo among traditional students may be why they perform with fewer setbacks in the pre-solo phase. But it appears that the "penalty" the SAFER students pay in the early lessons, are repaid later in the syllabus. The SAFER students seem to start reaping the rewards of their expanded curriculum after the first solo as the need for repeat lessons drops off to an average of only 0.76 setbacks per student between solo and the end of the SAFER stage 2 – which is approximately the cross country stage for Traditional student. Traditional students at this point experience an average of 9.73 setbacks. The evidence indicates that the largest benefit of the SAFER project is toward the end when both groups are preparing for the tests that cover the Instrument Rating. In that last phase of training the Traditional students had an average of 11.73 setbacks each, while the number of average setbacks among SAFER students was 1.76 each.

All the data presented here should be considered preliminary. The second SAFER cohort is underway at the time of this writing and the researchers will wait to see what additional data will bring to the conclusions. It is important to emphasize here that one of the overriding interest of the SATS program is to see if pilots can be trained in technically advanced aircraft that will meet or exceed the current training standards and to accomplish this in less time and with less money. The early information shows that the SAFER students who have completed the program and passed the combination Private Pilot and Instrument Rating test have done so with an average of 88.66 flight hours. The student who followed the traditional path completed the Instrument Rating at an average of 134.3 flight hours. The difference between the averages is approximately 45 hours. Forty-hours of flight instruction and airplane rental could cost the pilot approximately $6,000.

Although early in the project, the researchers are confident that the use of "glass cockpit" technology together with scenario training has great promise. Data from the remainder of the SAFER project will produce a list of "best practices" for flight instructors to use when teaching in TAAs. Ultimately, the project should lead to improvements and alterations to how pilots are to be trained in an environment of emerging technologies.

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COMPLEXITY MITIGATION THROUGH AIRSPACE STRUCTURE

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Cognitive complexity is a term that appears frequently in air traffic control research literature, yet there has not been a significant distinction between different components of complexity, such as environmental, organizational, and display complexity, all which influence cognitive complexity. It is not well understood if and how these different sources of complexity add to controller cognitive complexity and workload. In order to address this need for complexity decomposition and deconstruction, an experiment was conducted to explore whether or not different components of complexity could be effectively measured and compared. The goal of the experiment was to quantify whether or not structure in airspace sector design, in combination with changes in the external airspace environment, added to or mitigated perceived complexity measured through performance. The results demonstrate that for a representative ATC task, the dynamic environment complexity source was a significant contributor to performance, causing lower performance scores. There was no apparent effect, either positive or negative, from increasing airspace structure represented through a display.

Introduction

Addressing the difference between environmental and innate human complexity (often referred to as cognitive complexity), Herb Simon describes an ant's path as it navigates across a beach. The ant eventually reaches its destination, but because the ant must constantly adapt its course as a result of obstacles, the path seems irregular, laborious, and inefficient. Simon points out that while the ant's path seems complex, the ant's behavior is relatively simple as compared to the complexity of the environment. Simon proposes the following hypothesis as a result, "Human beings, viewed as behaving systems, are quite simple. The apparent complexity of our behavior over time is largely a reflection of the complexity of the environment in which we find ourselves (Simon, 1981, p. 53)."

This distinction between innate or cognitive complexity and environmental complexity is especially relevant considering the considerable research conducted in air traffic controller cognitive complexity. Several studies have investigated air traffic control (ATC) information complexity issues (see Hilburn, 2004; Majumdar & Ochieng, 2002) for a review). In this literature, several common complexity factors have emerged to include traffic density, traffic mix, aircraft speeds, sector size, and transitioning aircraft. These factors are asserted to affect cognitive complexity. However, in light of Simon's ant parable, these factors really represent environmental complexity factors that influence cognitive complexity. This is an important distinction because as can be seen in Figure 1, there are several levels of complexity that can affect an individual's cognitive complexity level.

Figure 1 illustrates the decomposition of "complexity" as it applies to human supervisory control systems. Human supervisory control (HSC) occurs when a human operator intermittently interacts with an automated system, receiving feedback from and providing commands to a controlled process or task environment (Sheridan, 1992). In complex HSC systems, in general two layers of interventions, organizational and display design can exist to mitigate environmental complexity, and thus reduce cognitive complexity. Organizational interventions include goals, policies, and procedures such as separation standards, checklists, airspace structure, etc. For example, many airspace sectors are designed to promote predominant

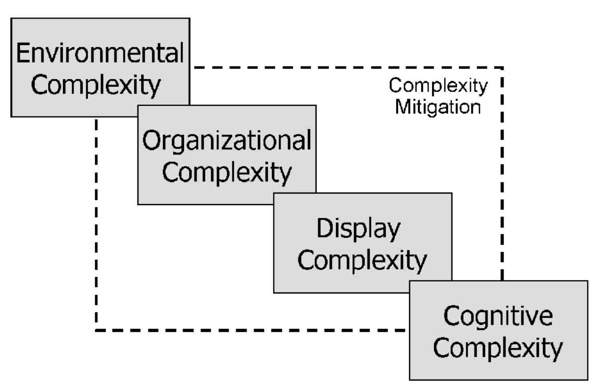

Figure 1: *Human Supervisory Control Complexity Chain*

traffic flows. Thus the design and the associated rules and procedures for control mitigate environmental complexity caused by increasing numbers of planes. However, when airspace becomes obstructed and saturated due to weather, congestion, etc., the need to follow procedures and sector limitations can over-constrain a problem, thus increasing the perceived complexity by the controller.

Displays are another example of intended complexity mitigation which could inadvertently add to complexity instead of reducing it. For air traffic controllers and in general all HSC operators, displays are critical in representing the environment so that a correct mental model can be formed and correct interactions can take place (Woods, 1991). In effect, to mitigate complexity, displays should reduce workload through transforming high-workload cognitive tasks such as mental computations into lower workload tasks through direct perception, i.e. visually (Miller, 2000). However, in complex and dynamic HSC domains such as ATC, it is not always clear whether a decision support interface actually alleviates or contributes to the problem of complexity.

Complexity and Structure

In addition to traffic density and related factors, it has also been hypothesized that the underlying airspace structure is a critical complexity factor (Histon et al., 2002). In theory, airspace structure provides the basis for mental abstractions which allows controllers to reduce complexity and maintain situation awareness. Histon et. al., (2002) propose that these mental abstractions, known as structured-based abstractions, can be generalized to standard flows (reminiscent of Pawlak's (1996) "streams"), groupings, and critical points. Providing air traffic controllers with these interventions, either explicitly through design or implicitly through policy, should help controllers improve through mental models, reduce overall complexity, as well as reduce perceived workload.

In a study investigating judgment and complexity, Kirwan et al., (2001) determined that airspace sector design was only second to traffic volume, in terms of contributing to cognitive complexity. In terms of the model in Figure 1, airspace sector design straddles both the organizational and display complexity categories. Designed by humans to mitigate environmental complexity, airspace structure is an organizational policy. However, airspace structure contains significant visual components represented in displays, thus it is an environmental complexity intervention both from an organizational and display perspective.

Including interventions in airspace sector design such as critical points (points through which aircraft must pass) and designated standard flows (such as jet ways) can increase order and improve predictability, and thus lower cognitive complexity. However, it is also possible that when uncertainty levels increase, usually as a function of dynamic environmental factors such as changes in weather and available airspace, these same airspace structures could actually add to complexity since a controller's mental model of the airspace design must be adapted to the new conditions. Airspace structure and procedures mitigate complexity in what are termed "nominal" situations, but when an "off-nominal" condition occurs, such as an emergency or unexpected weather phenomena, the resultant increasing uncertainty causes complexity to grow (Athenes, Averty, Puechmorel, Delahaye, & Collet, 2002).

While other research has attempted to quantify the individual elements of complexity as a function of traffic flow (Masalonis, Callaham, & Wanke, 2003), little attention has been directed towards understanding the different sources of complexity such as depicted in Figure 1. In addition it is not clear if and how these different sources of complexity add to controller cognitive complexity. In order to address this need for complexity decomposition and deconstruction, an experiment was conducted to explore whether or not elements of complexity as depicted in Figure 1 could be effectively measured and compared.

Method

Apparatus, Participants, and Procedure

To objectively investigate the impact of environmental and structural complexity factors on controller performance, a human-in-the-loop simulation test bed was programmed in MATLAB® (Figures 2 & 3). Since the subject pool consisted primarily of college students, it was necessary to devise a simplified and abstract task that addressed the aforementioned complexity concerns, but still represented fundamental elements of ATC. In a simplified en route task, subject controllers were assigned a single sector, and were only required to provide heading commands to aircraft, while velocities and altitudes were held constant.

Twenty egress areas were located in the periphery of the sector, and each incoming aircraft was assigned a specific egress point. The primary goal was to direct the aircraft (a/c) to the assigned egress, and when an aircraft exited correctly, a score was generated. To provide an incentive for flying through a pre-determined sequence of waypoints (representative of a flight plan), subjects could collect additional points by directing their a/c through these waypoints. The number of points that could be won at every waypoint was displayed. To discourage controllers from directing aircraft through unnecessary waypoints just to gain points, scores were penalized based on an aircraft's total time of presence in the airspace sector beyond that expected for the optimal pre-determined path. A final component of the overall score was the penalty for flying through a no-fly-zone. No-fly zones represented constrained ATC airspace such as thunderstorms, military operating areas, and prohibited areas. Example waypoints, optimal paths for particular ingress and egress points, and no-fly zones are represented in Figure 2. Maximization of total score was the subjects' goal, and their total score was displayed in real-time.

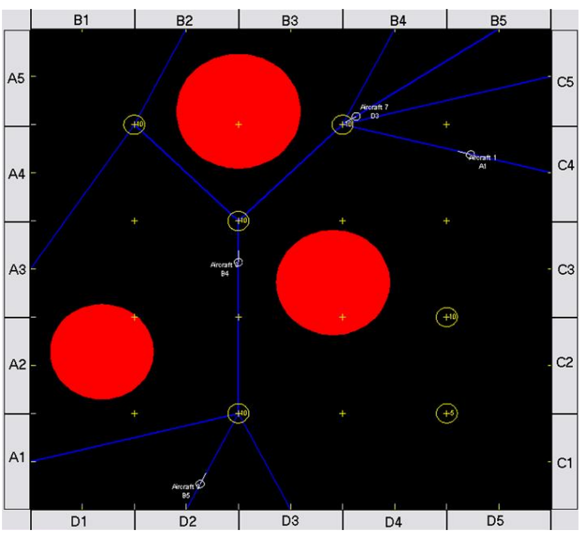

Figure 2: *Interface with optimal paths shown*

Training and testing were conducted using a Dell personal computer with a 21-inch color monitor, 16-bit high color resolution, and a 3.0GHz Pentium 4 processor. During testing, all user responses were recorded in separate files specific to each subject and scenario. A Visual Basic script was then written that scored and compiled the data into a single spreadsheet file for the subsequent statistical analysis. After signing required consent forms, subjects completed a tutorial that discussed the nature of the experiment, explained the context and use of the interface, and gave them the opportunity to understand the scoring mechanism. Subjects completed four practice scenarios that exposed them to every combination of independent variables. They then began the randomly ordered four test sessions, which also lasted until all aircraft had exited the airspace (approximately 6-7 minutes).

Experimental Design

Two independent variables were investigated. The first independent variable was the presence of structure, as displayed through the lines of maximum score (named "displayed structure"). As can be seen in Figure 2, in certain scenarios subjects were given structure through the display of the optimum paths (those that maximized the score as a function of waypoints and time). In the counter condition, subjects were given the waypoints (along with the number of available points), but were not shown the optimal path (Figure 3).

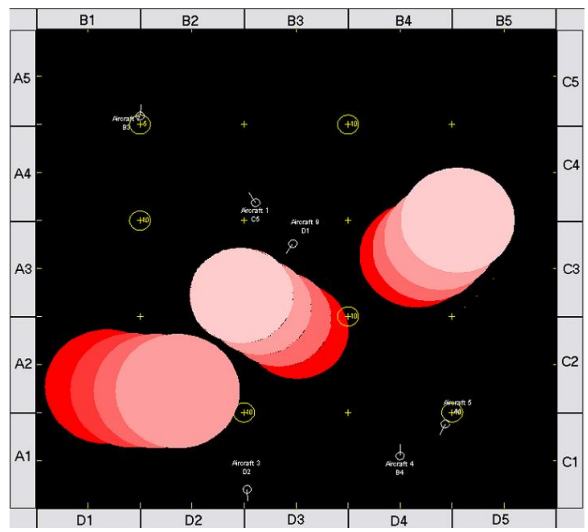

Figure 3: *Interface with dynamic no-fly-zones*

The second independent variable was the condition of the environment in terms of either static or dynamic no-fly-zones. In the dynamic condition, the no-fly-zones moved at rates of about two-fifths the aircraft velocity (figure 3), and representing changes in constrained airspace that often occur such as weather fronts and special-use airspace. It is important to note that the displayed lines were the optimum, but only in cases where they were not obstructed. In the dynamic condition, the dynamic no-fly zones cases would sometimes cover the paths, and thus the controller had to mentally regenerate new optimal paths. The motivation was to investigate whether or not such visual structure in an airspace sector, in combination with changes in the external airspace environment, added to or mitigated perceived complexity measured through performance.

A single dependent variable of total performance score was used. As described previously, the score was a linear and weighted function of aircraft egress correctness, bonus waypoints with penalties for no-fly-zone violations, and total time transitioning in sector. In the case of egress score, subjects received maximum points by directing their a/c to exit near the center of the egress, but did not receive points for exiting through the wrong egress. The egress scores decreased linearly from the center to the marked edges of the egress blocks. To maintain consistent scenario level of difficulty in order to minimize any learning effect, the four experimental scenarios were ninety degree rotations of each other. The statistical model used was a 2x2 fully crossed ANOVA and the four scenarios were randomly presented to a total of 20 subjects.

Results and Discussion

The 2x2 ANOVA linear model (with and without displayed structure and dynamic vs. static environment) revealed that for the performance dependent variable, the environment factor was significant ($F(1,74) = 54.55$), $p < .001$, all $\alpha < .05$). The displayed structure factor and the environment*displayed structure interaction were not significant. Figure 4 depicts the average performance scores across all four conditions. It can be seen on inspection that the performance scores were clearly higher in the static environment scenario as opposed to the dynamic environment phase. Whether subjects had less or more displayed airspace structure did not significantly affect their scores. These results demonstrate that for this representative ATC task, the environmental complexity factor was a significant contributor to performance, causing lower performance scores. There was no apparent effect, either positive or negative, from increasing airspace structure.

In terms of the model in Figure 1, this experiment demonstrated for this representative ATC task, the main component of complexity associated with controller workload was environment, and not organizational or display-related. Dynamically changing airspace structure was far more influential than the design of the airspace itself. Thus while sector design may be a contributing factor to air traffic controller performance, environmental complexity factors such as thunderstorms and special use airspace that intermittently becomes available, are significantly larger contributors to individual cognitive complexity.

These results provide quantitative support for previous subjective assessments of controllers that active special use airspace increases complexity and would benefit from some display intervention (Ahlstrom, Rubinstein, Siegel, Mogford, & Manning, 2001). In light of the results reported here, it is likely that special use airspace (SUA), an organizational constraint, can increase complexity for controllers not because of the actual structure of the airspace, because the status can change. When SUAs cycle between active and inactive, especially relatively rapidly, environmental complexity increases, and could negatively affect controller performance. Thus a by-product of an organizational policy could be increased complexity on the part of controllers.

These results indicate that the development of decision support tools to aid controllers in SUA management is an area of research that deserves more attention Because of the temporal and cyclic nature of SUA, possible design interventions could include some kind of timeline display for SUA scheduling as well as intelligent decision support agents that can predict in advance when airspace could become available or deactivated.

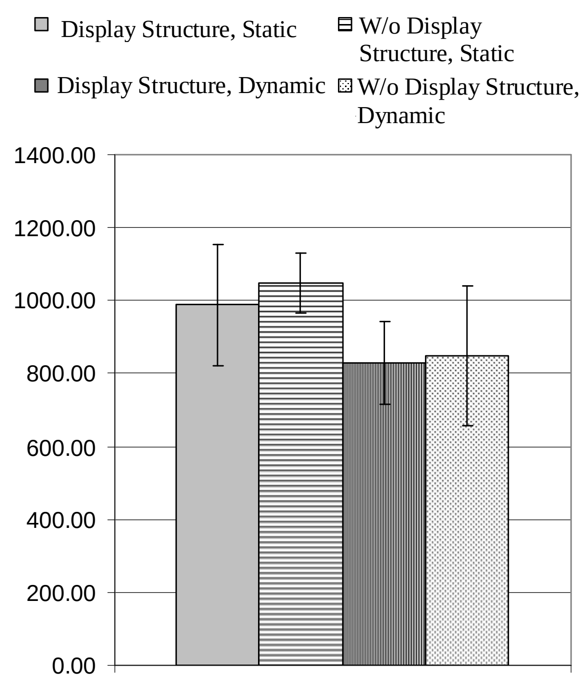

Figure 4: *Condition Mean Performance Times*

Conclusion

Complexity as it applies to the air traffic control environment cannot be simply categorized as "cognitive complexity," as there are different components of complexity, which are demonstrated in Figure 1. These components of environmental, organizational, and display complexity may not contribute in a linear and consistent manner to either cognitive complexity or performance. This study attempted to decompose two sources of complexity, an environmental factor caused by changing airspace, and an organizational/display factor caused by airspace design. Results show that the environmental complexity source of changing airspace was far more significant in influencing overall controller performance. These results support air traffic controllers' subjective opinions that special use airspace is a source of complexity (Ahlstrom et al., 2001), and that more work is needed for better display representation.

Acknowledgements

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