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Future En Route Workstation Study (FEWS I): Part 1 – Evaluation of Workstation and Traffic Level Effects

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16. Abstract

The Federal Aviation Administration (FAA) has projected a significant increase in air traffic over the next two decades. Compared to current traffic levels, estimates vary from 133% by 2015 to an average of 3 times (3X) by 2025. To meet the increase in demand, the Joint Planning and Development Office and the FAA are preparing the Next Generation Air Transportation System (NextGen). Plans for NextGen include increased use of advanced technologies for communications, surveillance, navigation, and decision support, as well as a change in roles and responsibilities of air traffic controllers and pilots. This first Future En route Workstation Study has investigated increases in traffic levels and integration of automation functions on the controller working position. The controllers that participated in this study experienced traffic at current levels and at increased levels of 133% and 166% of current busy sectors. The participants worked these traffic levels using either a workstation that was similar to their current environment with the availability of Controller-Pilot Data Link Communications (CPDLC) or a future concept environment that integrated several automation functions. The results indicate that when CPDLC and the additional future concepts were available, controllers could work 133% of current traffic levels (or 28 aircraft) at acceptable workload levels. When only Voice Communications were available, our workload measures indicated that several of the controllers experienced unacceptably high workload levels. At even heavier traffic volumes of 166% of current levels (or 35 aircraft), the bottleneck was no longer due to congestion of the voice channel but was likely due to the amount of information displayed on the ATC display.

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Executive Summary

The Federal Aviation Administration (FAA) has established a Target System Description for the National Airspace System (NAS) in 2015. With the expected increase in air traffic, it becomes essential to investigate how to assist controllers effectively without information overload or excessive workload. In this research program, we investigated how the integration of automation functions into a concept Future En Route Workstation Study (FEWS) may reduce controller workload while accommodating continued growth in air traffic.

The current NAS has evolved from a “stovepipe” approach to the introduction of automation. In the stovepipe approach, new systems attach to existing hardware and software as separate entities that controllers have access to through added objects in existing displays or auxiliary displays. We have applied best human factors principles to the Air Traffic Control (ATC) workstation to make controller interaction more efficient. This research investigates the integration of existing automation functions at the computer human interface.

In this project, we measured ATC performance and behavior of four separate studies. First, we investigated controller performance and behavior under three workstations and three air Traffic Level configurations. Second, we studied the effect of the presence of Controller-Pilot Data Link Communications (CPDLC) Build 1A for 70% of the aircraft. We compared the effect of the presence of CPDLC under our Baseline Workstation Configuration as well as a FEWS configuration. Third, we studied how the availability of a conflict probe on the radar display would affect ATC performance and behavior under current workstation conditions. Fourth, we investigated the effect of upgrading the Data-side display to a full radar display, instead of maintaining its Baseline configuration. In this report, we discuss the results of the effect of traffic levels and workstation configurations on controller performance and behavior. We conducted the study in the Research Development and Human Factors Laboratory at the FAA William J. Hughes Technical Center.

We used the FAA Target Generation Facility, Center TRACON Automation System, User Request Evaluation Tool, CPDLC, and the Distributed Environment for Simulation, Rapid Engineering, and Experimentation (i.e., DESIREE), which is an emulator for the Host computer system and the Display System Replacement (DSR). The controller environment included full DSR emulations with all operational functions, additional automation functions, and modified interfaces. We used the Genera Air Route Traffic Control Center with instrument flight rules in effect. We assessed eye movements, collected situation awareness measures, benchmarked controller performance, administered Post-Scenario Questionnaires, collected workload ratings, and calculated performance measures.

The results indicate that controllers could manage traffic level at a 33% increase of current traffic levels with traffic that contained 70% CPDLC-equipped aircraft and a Workstation configuration that automated some of the routine ATC tasks. At the higher levels of a 66% increase, the presence of CPDLC and the workstation changes were not enough to enable controllers to manage traffic at acceptable workload levels. At these high traffic levels, with CPDLC available, the bottleneck was no longer due to congestion of the voice channel but was likely due to the amount of information displayed on the ATC display.

1. INTRODUCTION

Historically, change in the National Airspace System (NAS) has been of an evolutionary manner. Much of our current workforce has evolved with that relatively slow change. Therefore, it may be difficult to convey to our workforce the speed at which the NAS is currently adapting to the increased demands of air transportation. We are seeing faster changes to the NAS than to what we have become accustomed, especially with the introduction of a performance-based organization that provides services to its customers (airlines, passengers, and companies that rely on air transportation). Within the last 10 years, the Federal Aviation Administration (FAA) has replaced the En Route Information Display System (ERIDS) with the Display System Replacement (DSR), as well as introduced the User Request Evaluation Tool (URET) in its limited distribution form (URET/CCLD) in the 20 Air Route Traffic Control Centers (ARTCCs). In addition, the FAA has introduced the Standard Terminal Automation Replacement System (STARS), as well as implemented the Domestic Reduced Vertical Separation Minima, introduced the Traffic Management Advisor (TMA) software in ARTCCs, and added several other automation systems. The next decade may see the implementation of reduced lateral separation and the introduction of many changes to existing systems with accompanying changes to procedures. Although these changes are necessary to increase the capacity of the NAS and to maintain safety, it is important that the changes take the strengths and weaknesses of the workforce into account.

1.1 Background

The FAA is modernizing the NAS to increase its capacity to cope with the projected increase in traffic. These changes will significantly alter the role of the controller. Examples of how automation tools may change the controller’s role include a change from active control to a role that includes more and more monitoring; from reliance on personal expertise to reliance on system-generated advisories; and from voice-based to computer-based interaction. When more systems become automated, controllers will move from actively controlling aircraft to monitoring them, potentially resulting in a loss of situation awareness (SA). In the current system, controllers derive many of their decisions from mental simulations of future traffic situations. Proposed systems suggest moving from mental simulation to computer-based advisories that require the controller to interact with a computer system to augment their own expertise. This change will result in controllers evaluating the effectiveness of system-generated solutions. With the introduction of several automation systems, controllers will interact with one another, for the first time, through messages sent across computer networks instead of phone lines for coordination. Text messages transferred between ground-based systems and aircraft will augment communication between controllers and pilots. All of these NAS modernization efforts will change the controllers’ job in a revolutionary manner. It is critical that we understand these changes to the job so that we can best accommodate the migration to the new situation. The application of human factors principles early in the process can assist to ensure success.

In the strategic plan for 2004-2008 (FAA, 2003), the FAA Administrator indicates that the passenger levels would not rebound to pre-2001 levels until 2005. The Radio Technical Commission for Aeronautics (RTCA) projections for the next 2 decades suggest that we can expect a traffic increase of 150-250%, which is 250-350% of the current level (RTCA, 2002).

Initial estimates obtained from the FAA's Aviation Policies and Plans Office (APO) show that the number of passengers will increase substantially by 2015 (FAA, 2004a). The overall increase in passengers by 2015 estimates reach as high as 58% and as much as 84% for passengers using commuter aircraft, but this increase in the number of passengers does not result in a proportional increase in the number of aircraft handled by ARTCCs nationwide. The monthly count of the number of aircraft handled by ARTCCs nationwide indicates that we could expect traffic increases between 27% and 39%, depending on how we take the events of September 11, 2001, into account. Of course, we have based this on national averages, so things may be different when we look at individual ARTCCs (FAA, 2004b).

Several research groups have developed automation tools for Air Traffic Control (ATC). But will it be sufficient to support the projected increases in air traffic? For example, Kirkman et al. (2003) found that the level of activities related to several of the elements mentioned in the RTCA Concept of Operations document is insufficient to achieve the target NAS capabilities of 2015. Gap analyses conducted by Kirkman et al. assess whether the technical capabilities will be available by 2015. In the Future En Route Workstation Study (FEWS) program, we assess the capabilities that we expect to be present in the NAS of 2015, and we analyze whether the human operators will be able to control the 2015 level of traffic that the FAA has projected. The FEWS program is an effort to integrate data and automation functions on a single display.

1.2 Relevance to Air Traffic Services

Although the introduction of new equipment provides great challenges to the controller workforce, it does not change operational procedures. In this study, we answer the following question related to the en route workstation redesign that will benefit Air Traffic Services: *Will the integration of automation functions into the Computer-Human Interaction (CHI) and the accommodation of the individual Radar Associate and Radar (R)-side controller displays benefit controllers and enable them to handle the increase in air traffic expected for 2015?*

1.3 Objectives

This study investigated how three instances of projected NAS evolution and changes to the Radar Associate and R-side controller FEWS affected controller performance and behavior in the en route airspace. We examined these effects through the analysis of performance and behavioral measures.

1.4 Scope

In this study, 16 controllers performed en route ATC simulations at three traffic levels (100%, 133%, and 166% of 2004 traffic levels corresponding with approximately 21, 28, and 35 aircraft under sector control). We presented controllers with an evolved version of the NAS; the system included a mixed fleet (70% of the aircraft used full state-of-the-art equipment, whereas the other 30% of the aircraft used equipment from 2004). The vertical separation standard was 1,000 ft (304.8 m), and the lateral separation standard was 3 nmi (5.556 km). The controllers worked in sector teams consisting of a Radar Associate and a Data (D)-side controller with either conventional or FEWS capabilities (see Table 1).

Table 1. Differences Between Conventional and Future En Route Workstation

Function	Conventional		FEWS	
Position	**R**	**D**	**R**	**D**
Hardware				
Input Device	Trackball	Trackball	Mouse	Mouse
	Display System Replacement (DSR) Keypad			
Keyboard	DSR-R	DSR-D	DSR-R + emphasis	DSR-D + emphasis
Display	29 in.	19 in.	29 in.	29 in.
Computer-Human Interaction (CHI): Aircraft Representation				
Track Data	Track and Position	Track and Position	Track and Position	Track and Position
Mode C Altitude	Full Data Block (FDB)		Integrated in Three-tier FDB	Integrated in Three-tier FDB
Assigned Altitude	FDB	Flight Plan Readout		
Indicated Airspeed		Through URET		
Coordinated Heading	Line 4 of FDB			
Coordinated Speed	Line 4 of FDB			
Interaction with FDB	Flyout Windows		Edit/Scroll	Edit/Scroll
CHI: Windows and Lists				
Traffic Management Data	Present in TMA List		Integrated in Three-tier FDB	Integrated in Three-tier FDB
Conflict Alert	Conflict Alert List			
Conflict Probe		URET/CCLD		
Trial Planning		URET/CCLD		
Data Link	Build 1A	INTEROP Build 1A		
Flight Plan Data (type, destination, etc.)	Multiple Flight-plan Readout (MFR) Window or Computer Readout Device (CRD)	CRD		
Emphasis	Multiple Dwell Lock/ Fourth Line Indicators		Emphasis Function	Emphasis Function
Multiple Flight Strip Readout	MFR Window		Electronic Flight Progress Strip (eFPS)	eFPS
Flight Progress	Paper Strips	URET Aircraft List (ACL)	eFPS	eFPS
Reminders	Paper Strips	URET ACL	eFPS	eFPS
CHI: Other				
Route Display	Radar Display		Radar Display	Radar Display
Trajectory Display	Radar Display	URET Graphical Plan Display (GPD)	Radar Display	Radar Display

2. METHOD

2.1 Participants

The 16 participants were Full Performance Level controllers who actively controlled traffic at Level 11 and 12 ARTCC facilities for at least 16 hours in the month preceding the experiment. To maintain a homogeneous participant pool, we recruited controllers with DSR certification and at least one month DSR experience on DSR release BCC22, including the use of URET/CCLD. The 16 participants in this study were Certified Professional Controllers from several ARTCCs within the Continental United States. The participants' mean age = 41.8 years (*SD* = 5.9), and the participants' mean experience in ATC = 17.8 years (*SD* = 7.2).

The controllers gave their written consent to participate in the experiment. The research team ensured them that their data were completely confidential. Participants had visual acuity not less than 20/30 corrected. Controllers could wear corrective lenses or soft contact lenses. However, the oculometer design limitations excluded bifocals, trifocals, and hard contact lenses.

2.2 Simulation Personnel

2.2.1 Experimental Staff

An Engineering Research Psychologist (ERP) and an ATC Subject Matter Expert (SME) conducted the simulations. The SME supplied knowledge to create the scenarios and conducted the Over-the-Shoulder (OTS) ratings. The ERP conducted the experiments, performed the data analyses, and wrote the final technical report. Support engineers ensured that the hardware and software functioned properly. Clerical staff assisted in preparing, copying, and distributing forms and questionnaires.

2.2.2 Simulation Pilots

In this study, we used six simulation pilots. To allow rotation, researchers trained nine simulation pilots using procedures from past experiments. The training of the simulation pilots lasted approximately 2 weeks. Training included procedures for issuing simulation pilot commands and familiarization with simulation equipment.

2.3 Simulation Equipment

In this section, we describe the simulated airspace and scenario materials. First, we describe the Generic Center airspace used in the experiment, and then we elaborate on the development of the traffic samples. We also describe the simulation environment, measurement tools, and instruments of this experiment.

2.3.1 Airspace and Scenarios

During the last decade, our group has investigated the use of generic airspace because of its ability to have all of our participants start on a level playing field, to increase the participant pool from which to draw, and to ease learning. Initially, the generic airspace used in our simulations consisted of a single sector, but it has grown into a generic ARTCC containing several sectors, fix posting areas, Terminal Radar Approach Control facilities and navigational aids, airways, STARs, and Standard Instrumented Departures. Although we have not made an official name change yet, we think of it as Goldman Center (i.e., or ZGN), which is the name of the resident SME who implemented most of the facility.

Sector frequencies are easy to learn because they all end with two digits that are identical to the sector number (e.g., 120.08 for Sector 08 and 120.18 for Sector 18). Sector 08 meters traffic into Genera airport (GEN) using two-meter fixes located in Sector 18, which is located below and south of Sector 08. By Letter of Agreement (LOA), controllers need to handoff aircraft to Sector 18 at 23,000 ft (7010.4 m) (FL230) before the aircraft physically leave Sector 08. It is the responsibility of the controller to feed aircraft to several smaller airports and to handoff aircraft to these airports at 22,000 ft (6705.6 m). The traffic flow depicted in Figure 1 requires controllers to merge two streams of traffic over Chicago while absorbing delays to meet arrival rates at GEN.

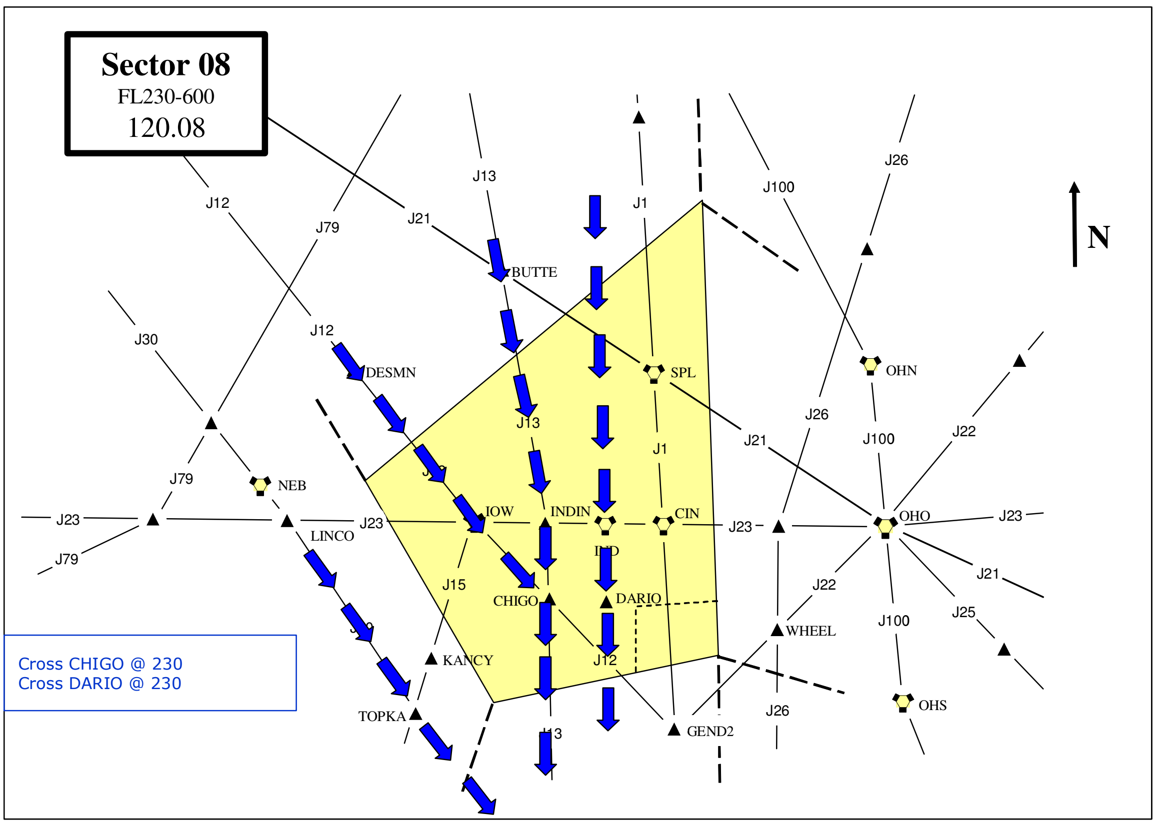

Figure 1. Airspace configuration.

We created traffic scenarios that had approximately 21, 28, and 35 aircraft in the sector at any point in time. These numbers represent 100%, 133%, and 166% of the Monitor Alert Parameter (MAP) used for a sector of the size used in this experiment. In the field, the MAP value serves as a threshold for the Traffic Management Unit (TMU). When the TMU predicts that the number of aircraft in a sector will reach the MAP value, the TMU will look for ways to reduce the number of aircraft in that sector by diverting aircraft around the sector or through other traffic flow initiatives.

Generating traffic for our simulations has always been labor intensive. When creating traffic scenarios, we often struggled with how to generate traffic that was similar enough to treat them as being the same, how to modify traffic level, and how to adjust traffic to include the right number and mix of aircraft in the sector that we wanted to study. As a result of our attempt to capture changes in traffic flow efficiency, we introduced a fast time simulation tool called AWSIM. AWSIM input consists of airspace and aircraft characteristics, a mix of aircraft types, routes flown between endpoints, and the total number of flights to create. AWSIM output consists of flight paths for each of the aircraft; after some massaging of the format, our Target Generation Facility (TGF) can ingest them as flight plans. The use of this tool has saved us considerable time in creating scenarios, and it has enabled us to create scenarios at different traffic levels with the same traffic characteristics by simply increasing the total number of flights. For this experiment, we focused on a high altitude feeder sector and created a traffic flow that was mostly North to South with some aircraft crossing that flow and a few flying in the opposite direction. We manipulated the total number of flights such that we created a total number of aircraft in our sector that matched the required traffic levels.

The experiment used 32 different scenarios based on the conditions described in the section on experimental design. We exposed controllers to these scenarios in the following manner:

1. Training. (16 scenarios).
2. FEWS concept x Traffic Level (3 x 3). Controllers controlled traffic at three experimental Traffic Levels for each of the concept designs (DSR, FEWS-E, and FEWS-S).
3. R-side Conflict Probe Presence (2). Controllers controlled one additional scenario at current plus 33% Traffic Levels with the R-side Conflict Probe Present for the Baseline workstation concept.
4. D-side Conventional Display (2). Controllers controlled one additional scenario at current plus 33% Traffic Levels with the enhanced FEWS concept on the R-side and a conventional display on the D-side. The full-enhanced FEWS concept (FEWS-E) with identical FEWS concept displays on the R-side and the D-side formed the control for this condition.

For each of the traffic levels, we created three simulation scenarios and two additional scenarios for the 133% condition. These scenarios rotated under the automation and team configuration conditions to ensure that effects are due to the conditions and not due to differences between scenarios.

Participants trained on 16 scenarios. Training included integrated use of the airspace and the DSR emulation. At the end of training, participants felt comfortable with the airspace and all of the equipment used in the experiment. Each training and experimental scenario lasted 45 minutes. Paper Flight Progress Strips (FPSs) were not available.

2.3.2 Target Generation and Airspace Representation

We modeled airspace and scenarios for the training sessions in the high-fidelity ATC simulator at the Research Development and Human Factors Laboratory (RDHFL). The airspace modeled for the training sessions was identical to the airspace used during the experimental sessions. We used an integrated system including the TGF and Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE), a DSR emulator. We used the TGF to generate targets and airspace. The airspace used in this study is the same as the generic airspace used in the Study of an ATC Baseline for the Evaluation of Team (i.e., SABET) Configurations (Willems, Heiney, & Sollenberger, 2005) and INTEROP (Sollenberger, Willems, Della Rocco, Koros, & Truitt, 2004), a human-in-the-loop simulation with only minor modifications.

2.3.3 Controller Environment

The familiarization with the airspace and the LOAs and the Standard Operating Procedures (SOPs) used two adjacent controller stations equipped with a radarscope, a DSR keyboard, and either a trackball or an alternative input device. One high-resolution monitor (2,048 x 2,048 pixels) displayed the radarscope, whereas another displayed either a D-side Computer Readout Device or a second radarscope (see Figure 2).

In Figure 2, we depict the scene planes used for our eye tracking equipment and software. Scene plane 1 is the radar display for the R-side controller. Controllers had electronic FPSs (eFPSs) available (Scene plane 3 and 5 for the R-side). The hardware for the eFPSs consisted of touch-based LCD panels. Table 2 provides the definitions of the scene planes for the FEWS experiment.

Figure 2. Controller environment.

Table 2. Scene Plane Definitions for the Future En Route Workstation Study Environment

Scene Plane	Description
1	R-side 2,048 x 2,048-pixels LCD radar display.
2	D-side 2,048 x 2,048-pixels LCD display used either to display the CRD, CPDLC, and URET windows under the Baseline condition or as the D-side radar display under the FEWS conditions.
3	Bottom eFPS panel for the R-side displayed metered aircraft over two metering fixes: ILL on the West side and SGF on the East side. The system posted aircraft automatically to the appropriate eFPS bay.
4	Bottom eFPS panel for the D-side.
5	Top eFPS panel for the R-side displayed eFPS bays for four small, unmetered airports to which aircraft fed aircraft as well as two bays for East- and West-bound traffic.
6	Top eFPS panel for the R-side.
7	R-side Desk Area.
8	D-side Desk Area.
9	R-side Map Area.
10	D-side Map Area.

The simulation pilots maneuvered the aircraft. For input of workload ratings, the researchers mounted a Workload Assessment Keypad (WAK) device (Stein, 1985) immediately next to the displays within easy reach of the participant (see Figure 3). The WAK device consists of 10 keys numbered 1 through 10, which were backlit when the system probed controllers for their workload assessment.

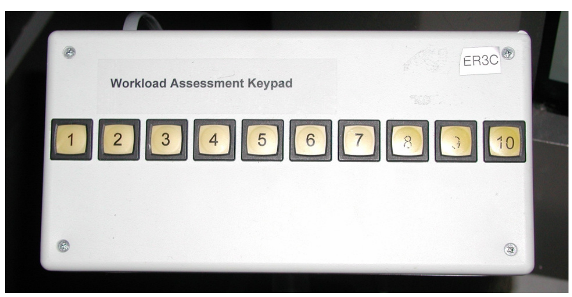

Figure 3. Workload assessment keypad.

Figure 4 displays the Keypad Selection Device (KSD), keyboard, and a trackball that were available for use. The KSD contains two pairs of up and down arrow keys. Controllers could use one set to change the radar display range, whereas the other set changed the look-ahead time of the speed vectors.

Figure 4. Data entry devices available on the controller desk area.

2.3.4 Simulation Pilot Terminal Configuration

A network linked the six simulation operator displays with the DSR positions. Each simulation operator station allows entry of simulation pilot commands for up to 50 aircraft.

2.3.5 Communication Equipment

We used communication systems that are different from the Voice Switching and Communication System used in the field. It has communication links between the controller, OTS observer, simulation pilots and experimenters, and Push-to-Talk (PTT) recording. The equipment monitored communications and recorded times and frequencies for subsequent data reduction and analysis.

2.3.6 Video Camera and Video Recording Configuration

We recorded the video images of the controller (R-side, D-side, and Overhead views). At an observation station, video monitors provided a video display of all ATC positions. A DVD recorder compressed the audio and video, streamed it in real time to DVDs, and stored it on a local hard drive.

2.4 Experimental Design

In this section, we provide information about experimental designs, independent and dependent variables, simulation resources, materials, and equipment. We have limited the results and discussion to the 3 x 3 (FEWS Concept x Traffic Level) design only, but we used other experimental designs in this study as well.

We investigated the effect of a change in Workstation Configuration and Traffic Levels on controller performance and behavior, which results in the following designs: 2 x 3 x 3 (Controller Position x Workstation Concept x Traffic Level). Controllers will control air traffic at three experimental Traffic Levels for each of the concept designs (see Table 3).

Table 3. Scenario and Independent Variable Mapping for Experiment I

Experimental Design		Traffic Levels					
		R-side			D-side		
		100	133	166	100	133	166
Workstation Concept	Conventional	a	b	c	a	b	c
	Identical enhanced R- and D-side	g	h	i	g	h	i
	Specialized enhanced R- and D-side	j	k	l	j	k	l

2.4.1 Independent Variables

Each experimental scenario had Traffic Levels of 100%, 133%, or 166% of acceptable 2004 Traffic Levels under one of the three Workstation Configurations: (a) current, (b) identical enhanced R-side and D-side (FEWS-E), and (c) specialized enhanced R-side and D-side (FEWS-S).

2.4.1.1 Traffic Level

Controllers trained on Traffic Level scenarios at 133% of current traffic levels and controlled traffic at three experimental levels. Based on the currently acceptable MAP values, sectors of the size of ZGN08 can be as high as 21 (i.e., 21 aircraft under control at any given time). Therefore, the four levels of traffic consisted of approximately 21, 28, and 35 aircraft under control at any given time.

2.4.1.2 Workstation Configuration

We used three Workstation Configurations for this experiment. In the Baseline condition, we configured the sector workstations as they are used in the NAS today. The second configuration consisted of two *identical* displays that integrate several automation functions for both the R-side and the D-side (FEWS-E). The FEWS-E configuration did not have any lists or windows available except for the Display Control View and the Computer Readout Device (CRD). Finally, the third FEWS level provided *specialization* of the displays based on the roles and responsibilities of the R-side and D-side (FEWS-S), respectively. The FEWS-S configuration provided some of the lists and views. When Controller-Pilot Data Link Communications (CPDLC) were available, controllers could use the Menu Text option through an integrated list in the CRD, similar to the Position Relief List. Controllers that worked the D-side radar display under the FEWS-S configuration also had the TMA list at their disposal.

2.4.2 Dependent Variables

The FEWS experiment collected many data sets (see Table 4). Except for the TGF recording files, we recorded the data for the R-side and D-side controller separately.

Table 4. Data Sets Collected During the FEWS Experiment

Data Set	**Content**	**Objective/Subjective**
Post-Scenario Questionnaires (PSQ)	NASA Task Load Index (TLX) SA	Subjective
Over-the-Shoulder (OTS) Ratings	SA Communications Efficiency	Subjective
Workload Assessment Keypad (WAK) Ratings		Subjective
Push-to-Talk (PTT)	Number and duration of communication events	Objective
Target Generation Facility (TGF) Recording	System variables Separation variables Distance/Time per aircraft	Objective
Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE) Recording	Controller Interactions - Modality, events, duration	Objective
Eye Movement Recording	Eye Movement Characteristics: - Fixations, Saccades, Blinks - Index of Cognitive Activity	Objective
Audio/Video Recording	- Transcriptions - Intra-team and air-ground communication coding	Objective

2.4.2.1 Push-to-Talk Recording

In the FEWS experiment, we recorded Voice Communication events by registering when someone keyed and released the microphone. We recorded the event data for controller participants, simulation pilots, and OTS raters. The DESIREE recorded the PTT data in a separate file created as soon as the experimenter started the simulation scenario. We reduced and reformatted the PTT data file using a parser written in LabVIEW (National Instruments Corporation, 2005). We then calculated the duration of individual PTT events using an algorithm written in LabVIEW. Finally, we imported the reduced data into Excel and calculated means and standard deviations (*SD*) for controllers and simulation pilots for each of the experimental simulation scenarios.

2.4.2.2 Post-Scenario Questionnaires

We included the National Aeronautics and Space Administration (NASA) Task Load Index (TLX) in our PSQs. For further analyses, we used the raw index values instead of using a weighting scheme as suggested by Hart and Staveland (1988). We asked participants to rate their workload on the six NASA TLX dimensions: Mental, Physical, and Temporal demand, as well as Effort, Performance, and Frustration.

2.4.2.3 Over-the-Shoulder Ratings

Sollenberger, Stein, and Gromelski (1997) developed and evaluated a method to assess controller performance. They designed a rating form to measure the effectiveness of new or enhanced ATC systems in simulation research. The rating form uses an 8-point format and a comment section for each of the questions. Sollenberger et al. showed that most of the rating scales were very reliable. The OTS ratings consist of six categories: Maintaining Safe and Efficient Traffic Flow, Maintaining Attention and SA, Prioritizing, Providing Control Information, Technical Knowledge, and Communication related questions.

2.4.2.4 Workload Assessment Keypad

The WAK device is a portable version of the Air Traffic Workload Input Technique (i.e., ATWIT) and is a reliable and unobtrusive real time, on-line measure of subjective workload (Stein, 1985). The system prompted the participants to rate their workload on the WAK device every 2 minutes throughout a scenario. The system prompted participants by emitting a beep and illuminating the keypad buttons. The participants pressed one of the keypad buttons labeled from 1 (*extremely low workload*) to 10 (*extremely high workload*). The participants had 20 seconds to respond; otherwise, the WAK recorded a code to indicate that *no response has been made*. Prior to each simulation, a member of our research team read the WAK device instructions to the participants to inform them how to use the device. The dependent variables that the WAK device provided are the workload rating and the rating latency.

2.4.2.5 Simulation Interactions

For each simulation, we calculated the total number of interactions of a particular type by the interaction modality and duration. We then ran analyses on these newly created dependent variables to determine how the values changed as a function of experimental manipulations. Where appropriate, we conducted a Multivariate Analysis of Variance (MANOVA) subsequent to a univariate analysis.

To test whether our changes to the system had an effect on the number of controller interactions with the system, we counted the number of keystrokes and button presses under each of the experimental conditions.

2.4.2.6 Data Reduction and Analysis Tool

The Data Reduction and Analysis Tool (DRAT) processed raw data files produced by the TGF. The DRAT provided the summary files, which contained the number of altitude, heading, and speed changes as well as the number of aircraft that switched to the R/T frequency of Sector 08 while within the sector boundary.

2.5 Procedures

The experiment took place at the RDHFL. The RDHFL provides a high-fidelity ATC simulation environment and is fully reconfigurable.

Controllers participated in the experiment for 2 weeks. The morning of their first day of participation consisted of a briefing and a familiarization period. The researchers explained the experiment, the oculometer, differences between experimental and their own equipment, and the confidentiality of their identity. Researchers provided an informed consent briefing and assurance that participation was voluntary. Participants then gave a written commitment to the experiment and their understanding of our informed consent policy. The controllers completed an Entry Questionnaire that included demographic questions about age, experience level, need for corrective glasses, and so forth.

After instructing the controllers about the LOAs and the SOPs, for the rest of the first week, we trained participants in the use of the airspace, scenario flow and traffic type, equipment (including the DSR emulation), communications, WAK, and the oculometer. The second week consisted of experimental scenarios. Controllers had a 30-minute break between trials and 90 minutes for lunch.

3. RESULTS

We used the data to measure participant performance and behavior across six constructs: communications, workstation complexity, workload, SA, performance, and visual scanning. We will report the analyses of the visual scanning data set in a separate report. We used a multivariate approach to Analysis of Variance (ANOVA) of repeated measures designs. We tested effects using the Wilks' Λ statistic at an alpha-level of $p < .05$ and, therefore, we report the equivalent F statistic. If the results of a MANOVA were statistically significant ($p < .05$), we performed univariate ANOVAs to determine which of the dependent variables were significantly different across experimental conditions. Where possible, we based the significance of an ANOVA result on an adjusted alpha level.

We used STATISTICA (StatSoft, 2005) to perform the statistical analyses. STATISTICA has some peculiarities that we need to point out. First, our bar graphs depict the means of the dependent variables, whereas the "whiskers" indicate the 95% confidence interval. We provide the confidence intervals to show the spread of observed values across participants. Second, we performed Tukey's Honestly Significant Difference (HSD) post hoc tests, where appropriate. Although STATISTICA reports the *p*-value, it does not provide the corresponding *t*-statistic the way other statistical software packages often do. When appropriate, we mention which pairs of conditions were statistically significant, but we do not mention the *t*-statistic and *p*-value.

3.1 Communications

3.1.1 Push-to-Talk Recordings

The multivariate analysis on the number and duration of PTT events showed an effect of Traffic Level, $\Lambda = .03$, $F(4, 3) = 26.49$, $p < .05$. Subsequent univariate analyses showed that Traffic Level affected the number of communication events per minute, $\Lambda = .05$, $F(2, 5) = 50.93$, $p < .05$, but not their duration (3.47 s, $SD = 0.58$). The number of communications per minute increased significantly with increasing Traffic Levels (see Figure 5).

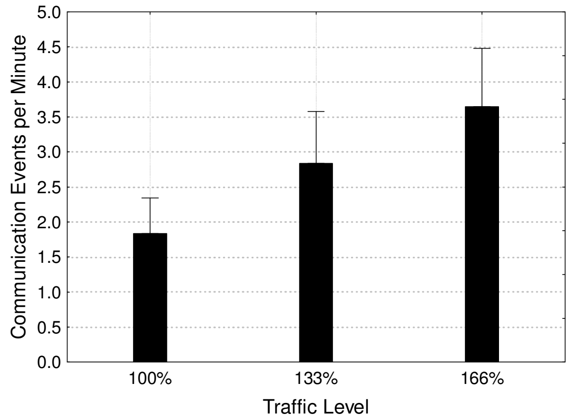

Figure 5. Number of communication events per minute as a function of Traffic Level.

3.1.2 Over-the-Shoulder Rating Forms

The OTS ratings showed that analysis of the overall rating of controller performance on communication showed a significant interaction of Controller Position and Traffic Level, $\Lambda = .44$, $F(2, 10) = 6.28$, $p < .05$. A Tukey HSD post hoc analysis revealed that R-side controllers performed significantly worse under the 166% Traffic Level conditions (see Figure 6). To assess how communications had changed as a function of our experimental conditions, we further investigated ratings of more detailed communication aspects.

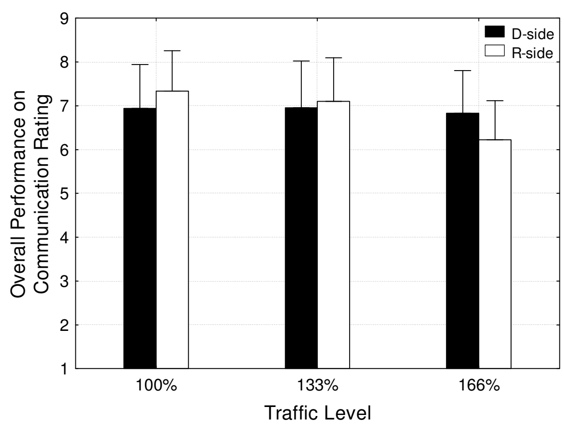

Figure 6. Over-the-shoulder rating of performance on communication as a function of Traffic Level.

3.1.2.1 Using Proper Phraseology

Analysis of the OTS ratings of controller performance on using proper phraseology showed a significant interaction between the effect of Controller Position and Traffic Level, $\Lambda = .16$, $F(2, 11) = 27.90$, $p < .05$. Our OTS raters indicated that the R-side controllers did not use proper phraseology as well under the 166% Traffic Level as under the lower Traffic Levels (Figure 7).

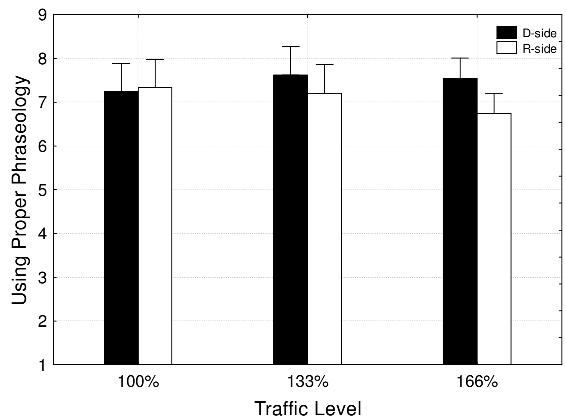

Figure 7. Over-the-shoulder rating of performance on using proper phraseology as a function of Traffic Level and Controller Position.

3.1.2.2 Communicating Clearly and Efficiently

We found a significant interaction between the effects of Controller Position and Workstation Configuration, $\Lambda = .46$, $F(2, 11) = 6.56$, $p < .05$. The R-side controllers performed best when using the FEWS-E configuration (Figure 8).

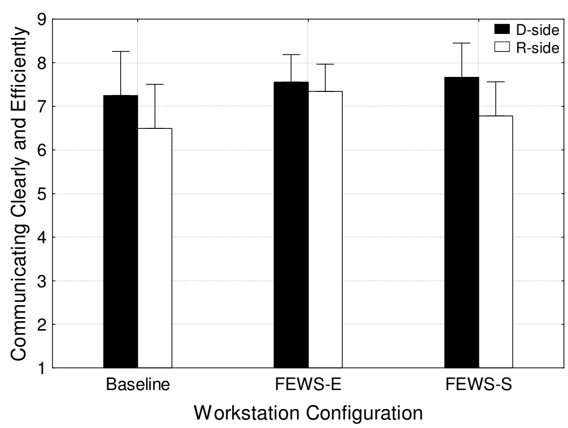

Figure 8. Over-the-shoulder rating of performance on communicating clearly and efficiently as a function of Workstation Configuration and Controller Position.

We also found a significant interaction between the effects of Controller Position and Traffic Level, $\Lambda = .46$, $F(2, 11) = 6.52$, $p < .05$. Only the R-side controller performed significantly poorer under the 166% Traffic Level condition (see Figure 9).

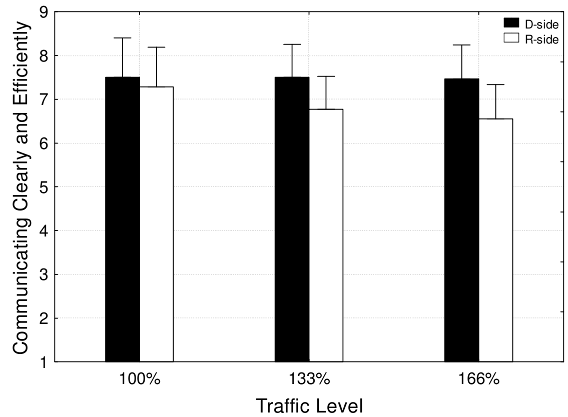

Figure 9. Over-the-shoulder rating of performance on communicating clearly and efficiently as a function of Traffic Level and Controller Position.

3.1.2.3 Listening for Pilot Readbacks and Requests

An analysis of the OTS ratings for controller performance on listening for pilot readbacks and requests showed a significant interaction between the effect of Controller Position and Traffic Level, $\Lambda = .46$, $F(2, 11) = 6.37$, $p < .05$. The ratings for the D-side controller did not vary; however, the 166% Traffic Level condition led to poorer performance of the R-side controller (see Figure 10).

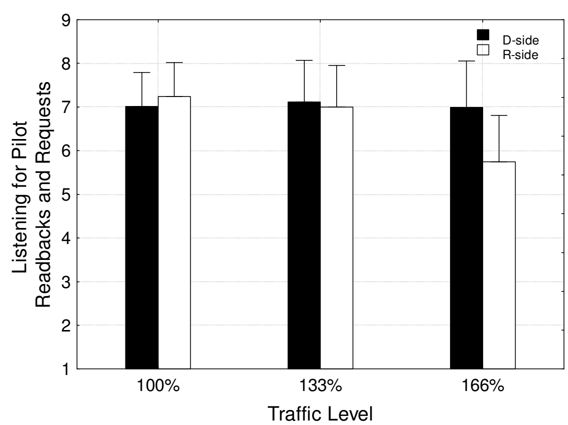

Figure 10. Over-the-shoulder rating of performance on listening for pilot readbacks and requests as a function of Traffic Level and Controller Position.

3.1.2.4 Providing Control Information

We found a main effect of Workstation Configuration on the performance of controllers on providing control information, $\Lambda = .52$, $F(2, 10) = 4.68$, $p < .05$. We found that controllers had a small but significant gain in their performance on providing control information when using the FEWS-E Workstation Configuration (see Figure 11). We also found Traffic Level significantly reduced how well controllers provided control information, $\Lambda = .46$, $F(2, 10) = 5.96$, $p < .05$ (see Figure 12).

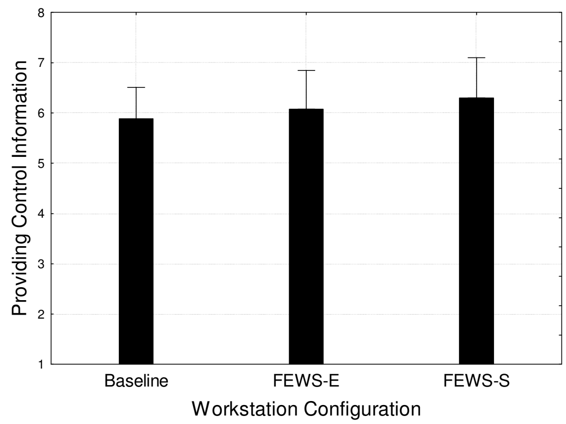

Figure 11. Over-the-shoulder rating of performance on providing control information as a function of Workstation Configuration.

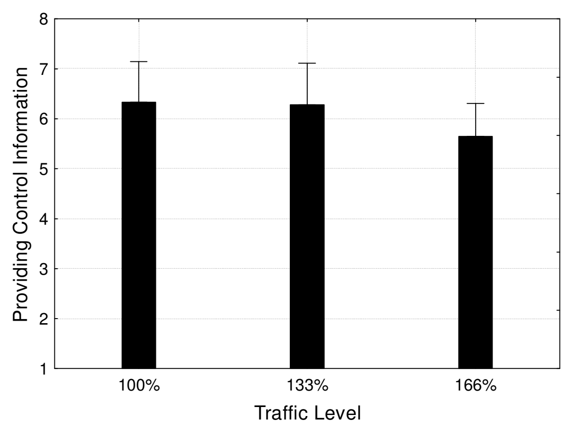

Figure 12. Over-the-shoulder rating of performance on providing control information as a function of Traffic Level.

We also analyzed the effects of Controller Position, Workstation Configuration, and Traffic Level on providing essential ATC information and on providing additional ATC information. We found almost identical effects of Traffic Level, but no effect of Workstation Configuration; the quality of the provision of essential and additional ATC information suffered considerably when working under the 166% Traffic Level condition.

3.2 Workstation Complexity

3.2.1 Display Complexity

We asked the controllers to rate display complexity along three dimensions: Perceptual, cognitive, and interaction complexity. To determine the effects of Controller Position, Workstation Configuration, and Traffic Level, we conducted an ANOVA using the mixed multivariate approach of a 2 x 3 x 3 (Position x Workstation Configuration x Traffic Level) design.

3.2.1.1 Perceptual Complexity

The results for the perceptual complexity indicated the existence of a three-way interaction of the independent variables, $\Lambda = .23$, $F(4, 9) = 7.36$, $p < .05$. Because we encountered a three-way interaction, we investigated simple effects (i.e., we analyzed the data within each level of the independent variables). For example, we determined the effect of Controller Position and Traffic Level within conditions with the Baseline Workstation Configuration. Controllers indicated that when working with the Baseline Workstation Configuration, the perceptual complexity was higher under the 166% Traffic Level than under the 100% and 133% Traffic Levels, $\Lambda = .44$, $F(2, 11) = 6.97$, $p < .05$ (see Figure 13).

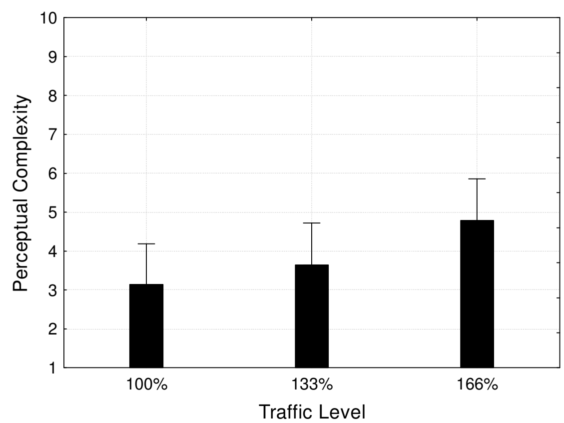

Figure 13. Perceived overall perceptual complexity as a function of Traffic Level within the Baseline Workstation Configuration.

Analyses further revealed that under the highest Traffic Level, controllers perceived perceptual complexity to be highest when working with the Baseline Workstation Configuration, $\Lambda = .46$, $F(2, 11) = 6.42$, $p < .05$ (see Figure 14).

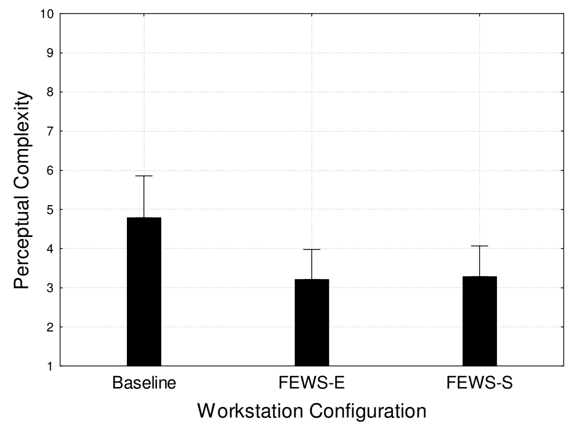

Figure 14. Perceived overall perceptual complexity as a function of Workstation Configuration at the highest Traffic Level.

3.2.1.2 Cognitive Complexity

Analyses of the data for the cognitive complexity uncovered an interaction of the effects of Controller Position and Traffic Level, $\Lambda = .53$, $F(2, 11) = 4.97$, $p < .05$ (see Figure 15).

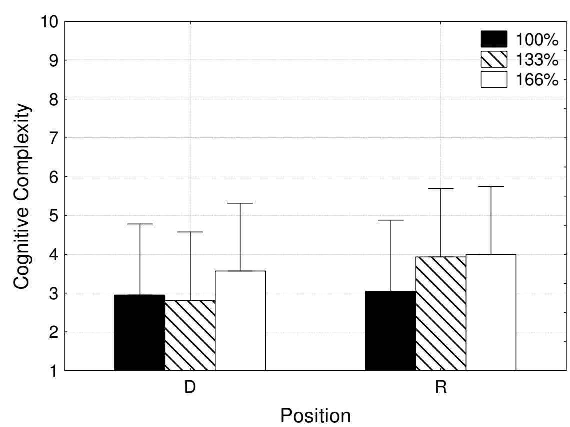

Figure 15. Perceived overall cognitive complexity as a function of Traffic Level and Controller Position.

The D-side controllers indicated that the cognitive complexity was higher under the 166% than under the 100% and 133% Traffic Level conditions, $\Lambda = .14$, $F(2, 5) = 4.97$, $p < .05$ (Figure 16).

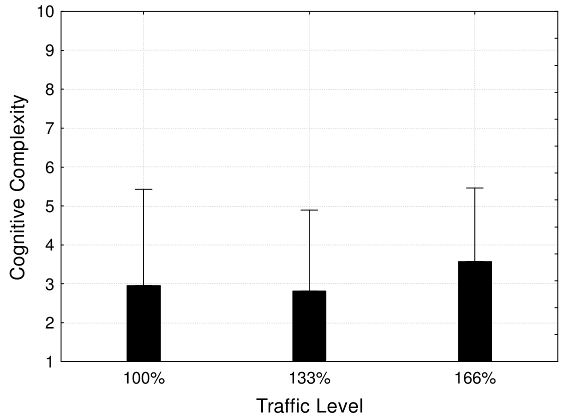

Figure 16. Perceived overall cognitive complexity as a function of Traffic Level for the D-side controller.

3.2.1.3 Interaction Complexity

We analyzed overall interaction complexity as well, but found no significant effects of Controller Position, Workstation Configuration, or Traffic Level.

3.2.2 Perceptual Complexity

Under the perceptual complexity section, we asked the controllers about how easy it was to find information, about how good the information organization was, and about display clutter. The controllers indicated that across these three dimensions, Traffic Level had a significant effect on perceptual complexity, $\Lambda = .20$, $F(2, 11) = 4.69$, $p < .05$. The controllers found it difficult to find information on the display under the 166% Traffic Level condition, $\Lambda = .48$, $F(2, 11) = 5.93$, $p < .05$ (Figure 17).

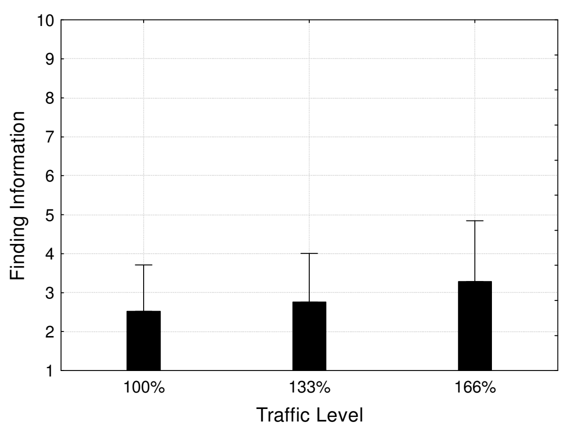

Figure 17. Perceived ease of finding information as a function of Traffic Level.

There were no significant effects of Controller Position, Workstation Configuration, and Traffic Level on perceived organization of the information. When asked about display clutter, the controllers indicated that the effects of Workstation Configuration and Traffic Level interacted, $\Lambda = .33$, $F(4, 9) = 4.53$, $p < .05$ (see Figure 18).

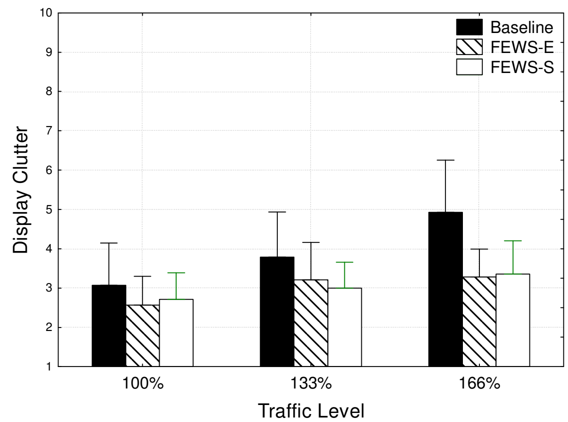

Figure 18. Perceived display clutter as a function of Traffic Level and Workstation Configuration.

To determine how this interaction manifested itself within Traffic Levels and Workstation Configurations, we analyzed simple effects. As illustrated in Figure 19, the results show that under the Baseline Workstation Configuration, the 166% Traffic Level resulted in significantly higher ratings for display clutter, $\Lambda = .37$, $F(2, 11) = 9.26$, $p < .05$ (see Figure 19); whereas the differences due to Traffic Level under the FEWS-E and FEWS-S conditions were not statistically significant.

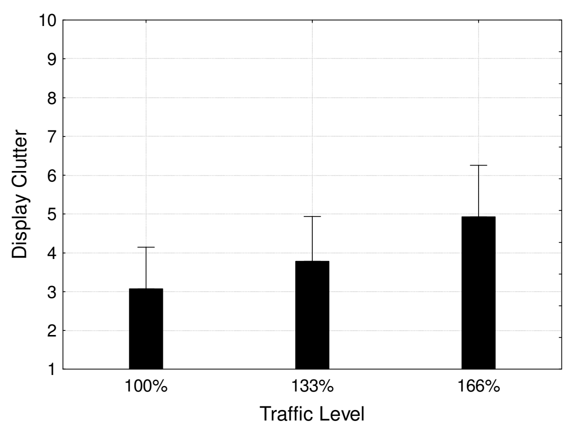

Figure 19. Perceived display clutter for the Baseline Workstation Configuration as a function of Traffic Level.

However, the controllers indicated that there was a significantly smaller rating for display clutter when using the FEWS-E and FEWS-S Workstation Configurations than under the Baseline Workstation Configuration, $\Lambda = .39$, $F(2, 11) = 8.62$, $p < .05$ (see Figure 20).

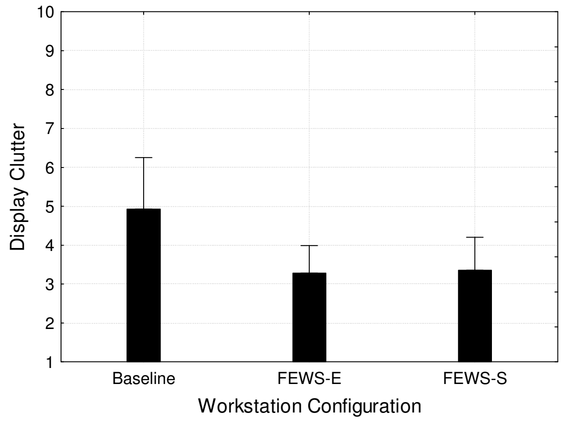

Figure 20. Perceived display clutter under the 166% Traffic Level as a function of Workstation Configuration.

The controllers responded differently about how Traffic Level affected display clutter, depending on the position they worked, $\Lambda = .35$, $F(2, 11) = 10.28$, $p < .05$. The analyses of simple effects showed that the display clutter increased for the D-side controller significantly under the 166% condition, $\Lambda = .06$, $F(2, 5) = 39.06$, $p < .05$ (see Figure 21), but that change did not reach significance for the R-side controller.

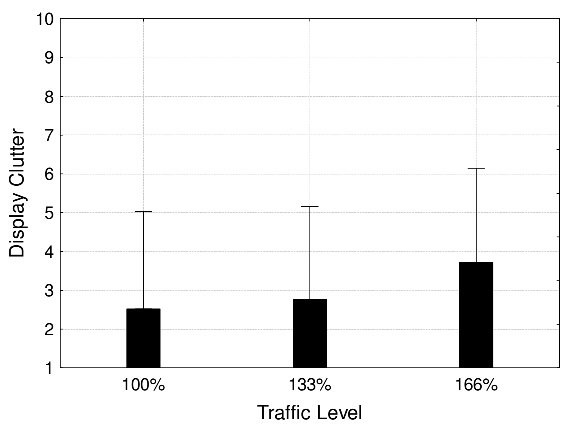

Figure 21. Perceived display clutter for the D-side controller as a function of Traffic Level.

3.2.3 Cognitive Complexity

The PSQ contained three cognitive-complexity-related questions, probing participants for awareness of displayed information, display dynamics, and relating displayed information. We found significant effects for awareness of displayed information and relating displayed information, but not for display dynamics.

The controllers rated that their awareness for displayed information was highest for current Traffic Levels and slightly lower for the higher Traffic Levels, $\Lambda = .49$, $F(2, 11) = 5.76$, $p < .05$ (see Figure 22). The difference between 133% and 166% Traffic Levels was not significant.

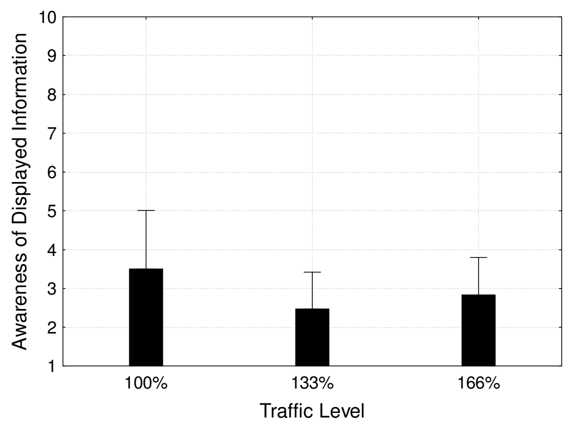

Figure 22. Perceived awareness of displayed information as a function of Traffic Level.

Perceived awareness was highest for the FEWS-S design. However, perceived awareness of displayed information was significantly higher only for the FEWS-S design than for the Baseline design, $\Lambda = .49$, $F(2, 11) = 5.76$, $p < .05$ (see Figure 23).

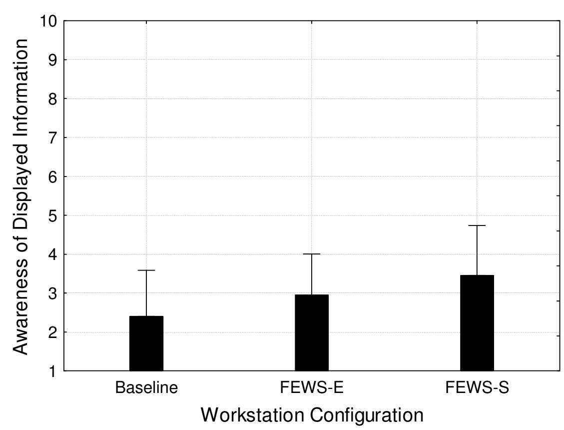

Figure 23. Perceived awareness of displayed information as a function of Workstation Configuration.

Traffic Level affected the ratings for the ease of relating display information but differently for the different Workstation Configurations, $\Lambda = .38$, $F(4, 9) = 3.66$, $p < .05$. Within the 100% Traffic Level conditions, participants perceived that it was easier to relate displayed information on the FEWS-S design than on the Baseline or the FEWS-E designs. The participants indicated that it was easier to relate display information on the FEWS-S design under the 100% Traffic Level condition than under all other tested Traffic Level and Workstation Configuration combinations except for the condition with 166% Traffic Level and FEWS-S design (Figure 24).

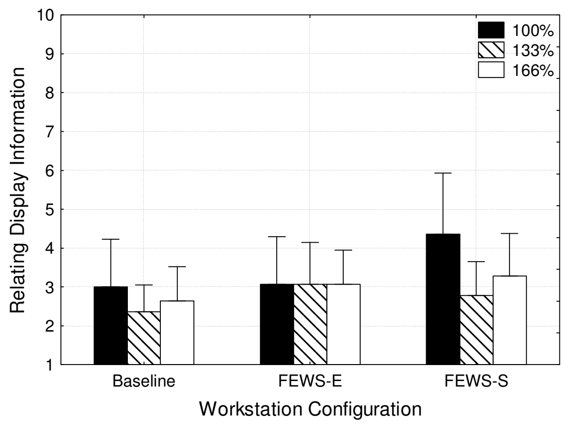

Figure 24. Ease of relating displayed information as a function of Traffic Level and Workstation Configuration.

3.3 Workload

In this study, we use the WAK, NASA TLX, and PSQ to assess participant workload. The WAK data collection occurred every 2 minutes during simulations, but the controllers provided the other measures after each scenario had ended.

3.3.1 Workload Assessment Keypad Ratings

To investigate the effects of Workstation Configuration and Traffic Level workload ratings, we ran an ANOVA on the ratings we had collected every 2 minutes. Because of the small number of participants and the fact that our controllers always worked in the same R-side and D-side team configuration, we nested the Controller Position within each controller group. Subjective workload ratings vary considerably between participants, Controller Positions, and experimental conditions, and our results show that the effects interacted on all independent variables. Figures 25 and 26 clearly show how much the inter- and intra-team workload ratings vary. Although we had emphasized in our instructions to rate instantaneous workload based on operational anchors, some of the controllers did not do so. This is most notable during the highest Traffic Level conditions where everyone was struggling to keep up with the traffic.

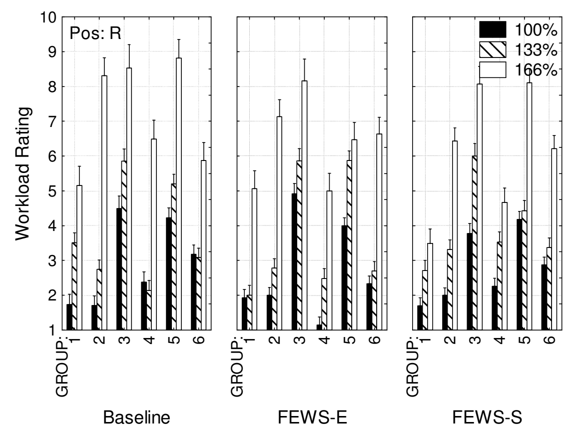

Figure 25. Traffic Level x Workstation Configuration within group for the radar Controller Position.

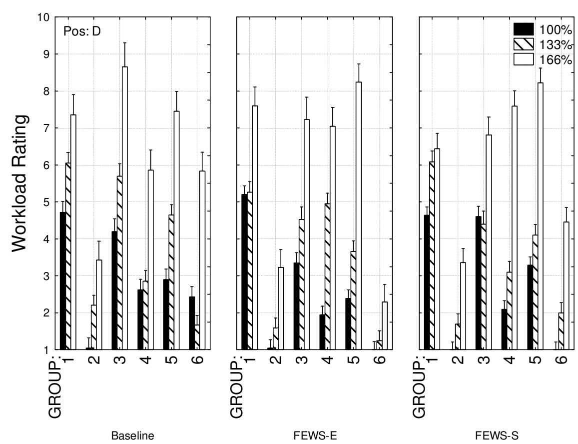

Figure 26. Traffic Level x Workstation Configuration within group for the data Controller Position.

Even at these high Traffic Levels, some controllers indicated that they perceived only moderate to high workload levels. Overall, however, the increase in Traffic Level resulted in an increase in perceived workload. Because we used repeated measures designed to eliminate the inter-team variability, we discuss interactions and main effects that did not involve differences between controller teams.

3.3.1.1 Radar Controller Workload Assessment Ratings

We found that the effects of Traffic Level and Workstation Configuration on the R-side workload ratings interacted, $\Lambda = .58$, $F(4, 117) = 21.049$, $p < .05$. The following paragraphs discuss the nature of the interaction in more detail.

Under the 100% Traffic Level condition, the R-side controllers indicated that the perceived workload was lowest with the FEWS configuration with identical displays on the R- and the D-position, but there was no difference in workload between the Baseline and the FEWS-S configurations. Although statistically significant, the difference was small (a difference of less than 0.25 on a 10-point scale).

Under the 133% Traffic Level condition, the R-side controllers indicated that the perceived workload was highest with the FEWS-S configuration and did not differ between the Baseline configuration and the FEWS configuration with identical displays on the R-side and the D-side positions. Although statistically significant, the difference was small (a difference of less than 0.30 on a 10-point scale).

Under the 166% Traffic Level condition, the R-side controllers indicated that the perceived workload was highest under the Baseline condition even though there was no difference between the two FEWS configurations. Here the statistically significant difference resulted in an operationally significant difference (of more than a full point on the 10-point scale).

Within each of the Workstation Configurations, the increase in Traffic Level resulted in significant increases in workload. Figure 27 clearly indicates the workload differences between traffic levels as well as the small differences between Workstation Configurations under the 100% and the 133% Traffic Level conditions. R-side controllers perceived highest workload levels under conditions of high Traffic Level and the Baseline Workstation Configuration.

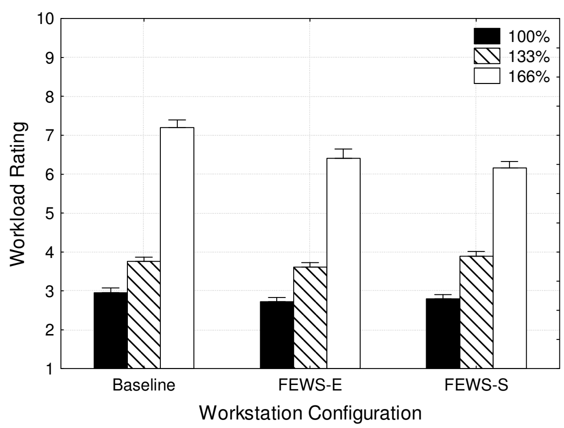

Figure 27. Radar controller workload assessment keypad ratings as a function of Workstation Configuration and Traffic Level.

3.3.1.2 Data Controller Workload Assessment Ratings

The D-side controllers perceived that the three Traffic Levels led to significantly different levels of workload, $\Lambda = .06$, $F(2, 120) = 948.00$, $p < .05$. The workload was highest for the 166% Traffic Level condition and lowest for the 100% Traffic Level condition (see Figure 28). Under the high Traffic Level condition, the D-side controllers perceived a moderately high workload. The differences between traffic levels were large and more so between the 133% and the 166% conditions (2.5 points on a 10-point scale).

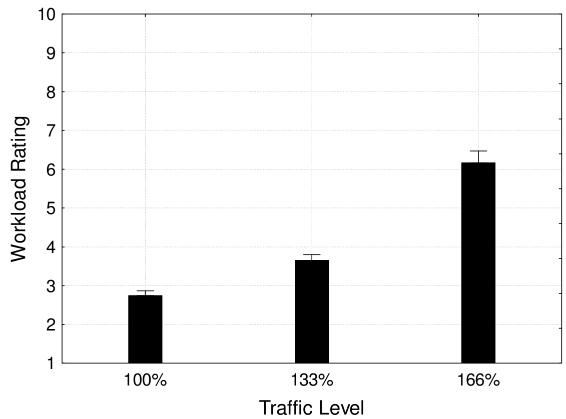

Figure 28. Data controller workload assessment keypad ratings as a function of Traffic Level.

The D-side controllers also perceived different levels of workload depending on the Workstation Configuration used during the simulations, $\Lambda = .62$, $F(2, 120) = 37.08$, $p < .05$. Although statistically significant, the differences in workload ratings are very small in comparison to the changes in workload due to changes in Traffic Level (see Figure 29). The D-side controllers perceived that workload was highest under the Baseline configuration, followed by the FEWS-S and the FEWS-E configurations. The differences were statistically significant, but small (0.40 on a 10-point scale).

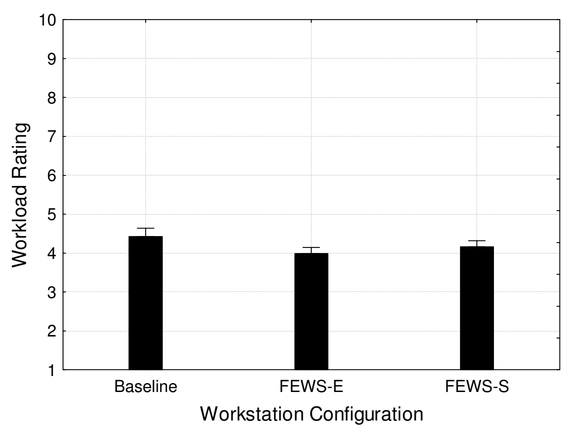

Figure 29. Data controller workload assessment keypad ratings as a function of Workstation Configuration.

3.3.2 NASA Traffic Load Index

Perceived mental demand increased significantly between traffic levels, $\Lambda = .11$, $F(2, 11) = 44.87$, $p < .05$ (see Figure 30). Controllers rated that the 166% Traffic Level condition was significantly more physically demanding than the 100% Traffic Level condition, but the 133% condition did not differ significantly from the other two conditions, $\Lambda = .54$, $F(2, 11) = 4.67$, $p < .05$ (see Figure 31).

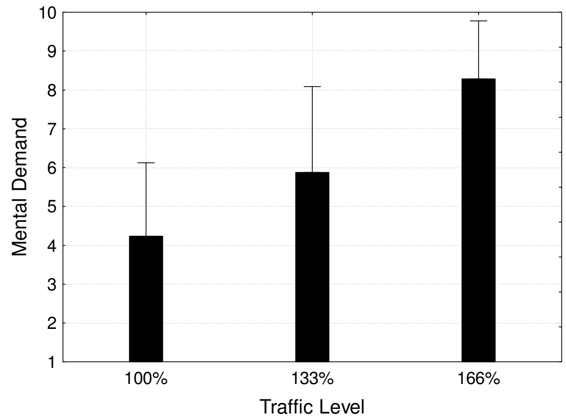

Figure 30. Perceived mental demand as a function of Traffic Level.

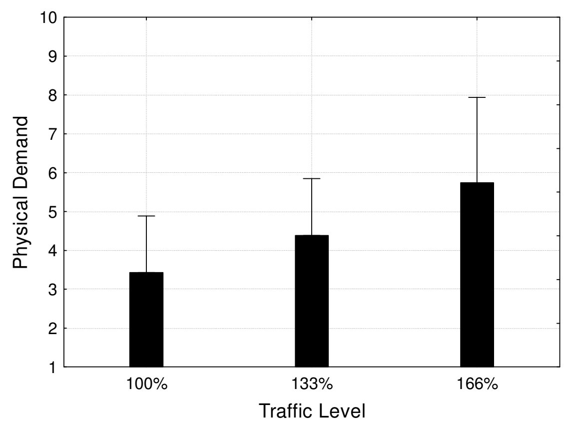

Figure 31. NASA TLX: Perceived physical demand as a function of Traffic Level.

Although the interaction between Workstation Configuration and Controller Position was significant, $\Lambda = .53$, $F(2, 11) = 4.83$, $p < .05$, a Tukey HSD post hoc test did not reveal significant differences between conditions (see Figure 32). The perceived temporal demand increased significantly with an increase in Traffic Level, $\Lambda = .17$, $F(2, 11) = 26.45$, $p < .05$ (see Figure 33).

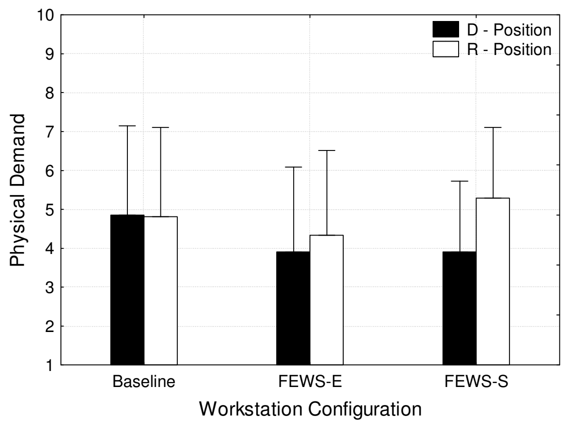

Figure 32. NASA TLX: Perceived physical demand as a function of Workstation Configuration and Controller Position.

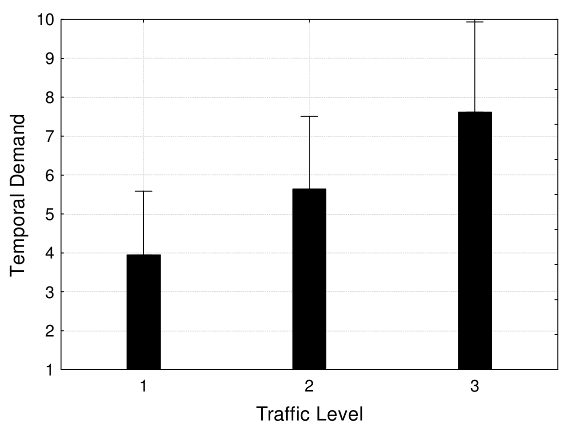

Figure 33. NASA TLX: Perceived temporal demand as a function of Traffic Level.

Although controllers rated that they performed very well, they rated that they performed significantly better when using the two FEWS configurations than with the Baseline design, Λ = .40, $F(2, 11) = 8.09$, $p < .05$ (see Figure 34). Controllers rated that they performed significantly better under the 100% and 133% conditions than under the 166% condition, Λ = .30, $F(2, 11) =$ 13.02, $p < .05$ (see Figure 35).

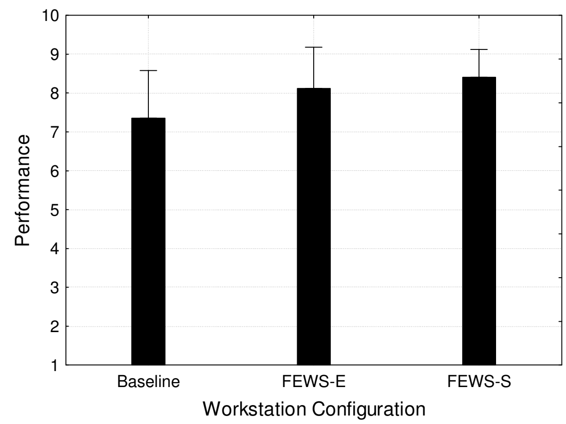

Figure 34. NASA TLX: Perceived performance as a function of Workstation Configuration.

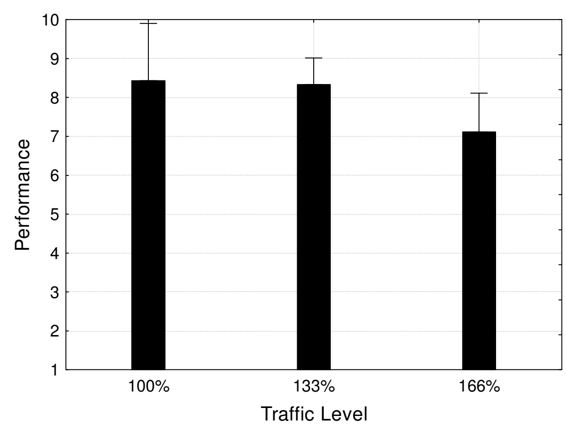

Figure 35. NASA TLX: Perceived performance as a function of Traffic Level.

The controllers rated they needed to exert significantly more effort to control the 166% Traffic Level conditions, whereas the 100% and 133% conditions did not differ from one another, Λ = .24, $F(2, 11) = 17.90$, $p < .05$ (see Figure 36).

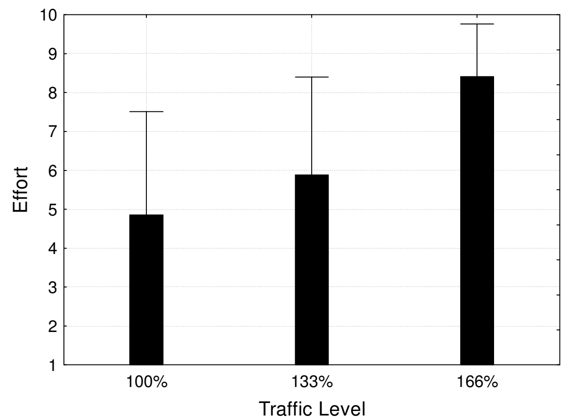

Figure 36. NASA TLX: Perceived level of effort as a function of Traffic Level.

The controllers rated that they were significantly more frustrated with the Baseline Workstation Configuration than with the FEWS concepts, Λ = .51, $F(2, 11) = 5.24$, $p < .05$ (see Figure 37). Under the 166% Traffic Level condition, controllers rated higher levels of frustration than under the 100% and 133% conditions, Λ = .34, $F(2, 11) = 10.73$, $p < .05$ (see Figure 38).

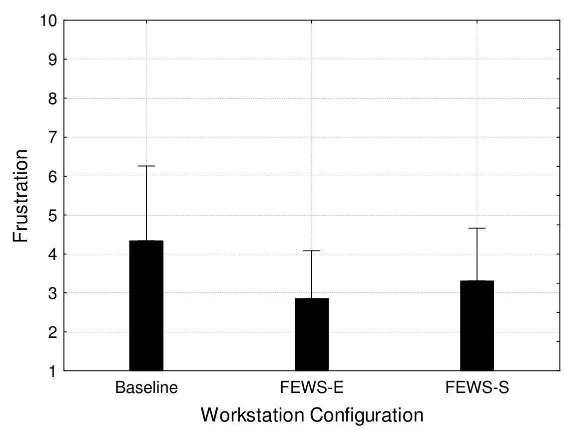

Figure 37. NASA TLX: Perceived frustration level as a function of Workstation Configuration.

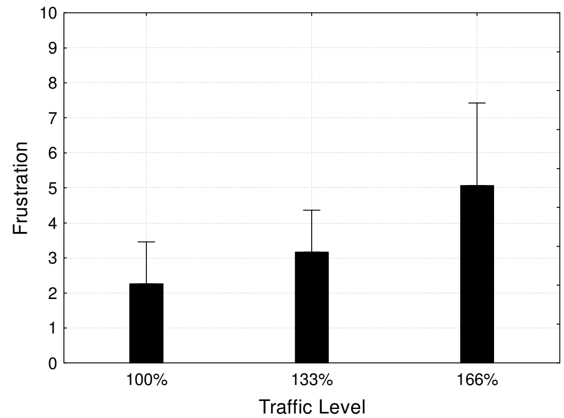

Figure 38. NASA TLX: Perceived frustration level as a function of Traffic Level.

3.4 Situation Awareness

3.4.1 Post-Scenario Questionnaires

The PSQ contained four SA-related questions, probing participants for awareness of current aircraft positions, projected aircraft positions, potential losses of separation, and potential handoff or airspace violations. We found significant effects for all four SA-related questions.

Workstation Configuration and Traffic Level affected controller awareness of current aircraft positions, $\Lambda = .57$, $F(2, 11) = 4.19$ and $\Lambda = .28$, $F(2, 11) = 14.17$, respectively, both at $p < .05$. Controllers rated their awareness for current aircraft position significantly better with the FEWS-E interface than with the Baseline or FEWS-S designs (see Figure 39).

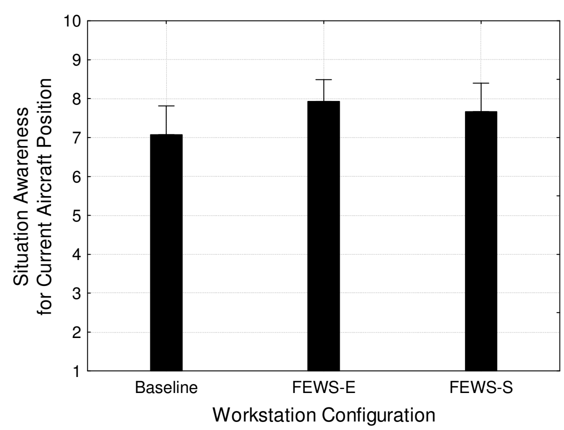

Figure 39. Perceived situation awareness for current aircraft position as a function of Workstation Configuration.

The controllers indicated that their awareness for current aircraft position was worst under the 166% condition but did not differ between the 100% and the 133% conditions (see Figure 40).

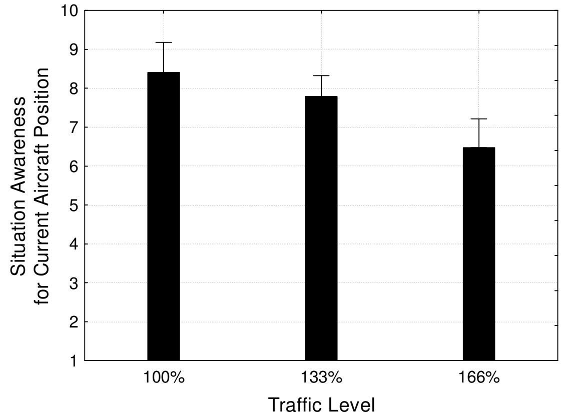

Figure 40. Perceived situation awareness of current aircraft position as a function of Traffic Level.

The controllers rated their awareness for projected aircraft positions better under the 100% condition with the FEWS-S interface than any of the other Traffic Level and Workstation Configuration combinations, $\Lambda = .51$, $F(2, 11) = 5.33$, $p < .05$ (see Figure 41). Under the 100% and 133% Traffic Level condition, Workstation Configuration did not affect controllers' perceived awareness of projected aircraft positions. Under the 166% Traffic Level condition, however, controllers indicated that they were less aware of projected aircraft position when using the Baseline Workstation Configuration than when using either of the FEWS designs.

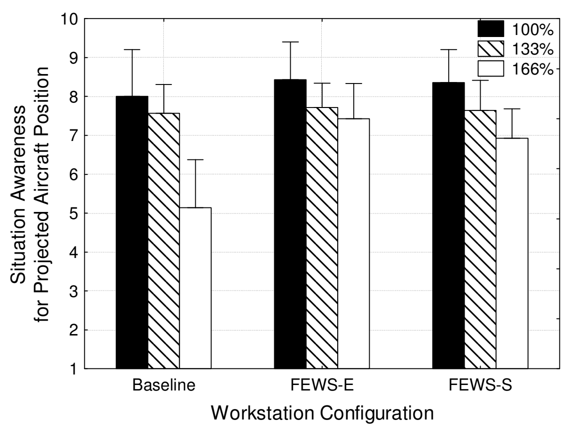

Figure 41. Perceived awareness of projected aircraft positions as a function of Workstation Configuration and Traffic Level.

3.4.2 Over-the-Shoulder Rating Forms

Only Traffic Level affected the performance of controllers on maintaining attention and SA, $\Lambda = .36$, $F(2, 10) = 9.92$, $p < .05$. Similar to our item on safety and efficiency, controllers performed poorest under the highest Traffic Level condition, whereas the 100% and the 133% conditions did not differ significantly (see Figure 42).

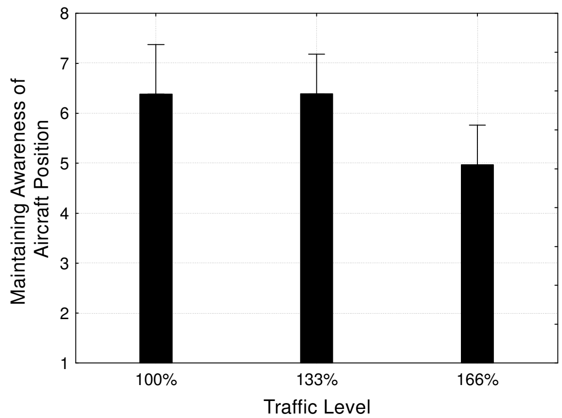

Figure 42. Over-the-shoulder rating of performance on maintaining attention and situation awareness as a function of Traffic Level.

3.4.2.1 Maintaining Awareness of Aircraft Positions

The controllers were less aware of aircraft position under the 166% Traffic Level conditions than either of the other Traffic Level conditions, $\Lambda = .31$, $F(2, 11) = 12.48$, $p < .05$ (see Figure 43).

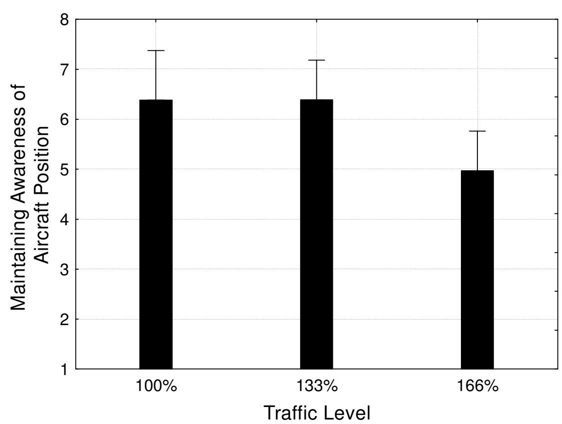

Figure 43. Over-the-shoulder rating of performance on maintaining awareness of aircraft positions.

3.4.2.2 Ensuring Positive Control

Controllers ensured positive control better when working with the FEWS configuration than with the Baseline configuration, $\Lambda = .44$, $F(2, 11) = 6.97$, $p < .05$ (see Figure 44). Controllers ensured positive control better when working under the lower Traffic Level conditions than when working under the 166% Traffic Level, $\Lambda = .35$, $F(2, 11) = 10.36$, $p < .05$ (see Figure 45).

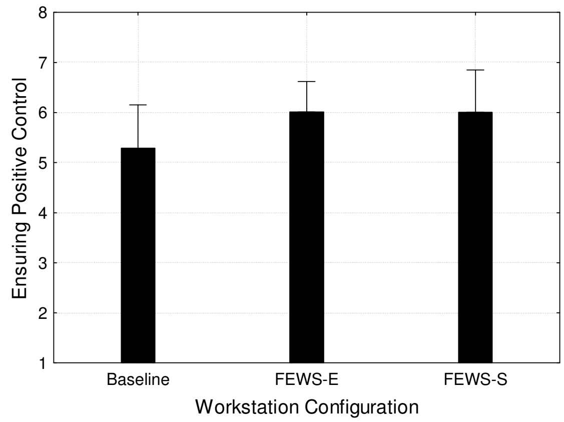

Figure 44. Over-the-shoulder rating of performance on ensuring positive control as a function of Workstation Configuration.

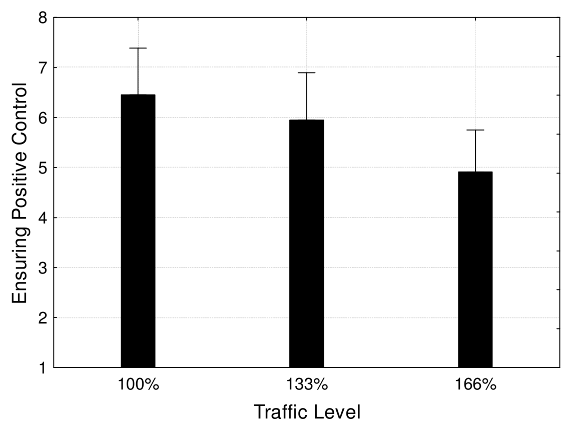

Figure 45. Over-the-shoulder rating of performance on ensuring positive control as a function of Traffic Level.

3.4.2.3 Detecting Pilot Deviations

Controllers did not detect pilot deviations as well under the 166% Traffic Level conditions than under the two other traffic levels, $\Lambda = .41$, $F(2, 11) = 7.78$, $p < .05$ (see Figure 46).

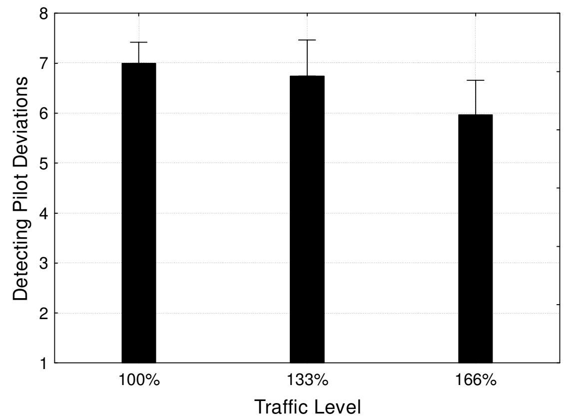

Figure 46. Over-the-shoulder rating of performance on detecting pilot deviations as a function of Traffic Level.

3.4.2.4 Correcting Own Errors in a Timely Manner

R-side controllers were less able to detect their own errors in a timely manner under the 166% Traffic Level condition, whereas Traffic Level did not significantly affect the ability of the D-side controller, $\Lambda = .60$, $F(2, 11) = 4.33$, $p < .05$ (see Figure 47).

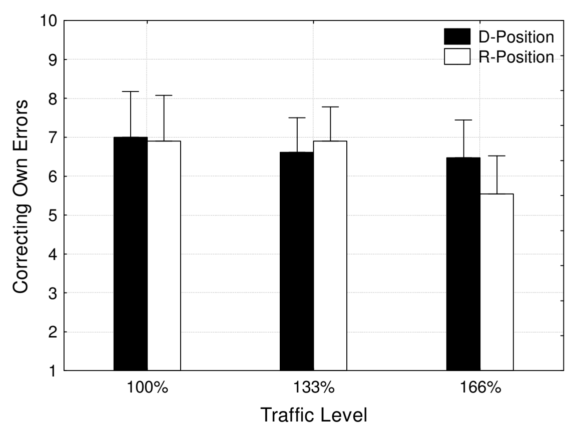

Figure 47. Over-the-shoulder rating of performance on correcting own errors in a timely manner as a function of Traffic Level and Controller Position.

3.5 Performance

3.5.1 Simulation Interactions

3.5.1.1 Number of Keystrokes

The reduction in the number of keystrokes with the use of the FEWS configurations interacted with the effect of Traffic Level, $F(4, 40) = 3.76$, $p < .05$. Figure 48 shows that the effect of Traffic Level is less pronounced for the FEWS configurations. The most pronounced effect is visible for the highest Traffic Level between the Baseline and the FEWS-S conditions. When working with the FEWS-S condition, the number of keystrokes is more than 40% less than when controllers use the Baseline interface.

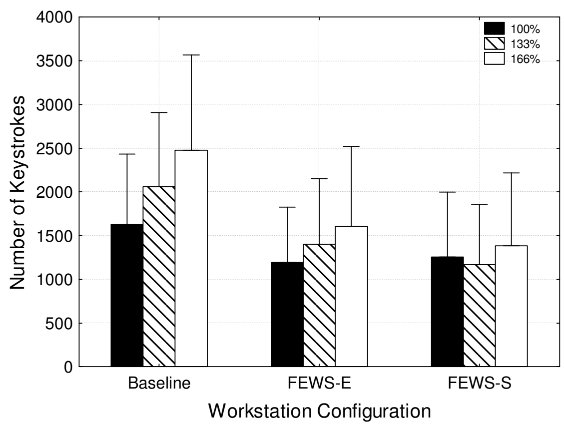

Figure 48. The number of keystrokes as a function of Workstation Configuration and Traffic Level.

3.5.1.2 Number of pointing device interactions

The simulation recordings contained five separate interactions with pointing devices. We distinguished left clicks (or pick events), center clicks (or pick and enter events), right clicks (or homing events), upward scrolls, and downward scrolls.

When working with the Baseline Workstation Configuration, the left click is frequently used to select an aircraft without sending an entry to the system to update the aircraft's status. There were no differences in the number of these events when controllers used the Baseline Workstation Configuration. The FEWS configurations showed a significantly higher number of left clicks than the Baseline configuration. Traffic Level modified that effect, resulting in a significantly higher number for the 166% Traffic Level condition when using the FEWS-E interface, whereas the 166% Traffic Level condition only differed significantly from the 100% condition when using the FEWS-S interface, $\Lambda = .26$, $F(4, 7) = 5.03$, $p < .05$ (see Figure 49).

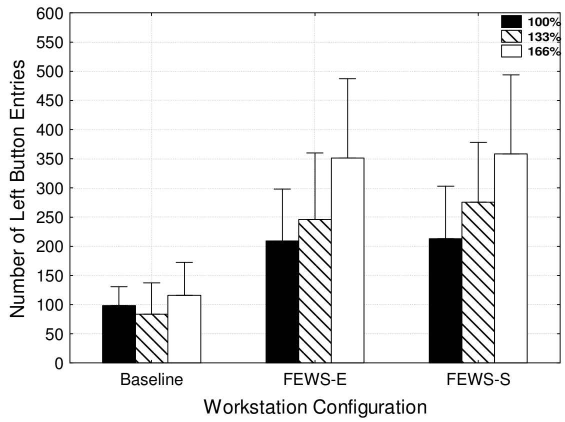

Figure 49. Number of left clicks as a function of Workstation Configuration and Traffic Level.

The R-side controllers used significantly more center clicks under the Baseline Workstation Configuration than under either of the FEWS configurations, $\Lambda = .46$, $F(2, 9) = 5.35$, $p < .05$ (see Figure 50). When using the baseline workstation, D-side controllers rarely used center clicks because they do not have their own radar display.

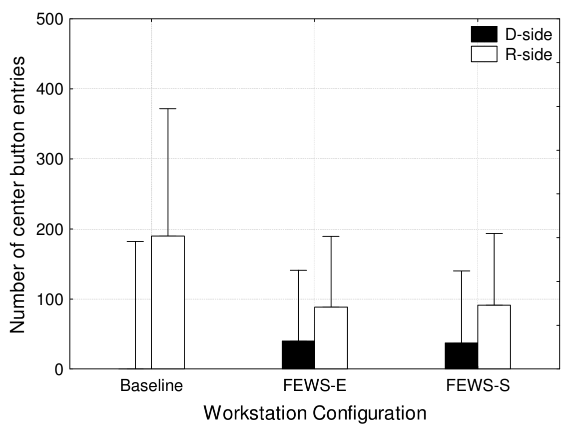

Figure 50. Number of center button entries as a function of Controller Position and Workstation Configuration.

We analyzed the right-button clicks and found only few entries of this type. The scroll option was available only under the FEWS conditions, and controllers used it to move through values within the interactive Full Data Block (FDB) fields. In comparison, the R-side controllers used the scroll option more frequently than the D-side controllers did, which reflects that the R-side controllers were providing CPDLC clearances using this method more frequently than the D-side controllers (see Figure 51).

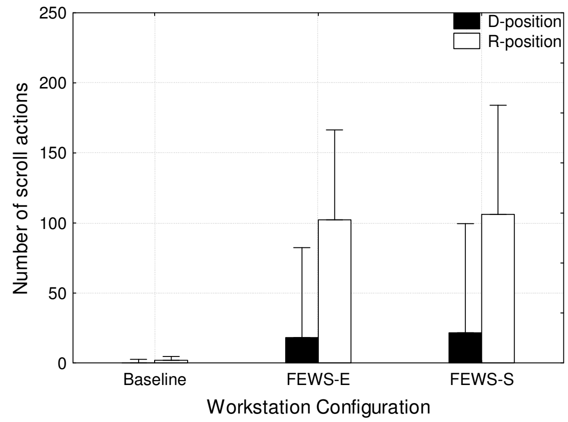

Figure 51. The use of scrolling as a function of Workstation Configuration and Controller Position.

<u>3.5.1.3 Controller entries</u>

To determine how the number of controller entries reflected the changes in the number of keystrokes and button clicks, we analyzed the overall number of controller entries and three specific types of entries. These three entry types were the task that accepts a handoff, forces a data block or drops a data block (all accomplished by entering a flight identification through the keyboard, pointing device, or a combination of the two), manual handoff to the next sector, and moving data blocks.

Controllers made significantly more entries under the 166% Traffic Level condition than under the other traffic levels, whereas Workstation Configuration did not affect the number of controller entries, $\Lambda = .51$, $F(2, 9) = 4.27$, $p < .05$ (see Figure 52).

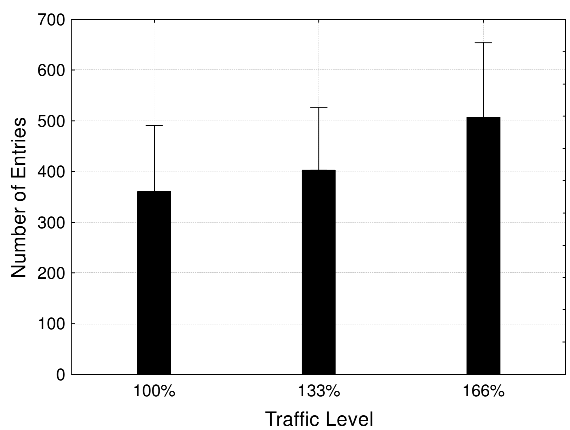

Figure 52. Total number of controller entries as a function of Traffic Level.

We found that the effects of Workstation Configuration and Traffic Level on entries representing forced data blocks, manual acceptance of handoffs, and dropping data blocks interacted, $\Lambda = .22$, $F(4, 7) = 6.14$, $p < .05$. We analyzed the effects of Workstation Configuration under each Traffic Level and found that Workstation Configuration had a significant effect under the 133% and 166% Traffic Level conditions, $\Lambda = .20$, $F(2, 9) = 18.14$ and $\Lambda = .23$, $F(2, 9) = 15.52$, respectively, both at $p < .05$. As Figure 53 shows, controllers made significantly fewer flight identification entries when using the FEWS configurations – the difference reached significance and became more pronounced with an increase in Traffic Level.

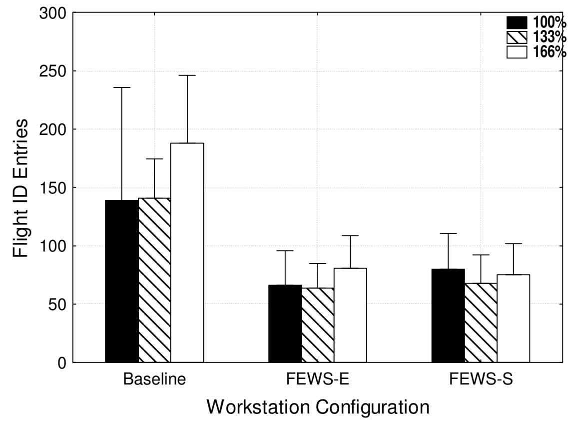

Figure 53. Flight ID entries as a function of Workstation Configuration and Traffic Level.

Controllers moved significantly fewer data blocks when using the Baseline Workstation Configuration than when using the FEWS configurations, whereas controllers moved significantly more data blocks with increasing Traffic Levels, $\Lambda = .40$, $F(2, 9) = 6.84$ and $\Lambda = .13$, $F(2, 9) = 31.04$, respectively, both at $p < .05$ (see Figure 54).

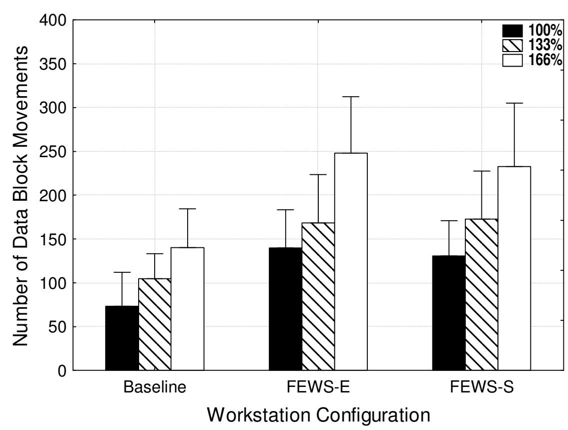

Figure 54. Number of data block movements as a function of Workstation Configuration and Traffic Level.

3.5.2 Data Reduction and Analysis Tool

We tested the differences across conditions in a repeated measure 3 x 3 (Workstation Configuration x Traffic Level) design. We found a significant effect of Traffic Level on the number of altitude changes per aircraft, $\Lambda = .10$, $F(2, 4) = 17.84$, $p < .05$. A Tukey HSD post hoc test revealed that controllers gave significantly fewer aircraft altitude clearances inside the sector boundaries under the 133% Traffic Level than either the 100% or the 166% traffic levels (see Figure 55).

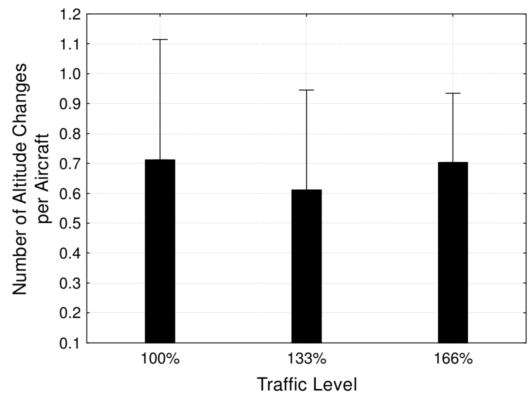

Figure 55. Number of altitude changes per aircraft as a function of Traffic Level.

We also tested the effects of Workstation Configuration and Traffic Level on the number of heading and speed changes per aircraft but did not find significant effects. The number of frequency switches to Sector 08 within the sector boundaries, however, showed a significant interaction between the effects of Workstation Configuration and Traffic Level, $\Lambda = .00$, $F(4, 2) = 3477.30$, $p < .05$. More than 50% of the aircraft switched their frequency to Sector 08 within the sector boundaries under the Baseline Workstation Configuration – although this was less than 10% for both FEWS conditions (see Figure 56). The effect of Workstation Configuration interacted with the effect of Traffic Level. To investigate that interaction further, we calculated statistics for simple effects of Traffic Level within each of the Workstation Configurations. We found that the effect of Traffic Level on the number of aircraft that switched within the sector boundaries was only significant for the FEWS-E condition.

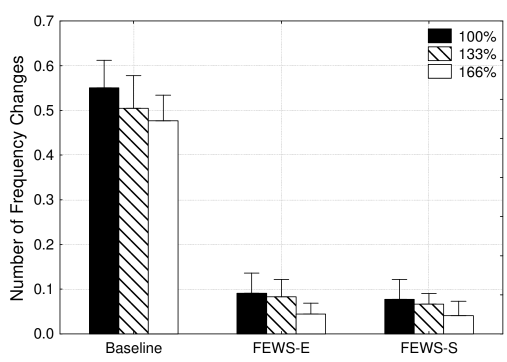

Figure 56. Number of frequency changes within the sector boundaries as a function of Workstation Configuration and Traffic Level.

3.5.3 Over-the-Shoulder Rating Forms

3.5.3.1 Maintaining Safe and Efficient Traffic Flow

The Workstation Configurations did not affect the performance rating of the D-side but did affect that of the R-side controller. The R-side performance on maintaining a safe and efficient flow of traffic was worst when using the Baseline Workstation Configuration, $\Lambda = .38$, $F(2, 10) = 8.28$, $p < .05$ (see Figure 57).

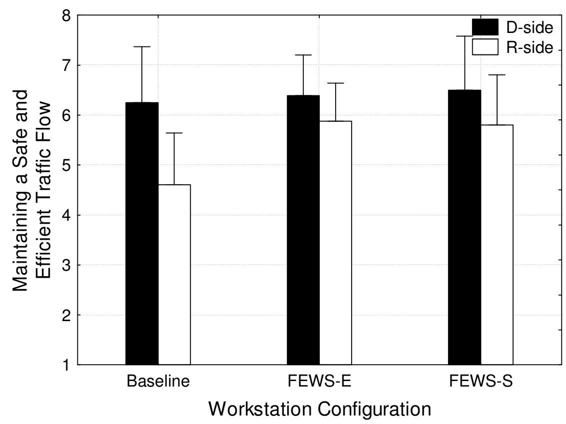

Figure 57. Over-the-shoulder rating of performance on maintaining a safe and efficient traffic flow as a function of Workstation Configuration and Controller Position.

Traffic Level affected performance on maintaining a safe and efficient traffic flow as well, $\Lambda = .28$, $F(2, 10) = 13.09$, $p < .05$. A Tukey HSD post hoc test showed that controllers performed significantly worse under the highest Traffic Level, but the difference between the 100% and the 133% traffic levels did not reach significance (see Figure 58).

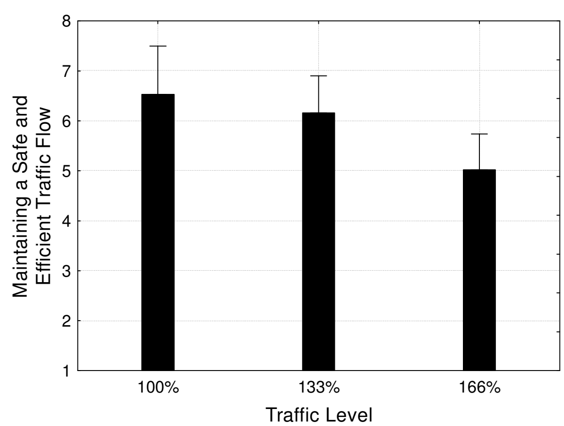

Figure 58. Over-the-shoulder rating of performance on maintaining a safe and efficient traffic flow as a function of Traffic Level.

To further investigate how our experimental manipulations affected maintaining a safe and efficient traffic flow, we analyzed three sub-elements. We asked our OTS raters to specify how controllers performed on maintaining separation and resolving potential conflicts, sequencing arrival and departure aircraft efficiently, and using control instructions effectively.

<u>*Maintaining Separation and Resolving Potential Conflicts*</u>

Controllers maintained separation and resolved potential conflicts better under low Traffic Levels, but controllers performed significantly worse under the 166% Traffic Level condition, $\Lambda = .26$, $F(2, 11) = 15.5$, $p < .05$ (see Figure 59).

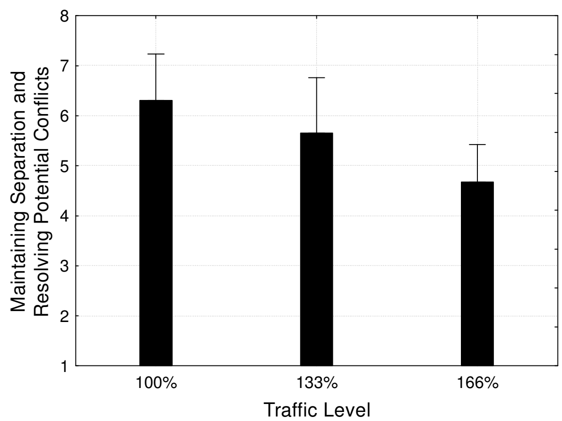

Figure 59. Over-the-shoulder rating of performance on maintaining separation and resolving potential conflicts as a function of Traffic Level.

Controllers maintained separation and resolved potential conflicts better when using the FEWS configurations, but the effect was different for the R-side and the D-side controllers, $\Lambda = .51$, $F(2, 11) = 5.28$, $p < .05$. R-side controllers performed worse when using the Baseline Workstation Configuration, whereas Workstation Configuration did not affect performance for the D-side controllers (see Figure 60).

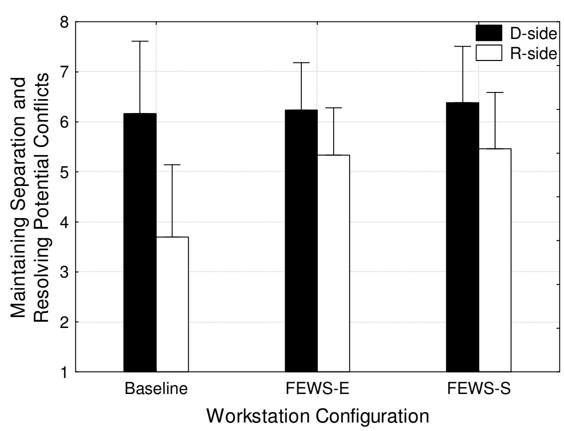

Figure 60. Over-the-shoulder rating of performance on maintaining separation and resolving potential conflicts as a function of Workstation Configuration and Controller Position.

Sequencing Arrival and Departure Aircraft Efficiently

Our OTS raters indicated that controllers sequenced aircraft more efficiently with the FEWS configurations, but the effect interacted with Controller Position, $\Lambda = .52$, $F(2, 11) = 5.12$, $p < .05$. D-side controllers performed equally well on all three Workstation Configurations (see Figure 61). The R-side controller performed better on sequencing aircraft when using the two FEWS configurations. The two FEWS configurations did not differ.

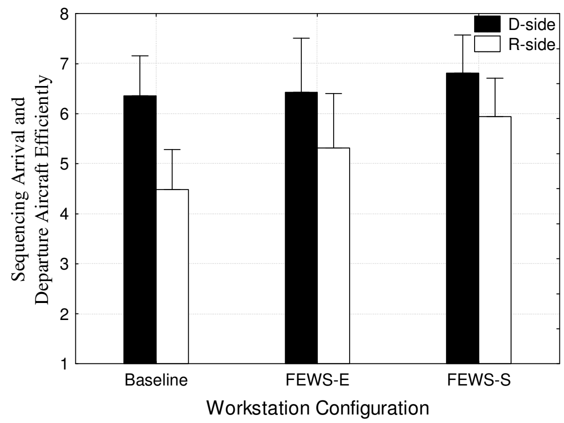

Figure 61. Over-the-shoulder rating of performance on sequencing arrival and departure aircraft efficiently as a function of Workstation Configuration.

With an increase in traffic, the controllers performed worst on sequencing aircraft. The Traffic Level effect interacted with Controller Position, $\Lambda = .52$, $F(2, 11) = 5.01$, $p < .05$ (see Figure 62). The OTS ratings for the D-side controller differed only between the 100% and the 166% condition. The ratings for the R-side controller did not differ between the 100% and the 133% traffic levels, but the 166% condition was significantly lower than the 100% and the 133% conditions.

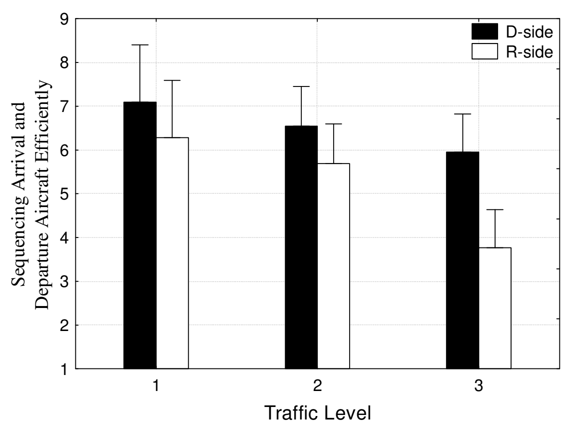

Figure 62. Over-the-shoulder rating of performance on sequencing arrival and departure aircraft efficiently as a function of Traffic Level and Controller Position.

Using Control Instructions Effectively

We found a main effect of Workstation Configuration on the effective use of control instructions, $\Lambda = .58$, $F(2, 11) = 4.01$, $p < .05$. A Tukey HSD post hoc test showed that the SMEs rated the use of control instructions effectively to be better when controllers used the FEWS configuration with identical workstations (see Figure 63).

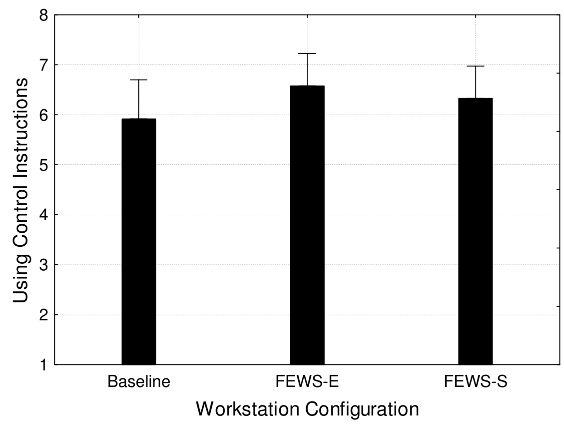

Figure 63. Over-the-shoulder rating of performance on using control instructions effectively as a function of Workstation Configuration.

The ratings were significantly lower for the 166% Traffic Level condition, $\Lambda = .33$, $F(2, 11) = 11.46$, $p < .05$ (see Figure 64).

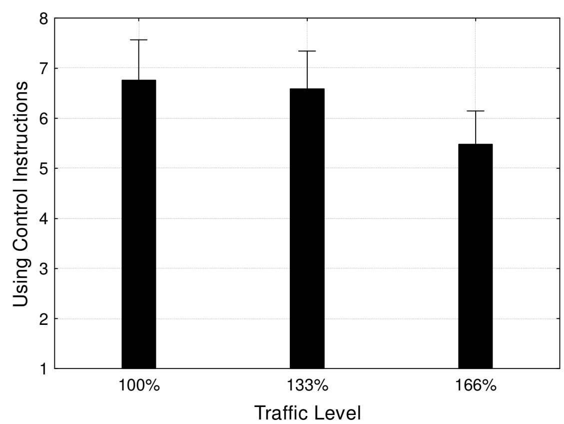

Figure 64. Over-the-shoulder rating of performance on using control instructions effectively as a function of Traffic Level.

3.5.3.2 Prioritizing

Our OTS raters indicated that the prioritization task suffered. That is, under the highest Traffic Level, controllers prioritized worse than under either the 100% or 133% traffic levels, $\Lambda = .34$, $F(2, 10) = 9.92$, $p < .05$ (see Figure 65).

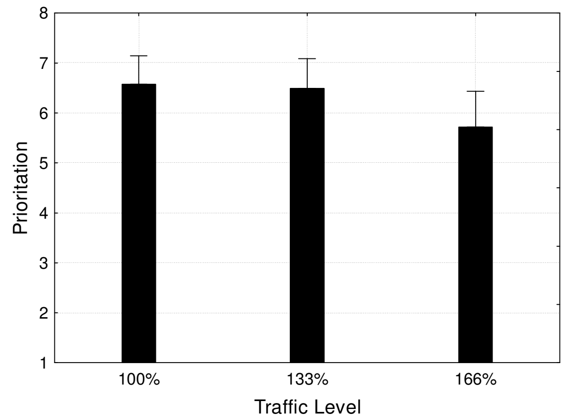

Figure 65. Over-the-shoulder rating of performance on prioritization as a function of Traffic Level.

Taking Actions in an Appropriate Order of Importance

The OTS raters indicated that controllers took action in a more appropriate order of performance with the FEWS configurations, $\Lambda = .58$, $F(2, 11) = 3.99$, $p < .05$ (see Figure 66).

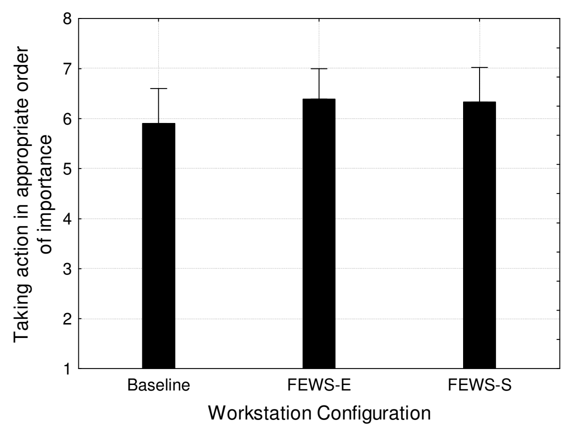

Figure 66. Over-the-shoulder rating of performance on taking actions in an appropriate order of importance as a function of Workstation Configuration.

Our OTS raters indicated that controllers took actions in a less appropriate order of importance when working under the highest Traffic Level condition, $\Lambda = .35$, $F(2, 11) = 10.21$, $p < .05$ (see Figure 67).

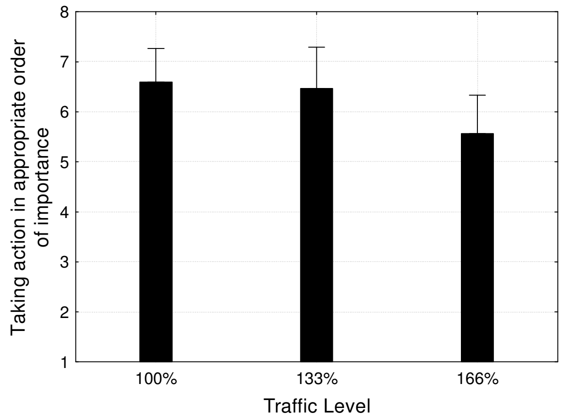

Figure 67. Over-the-shoulder rating of performance on taking actions in an appropriate order of importance as a function of Traffic Level.

Preplanning Control Actions

We found that when working with the Baseline workstation under high Traffic Level conditions, controllers performed significantly worse than when working under any of the other conditions, $\Lambda = .34$, $F(4, 9) = 4.35$, $p < .05$ (see Figure 68).

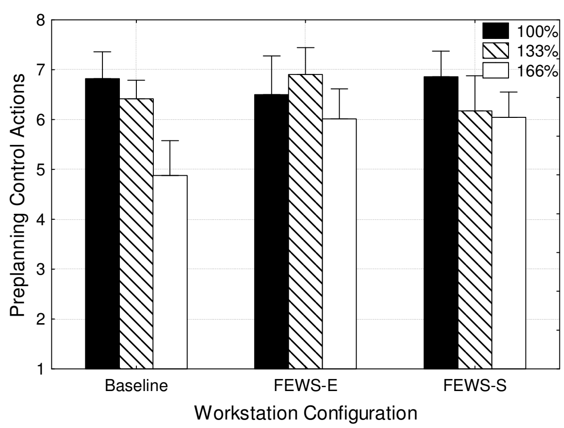

Figure 68. Over-the-shoulder rating of performance on preplanning control actions as a function of Controller Position.

Handling Control Tasks for Several Aircraft

Controllers handled control tasks for several aircraft significantly better under the 100% and 133% conditions than under the 166% Traffic Level condition, $\Lambda = .33$, $F(2, 11) = 11.20$, $p < .05$ (see Figure 69). The reduction in that ability between the 100% and 133% Traffic Level condition did not reach significance.

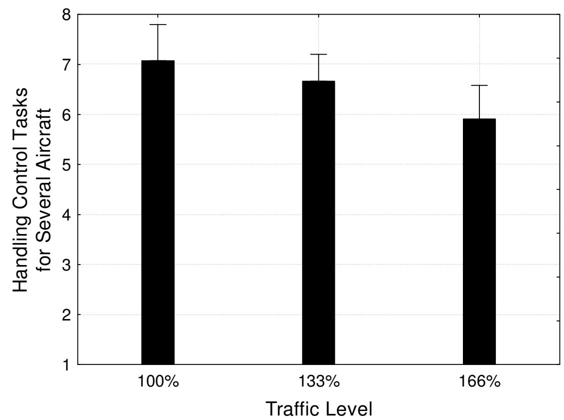

Figure 69. Over-the-shoulder rating of performance on handling control tasks for several aircraft as a function of Workstation Configuration and Traffic Level.

3.5.3.3 Technical Knowledge

Our analysis of the OTS rating items that focused on technical knowledge showed that controllers demonstrated less technical knowledge as Traffic Levels increased (see Figure 70).

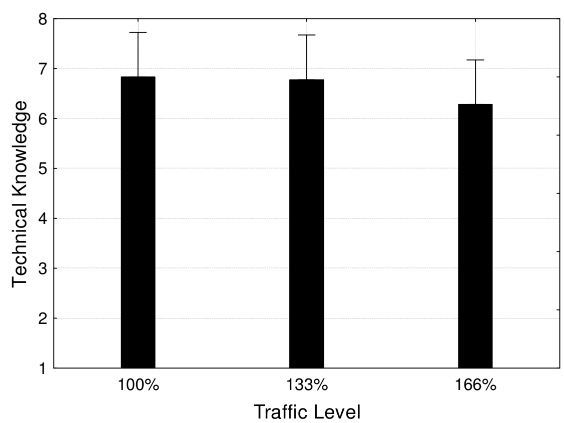

Figure 70. Over-the-shoulder rating of performance on technical knowledge as a function of Traffic Level.

4. DISCUSSION

The FEWS environment exposed controllers to many changes, some more subtle than others. In this section, we discuss the impact that our changes made on controllers in the areas of communications, workstation complexity, workload, SA, and performance.

4.1 Communications

The objective measures of communications that we analyzed for this report included the number and duration of PTT events. All traffic samples used in conditions discussed in this report contained approximately 70% of aircraft equipped with CPDLC Build 1A capabilities. Under these conditions, the number of Voice Communication events increased by 50% when Traffic Levels increased by 33% and doubled when traffic increased by 66%. When analyzing our traffic data, we have found that the Traffic Levels under the 133% condition were somewhat lower than expected. Therefore, we do not want to conclude that the number of communication events increase linearly by 50% for every 33% of traffic increase, although our current analyses certainly seem to indicate such a linear relationship. We did not find an effect of changes to the workstation on the number of communication events. Even more surprising is the fact that the duration of communication events did not differ with increasing Traffic Levels or changes to the workstation. In this report, we have used PTT recordings to determine the number and duration of communication events, but we have also reduced our audio recordings to probe the content of controller and pilot communications. We will need to verify that our PTT recordings correspond to full clearances and do not reflect clearances broken up across two or more PTT events.

The subjective measures included items from our OTS rating forms. We often found interactions with Controller Position for one obvious reason: The D-side controller did not directly communicate with pilots and could only do so indirectly through Data Link. Data Link communications are not directly observable and, therefore, D-side communication performance did not show effects from our experimental manipulations, whereas the R-side communication performance did. In follow-on analyses of our data, we will look into intra-team communications and expect to see effects of experimental manipulations on the characteristics of the communications that take place offline. In general, our OTS raters indicated that R-side controllers performed well, but performance suffered under the 166% Traffic Level condition. When we investigated the aspects of controller communications that suffered, OTS raters indicated that controllers did not perform as well when using proper phraseology, communicating clearly and efficiently, and listening for pilot readbacks and requests. Our OTS raters indicated that controllers communicated more clearly and efficiently when using the FEWS-E Workstation Configuration.

4.2 Workstation Complexity

One of the goals of the FEWS program is to make data entry and retrieval easier and more direct. Researchers at the Civil Aviation Medical Institute developed a questionnaire designed to assess display complexity; we incorporated the items into our PSQs. Controllers rated that all Workstation Configurations had very low display complexity. In our opinion, this reflects the extensive experience that controllers have in using the fielded systems. Overall, perceptual complexity increased as the traffic levels increased. Because the CHI did not change between Traffic Levels, the amount of displayed traffic added to the complexity. Under the 166% Traffic Levels, controllers monitored displays that contained approximately 35 aircraft under control. To maintain awareness of these aircraft takes, on average, 1 second per aircraft. Willems, Allen, and

Stein (1999) assert that an average controller's fixation lasts approximately 600 msec. So, if controllers treat these aircraft independently, it would take approximately three radar sweeps (12 seconds per sweep for long-range radar). At 420 knots (777.84 km/h), aircraft would cover approximately 7 nmi (12.964 km) per minute. To keep up with the changes in the traffic situation, controllers would fall behind in their scanning of traffic. To counter the effect of increasing Traffic Levels on display complexity, controllers need automation functions that can reduce the number of elements they need to monitor to a more manageable amount.

In the FEWS configurations, we eliminated many of the lists and windows available in the Baseline configuration. As a result, the controllers indicated that the FEWS configurations were less complex and their awareness of displayed information was better for the FEWS-S workstation than for the Baseline workstation.

4.3 Workload

Our workload measures all showed clearly that most controllers honestly respond to workload queries and indicate that their workload is indeed high when Traffic Levels are high. Other researchers have suggested that controllers underestimate their workload. In previous research, however, we have often exposed controllers to Traffic Levels that are normal for a normal day at their home facility. The instructions that we gave to the controllers provided operational anchors attached to specific ranges on the workload scale. When controllers indicated workload levels of six and over, they admitted that it became more likely for them to make mistakes. In field facilities, making mistakes may result in compromising safety, which controllers will try to prevent at all cost. So, the threshold for what is acceptable to controllers as their workload level – given our operational anchors – is likely 6 on a 10-point scale. The highest Traffic Level on average exceeded that threshold. That is, controllers could not manage the 35 aircraft to which we exposed them under any of the Workstation Configurations. Granted, the FEWS configurations reduced controller workload levels, but not enough to bring most of the controllers down to a level that would not result in mistakes. At the 133% Traffic Level, controllers reported workload levels that were below the threshold, indicating that with 70% Data-Link equipped aircraft, they rated that they were *not likely* to make mistakes. That level of equipage is not likely to be available in the United States within the next 6 or 7 years, at which time the FAA's projections suggest that some of our facilities will have an increase in traffic of more than 33%.

4.4 Situation Awareness

Controllers and OTS raters agreed that SA suffered with increasing Traffic Levels and was better when using FEWS configurations. The FEWS configurations provided added automation that took care of routine tasks such as accepting handoffs and dropping data blocks. This may have freed up resources that controllers could use to maintain their picture of the traffic situation in the sector. The FEWS configurations also provided the R-side and the D-side controllers with a 2,048 x 2,048 radar display, whereas the baseline only had the DSR radar display on the R-side and URET and D-CRD on the D-side.

Although our data on SA of controllers suggest a positive impact of the changes to the Workstation Configurations and a negative impact of the increase in Traffic Level, we have observed several situations that we need to address in future experiments. First, there is confusion about which aircraft have Data Link capabilities. Because of the high proportion of the traffic mix that did have Data Link, the controllers started to assume that all aircraft had Data Link available. The feedback was not salient enough, and controllers were too busy with the traffic situation at hand and frequently attempted to uplink a message to a non-Data Link equipped aircraft. They would find out at a later point that they did not send a data link message, and the aircraft did not execute the clearance they thought they had sent to the pilot. In most instances, the controllers were able to recover from these mistakes, but it led to at least one instance where aircraft violated the minimum separation of 3 nmi (5.556 km) required in the experiment. A clear and integrated warning may prevent mistakes of this type. We will implement prominent feedback in our next experiment.

The FEWS configurations introduced automatic acceptance of aircraft by the system. This seemed to work well, with the exception of some aircraft that did not have Data Link capabilities. These voice-only aircraft tried to establish two-way radio communications on entering the sector airspace, and we observed controllers looking for the aircraft or requesting position reports to locate the aircraft calling in. There may be several solutions to this issue of loss of awareness of position of non-Data Link equipped aircraft when they enter the sector. A relatively simple solution consists of providing controllers with an indication that the system has accepted the handoff on an aircraft. Initially, we had discussed this as providing controllers with an indication of who took action. The controllers had indicated that they did not need to know that information, but with the changed capabilities available to the D-side controller and the increase in Traffic Levels, it becomes more important to understand whether a human sector team member or the system has taken action. In our next experiment, we will implement a feature that will indicate whether the R-side, the D-side, or the system has taken action on an aircraft. The indication will disappear after a preset time interval. Such a feature would work for automatic handoff acceptance and would be available for other air traffic functions. Another option, albeit not as easy to implement, is to provide controllers with a clear indication of which aircraft is calling in. EUROCONTROL has conducted research on implementing a watermarking technology that would identify the aircraft that is calling in (Hagmueller & Kubin, 2005).

4.5 Performance

One of the goals of the FEWS program is to free controller resources from routine tasks, and thereby increase the controller's ability to handle more aircraft. When observing controllers in an en route environment with high Traffic Levels, their hands are continuously using their keyboards to update the system with data entries and to transfer control to and from other sectors. Our recordings included keystrokes and pointing device-related actions. The FEWS configurations drastically reduced the number of keystrokes controllers made when working identical traffic scenarios. This effect was most pronounced when controllers were handling 35 aircraft at a time in the 166% traffic conditions. When using the FEWS-S configuration, controllers entered more than 40% less keystrokes than with the Baseline configuration (or down from 2,500 keystrokes in a 45-minute scenario to less than 1,500 keystrokes). Some of the automation changes we made in the FEWS environment may have caused this effect. FEWS configurations contained a feature that allowed the system to automatically (a) accept a handoff when no potential conflict was detected in the sector and (b) drop data blocks when aircraft left the sector. In the Baseline configuration, controllers executed these tasks manually through a pointing-device action or a keyboard entry. When controllers use keyboard entries to execute these tasks, each entry requires at least three keystrokes.

The FEWS configurations also contained a feature that enabled controllers to click on the call sign in a data block to drag the data block to a new position. In the Baseline condition, controllers need to use a cardinal orientation and, sometimes, a leader-line length followed by a flight identification entry. Therefore, the Baseline action requires at least (a) one keystroke and, when using the keyboard for the flight identification, a space and three digits for the computer identification of the aircraft or (b) five keystrokes to complete a data block movement when using the keyboard only. When dragging a data block to its new location, it requires only a single click-and-drag action with the pointing device. We found a corresponding increase in the number of pointing-device interactions with the use of the FEWS configurations (most likely reflecting the ability to drag data blocks). When we analyzed the total number of controller entries, however, we did not find an effect of Workstation Configuration. Instead, we found that at 166% Traffic Levels, controllers made approximately 40% more entries. In our analyses, we have counted controllers dragging a data block to a new position as a controller entry. As a result, we have seen a large increase in the number of these entries when controllers were using the FEWS configurations to an extent that it offset the reduction of controller entries necessary to accept handoffs or drop data blocks.

Under the 133% Traffic Level, controllers made fewer altitude changes to aircraft within the sector boundaries. When we briefed controllers on the airspace and its SOPs, we instructed them that they had full control for all clearances on handoff acceptance. This provided controllers the opportunity to shed workload by clearing traffic that we had intended to cross their sector to descend to 22,000 ft (6,705.6 m) (FL220), which resulted in aircraft entering the sector briefly before disappearing to the sector below. The instruction to descend to FL220 took place outside of the sector boundary, and our algorithm therefore did not count it in our tallies. When Traffic Level was low (if we consider 21+ aircraft in the sector to be low), controllers did not need to shed workload. Under low Traffic Level conditions, controllers left aircraft at altitude, descending when necessary to meet the SOP altitude. When Traffic Level was higher (under the 133% condition), controllers rated that they needed to shed workload (and used our way out) and descended aircraft early. This, however, requires planning and finding aircraft that have the potential to apply this strategy. When Traffic Level was high, the extra planning and the lack of SA made it difficult to use that strategy, and controllers did not descend aircraft early to shed workload.

We found an equally interesting effect of Workstation Configurations. Under the FEWS configurations, pilots switched to the frequency of our sector much less within the sector boundaries. The automatic handoff acceptance by the system is mostly likely the cause of this effect. Our system automatically accepted handoffs and the simulation then automatically transferred the frequency to our sector. For aircraft that had Data Link equipment, aircraft entered the sector without calling in. For voice-only aircraft, the aircraft were on their way into the sector and pilots called in to establish two-way radio communications. In the Baseline condition, controllers needed to manually accept every handoff coming into the sector. The controllers accepted handoffs later than our parameters used in the automatic handoff acceptance, leading to aircraft switching within the sector boundaries.

5. GENERAL OBSERVATIONS

In the experimental design used for this report, all traffic samples contained a mix that had 70% of the aircraft equipped with nine service CPDLC 1A. We noticed that controllers attempted to uplink Data Link messages to aircraft that did not carry Data Link equipment. When controllers attempted to do that using a keyboard-only entry method, the system provided feedback in the form of an error message, which stated that the Data Link services were not available for the aircraft. When interacting with the aircraft representation under our Baseline condition using the pointing device and the interactive data block, controllers executed an identical sequence of actions whether they were updating the NAS only or uplinking a Data Link message as well. In the Baseline configuration, therefore, an intended uplink entered through the CHI will not result in an error as far as the system is concerned. The NAS will receive an update, but the aircraft will not receive an electronic message. In the FEWS environment, the actions are different for a NAS update only vs. a NAS update and an uplink. We found, however, that controllers continued to make the same mistake (i.e., assumed that they uplinked a message to an aircraft when the aircraft did not carry data link equipment). In the FEWS environment, we provided the appropriate error message in the CRD, but it was not sufficient to warn controllers that the intended action did not take place. We plan to circumvent this issue in the follow-up study to FEWS I, by providing immediate feedback to the controller that the NAS update has taken place, but that the aircraft requires a voice clearance because it only has Voice Communications available.

In the FEWS-I study, we provided controllers with an automation function that enabled them to highlight aircraft that shared a feature. We derived that functionality from existing automation functions such as the quick-look function and the quick-look function on a flow scope. In the former example, controllers can quickly look at aircraft under control of up to five other sectors. In the latter example, controllers can look at a stream of aircraft destined for a particular aircraft. We had seen similar examples on CENA's DigiStrips (Mertz, Chatty, & Vinot, 2000), where highlighting the altitude of one aircraft highlighted all altitude fields of other FPSs that were at the same altitude. The emphasis function in FEWS enabled controllers to enter a valid NAS command and, by replacing the flight identification with the emphasis key entry, the system briefly highlighted all aircraft sharing that feature. Therefore, by entering an altitude command with the emphasis key instead of the flight identification, the system would highlight all aircraft at that altitude. In a similar fashion, controllers could show all aircraft that had a particular waypoint in their route. Although the controllers indicated that this feature would prove beneficial, hardly any controllers used it during the experiment. In our opinion, the emphasis function was too cumbersome to get to the additional information. We suggest that, in a follow-up study, we implement a function to automatically highlight aircraft that share a feature that controllers manipulate; similar to how DigiStrips were used for altitudes.

We have implemented eFPSs in two formats. The first format was almost identical to the paper FPSs that controllers used in the field. The major difference is that the system takes advantage of the fact that the strips are electronic and updates displayed data on the strips whenever updated data becomes available. The system automatically sorted DSR eFPSs in the appropriate flight strip bays based on destination and waypoints. The second format was new and reflected the format of the FDB on the left-hand side with additional data depicted on the right-hand side. Similar to the DSR eFPSs, the system automatically updated available data and sorted the eFPSs.

The FEWS eFPSs, however, were interactive in a similar fashion as the data block fields. The controllers were able to change speed, heading, and altitude on the eFPS as well as to decide whether to either just update NAS or update NAS and uplink a message to an equipped aircraft. Interaction with a flight strip highlighted the aircraft on the controller display and vice versa. The controllers hardly ever used the FPSs. We attribute part of this disappointing finding to the placement of our eFPSs, but most controllers agreed that they had the data available on the radar display and using the eFPSs would have taken them away from the tactical control workspace. Some controllers indicated that features, such as switching aircraft between arrival streams and metering fixes by dragging flight strips between flight strip bays, would certainly make it more likely that they would use the eFPSs. We believe, however, that if that functionality is useful, we should find a way to integrate it into the controller workstation on the radar display as well.

It may be more useful to integrate the idea of eFPSs into the radar display. To some extent, URET is doing that in its Aircraft List (ACL), but the ACL is lacking quite a few of the features that the eFPSs have. Over the years of use of URET in the field and the corresponding reduction or elimination of paper FPSs, several of the functions that the paper strips served have transferred silently into other areas of the controller workstation. For example, in the past, controllers used paper FPSs to indicate coordinated headings, speeds, or other coordinated items. The introduction of the fourth line of the data block now provides that functionality on the radar display, as does the ACL in the speed and heading column and a separate remarks line that controllers can bring up. FPSs also functioned as reminders of weather related messages. ERIDS is now capable of displaying that data, even though its initial intent was to provide the sector controllers with information that was initially available in paper format in sector binders. The En Route Automation Modernization program has overlapping requirements with ERIDS and specifies that the D-side display will provide windows for Notices to Airmen (NOTAMS), Pilot Reports (PIREPs), and Significant Meteorological Information. The question or issue is not really *where* we should display this type of information but *how* we can integrate the information in a manner that supports and extends the way controllers currently perform their jobs. As Moertl et al. (2002) eloquently advises, we need to implement a goal to identify essential information that supports air traffic planning and determines how to improve air traffic planning by optimizing the representation of that information. Integrated data for NOTAMS and PIREPs, for example, should not require controllers to scan that information when it becomes available but, instead, should be available when and where needed.

In FEWS, we introduced automatic acceptance of handoffs that did not have potential conflicts. Our SMEs predicted that controllers would find it hard to accept such a drastic procedural change. Indeed, when we first briefed controllers on this automation function, we received feedback that it would not work well. We discussed how R-side controllers knew that the D-side had taken a handoff for them if the team was busy with traffic. During the simulations, we have seen that controllers often did not manually accept handoffs before the automation did it for them. After the experiment, we discussed the automatic handoff acceptance again, and controllers informed us that it was acceptable as long as a conflict probe could adequately predict issues, and thereby stop the automatic handoff process. During the experiment, however, we did observe some issues that we need to address further. When aircraft did not carry Data Link equipment and the automation system accepted the handoff, the controller at the previous sector told the pilot to switch their frequency to the receiving sector's frequency. When pilots called in for these non-Data Linked aircraft, we frequently heard controllers ask for position reports or discuss (within the sector team) who was calling in and the location of that aircraft. This indicates a loss of awareness of the location of these aircraft. We need to determine, from the data that we have collected, *how frequently* controllers could not immediately identify the location of an aircraft and the reason for failure to find it. Several potential solutions to this issue exist. EUROCONTROL has published work that embeds a digital signature into the voice signal that a ground system extracts and uses to identify which aircraft is calling in (Hagmueller & Kubin, 2005). This "voice watermarking" would eliminate the need for controllers to look for the aircraft other than identifying which aircraft is displaying a feature that indicates that it is using the voice channel. Other potential solutions consist of identifying those aircraft that are most likely to call in next. In this experimental design (with only 30% of the aircraft not carrying Data Link equipment), this results in a relatively small number of aircraft. We can reduce the number of candidate callers even further if we provide controllers with the ability to indicate on the display that they have confirmed two-way radio communications. The FEWS interface has that capability, but this function did not provide the filtering it could have (a) because we did not staff adjacent sectors and (b) because controllers were not using their FPSs.

6. CONCLUSION

This study is one in a series that has investigated the effect of automation on air traffic controllers. It is the first study that has increased traffic to levels projected for 2015 and beyond. The goal of the changes to the workstation was to assist controllers in coping with the increased Traffic Levels without increasing workload, reducing SA, or negatively affecting safe and efficient flow of traffic. To support controllers, we have tried to automate routine tasks and provide assistance in ways that are a natural extension of current controller activities.

In general, the FEWS configurations performed better than the Baseline condition, but controllers did not use all of the available features. The controllers also indicated that some additional changes to existing FEWS features would be useful. We found very little differences between the FEWS-E and FEWS-S configurations. This study has shown that with 70% equipped aircraft and the additional features provided in FEWS, controllers could handle 133% of current Traffic Levels. However, at a further increase to 166% of current Traffic Levels, the controllers experienced workload levels that were so high that it would affect safety and efficiency despite the benefits of 70% Data Link equipage and the improvements made in the FEWS configurations.

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Acronyms

ACL	Aircraft List
ANOVA	Analysis of Variance
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
CHI	Computer-Human Interaction
CPDLC	Controller-Pilot Data Link Communications
CRD	Computer Readout Device
DESIREE	Distributed Environment for Simulation, Rapid Engineering, and Experimentation
DRAT	Data Reduction and Analysis Tool
D-side	Data-side
DSR	Display System Replacement
eFPS	Electronic Flight Progress Strip
ERIDS	En Route Information Display System
ERP	Engineering Research Psychologist
FAA	Federal Aviation Administration
FDB	Full Data Block
FEWS	Future En Route Workstation Study
FPS	Flight Progress Strip
GEN	Genera Airport
HSD	Tukey's Honestly Significant Difference
KSD	Keypad Selection Device
LOA	Letter of Agreement
MANOVA	Multivariate Analysis of Variance
MAP	Monitor Alert Parameter
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NOTAMS	Notices to Airmen

OTS	Over-the-Shoulder
PIREPs	Pilot Reports
PSQ	Post-Scenario Questionnaire
PTT	Push-to-Talk
RDHFL	Research Development and Human Factors Laboratory
R-side	Radar-side
RTCA	Radio Technical Commission for Aeronautics
SA	Situation Awareness
SME	Subject Matter Expert
SOP	Standard Operating Procedure
STARS	Standard Terminal Automation Replacement System
TGF	Target Generation Facility
TLX	Task Load Index
TMA	Traffic Management Advisor
TMU	Traffic Management Unit
URET	User Request Evaluation Tool
WAK	Workload Assessment Keypad