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Abstract. By 2020 all aircraft in United States airspace must use ADS-B (Automatic Dependent Surveillance-Broadcast) Out. This is a key component of the Next Generation (NextGen) Air Transportation System, which marks the first time all aircraft will be tracked continuously using satellites instead of ground-based radar. Standard Terminal Automation Replacement System (STARS) in the Terminal Radar Approach Control (TRACON) is a primary NextGen upgrade where digitized automation/information surrounds STARS controllers while controlling aircraft. Applying the SHELL model, the authors analyze human factors changes affecting TRACON controllers from pre-STARS technology through NextGen technologies on performance. Results of an informal survey of STARS controllers assessed cognitive processing issues and indicates the greatest concern is with movements to view other displays and added time to re-engage STARS.

Keywords: SHELL · Human factors · NextGen · STARS · TRACON · Cognitive loading · Distraction

1 Introduction

The Federal Aviation Administration (FAA) has mandated that by 2020 all aircraft flying in Controlled Airspace of the United States (U.S.) use an Automatic Dependent Surveillance Broadcast-Out (ADSB-Out) device to designate aircraft location in controlled airspace. This does not seem like a big change in the air traffic control (ATC) system, however the reality is that it marks a drastic shift in ATC operations moving from a ground-based radar system with navigational aids that is nearing capacity to a satellite-based system that can absorb the predicted future growth of the aviation industry. NextGen has been a work in progress for over 25 years. Most of the attention to NextGen has focused on how it will make flight operations safer and more efficient. One area of utmost importance and central to making NextGen ATC a success is the TRACON (Terminal Radar Approach Control) with STARS (Standard Terminal Replacement System) display. Currently the FAA requires STARS as a mandatory cornerstone to NextGen terminal area operations. The TRACON controllers must direct

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aircraft safely and efficiently, but many of the terminal airspaces in the U.S. have become crowded due to increased popularity of air travel along with the growth of air cargo. Consequently, ATC needs a viable solution.

2 Intent of Study on STARS TRACON Controller Cognition

The intent of this study was to analyze the dark room environment of controllers to gain an understanding of how human factors affects their work in relation to NextGen equipment upgrades like the STARS display. As the ADSB-IN/OUT is important to the NextGen cockpit, so too is the STARS display equipment to the controller. Of particular interest is how STARS controllers' job performance is affected cognitively by this technology. Although the combined STARS equipment and NextGen satellite ATC system should be a substantial gain in safety and efficiency for the controller, these potential gains could be negated by human error caused by a myriad of cognition issues. In terms of cognitive workload, the work of the TRACON controller is one of the most challenging in the world. Unlike their tower controller counterparts who can see aircraft and clear them to take off and land, the TRACON controller creates a three-dimensional cognitive map from a two- dimensional screen to simultaneously track aircraft. A cognitive slip could cause the controller to lose situational awareness of an aircraft under their control. This could lead to unfortunate accidents.

3 The Serious Threat to Aviation Safety

Although accidents involving TRACON controllers have become rare in the U.S., serious incidents still occur. With the pending future growth in the industry and ever shrinking skies looming ahead, accidents with TRACON involvement could pose a threat to the industry. An example of TRACON controllers heavily involved in an accident was the Avianca Flight 52 crash that occurred in 1990 on Long Island. The crash caused 73 fatalities when the aircrew failed to declare a fuel emergency to the New York TRACON controllers. Although the probable cause was rooted in failures to communicate from the cockpit, the National Transportation Safety Board [1] also determined that there were serious flaws in the ATC handling of the aircraft. Accidents like the Avianca crash illustrate how the controllers can err and contribute to an accident. Human factors is critical to TRACON operations and to gain a deeper understanding of the potential human error in the TRACON, it is important to evaluate how cognition has been affected by the upgrades in ATC technologies. The authors analyze how the NextGen system will influence controllers' cognitive performance.

4 The SHELL Model Revisited, Pre-STARS Analysis

To analyze TRACON controller human factors and their influences on cognition, the study utilized the basic SHELL model of human factors introduced in 1987 [2] to assess the TRACON controller's position before STARS, followed by an analysis with

STARS, and finally an analysis of STARS fully integrated with the NextGen satellite ATC system. The SHELL model of 1987 employed a block layout placing the human (controller) represented as Liveware (L) in the center, then surrounding it by four interfaces: Software (S), Hardware (H), Environment (E) and other Liveware (L).

Referencing the SHELL diagram in Fig. 1., the TRACON controller in the pre-STARS environment had a different set of hardware to work with ergonomically to control aircraft. Many controllers who started in the last century were exposed to older analog/CRT (Cathode Ray Tube) radar screens. When analyzing the L-H linkage of this older SHELL, the controllers had screens that could depict the target, but did not have the capability to filter weather. Their map overlays were not clear and accurate. Color was also limited on these older radar screens. In tracking aircraft, separation was not reliable because controllers had to predict aircraft vectors for where they thought the aircraft was going. The screen had very little adjustment for light, color or layout. This older radar equipment was manufactured ergonomically as one size for all controllers. There were no altitude or separation alerts to increase margins of safety. Communications via radio were critical to confirm aircraft location.

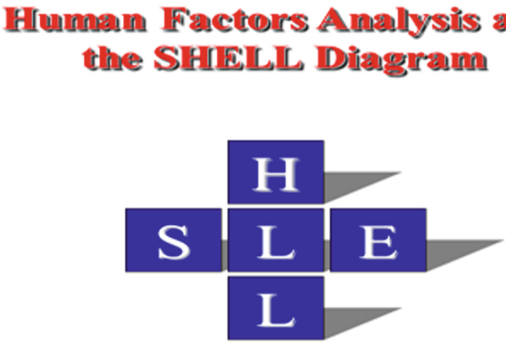

Fig. 1. SHELL model by Hawkins in 1987 featuring the Liveware-Liveware interface [2].

The L-E interface in pre-STARS was two-fold: one representing the physical environment and the other representing the artificial environment. The physical environment called for a dark room to see the radar screen and a cool room to maintain temperature at the correct level for the CRTs. The artificial environment kept distraction and noise levels to a minimum. Work rules included breaks and work shifts for rest. All FAA ATC policies were adhered to, including the team concept. Other variables affecting the controller's environment were volume of traffic handled, VFR or IFR conditions, weather severity and types of aircraft controlled for wake turbulence.

The L-S interface of SHELL in the pre-STARS era was challenging as the Software represented such things as FAA ATC procedures, ATC regulations, approach plates, weather, winds, ATIS and flight strip information. This information was gathered from many places and funneled to the controller. FAA ATC procedures and regulations were usually stored in several bulky volumes of FAA paper publications located in the TRACON radar room. The approach plate to back up what approach an aircraft was flying was a paperbound booklet. Weather was usually updated via the telephone and noted on paper nearby with wind conditions. The ATIS information for the aerodrome was broadcast via radio. Perhaps the most widely used piece of information of critical importance was that of the flight strips. These paper/plastic flight strips held aircraft information such as call sign, altitude, destination and aircraft type. Ergonomically these were challenging as they were hand created and used manually.

The most compelling part of the pre-STARS SHELL analysis is the relationship of the controller and how they interact with other Liveware in the L-L interface. The TRACON L-L interface was quite strong in the analog/CRT radar period. The perspective gained from analysis of the three previous interfaces (L-H, L-E, and L-S) is that the radar controller was not a one-person job. It required a team of controllers to work together safely and effectively to ensure that all the information was updated accurately and then disseminated to the radar controller to control the aircraft. At a minimum, there would be a radar controller, flight strip controller and manager. Teamwork in this older TRACON environment also required exceptional communication. While internal TRACON communications were based on teamwork and standard operating procedures, the external communications were accomplished through a complicated radio communications panel with multiple switches for the controller to manually switch. Training and qualification of new controllers was accomplished by studying procedures, radar training and on the job training with a qualified controller.

5 From Analog/CRT Radars to STARS Digital Equipment

Although challenged and susceptible to a multiple number of human factors issues in each interface of the SHELL diagram, the training, teamwork and professionalism seemed to work for pre-STARS radar controllers. Being that this model was already very work intensive as more aircraft took to the skies, future growth of the U.S. industry in the new deregulated environment of the 1980's and 1990's would force the TRACON to upgrade to safer and more efficient technologies. TRACONs would need to maintain the high level of professionalism and teamwork for future success. The shift to modern TRACON technologies was accomplished by phasing out the older analog/CRT displays with digital replacements like STARS. To help support the FAA's choice of the digital STARS display for future use with the NextGen satellite system, other equipment has also become digital to help the controller. With these multiple additions of computer automation/information becoming commonplace in support of the STARS controller, the original SHELL model of direct linkages now must be adjusted to account for computerized indirect linkages that now exist between the STARS controller (L at the center of SHELL) and the four interfaces caused by the computer automation/information. To accomplish a human factors analysis of the current STARS controller and account for the computer automation/information, the updated SHELL Model 2017 used by Miller [3] and shown in Fig. 2 was used.

The benefits of using SHELL 2017 are seen in the L-H analysis of the digital STARS controller, because the STARS display is not only digital, it is also highly computer-automated with extensive information. As a digital and optimally designed air traffic display, the STARS controller now customizes the display so they can

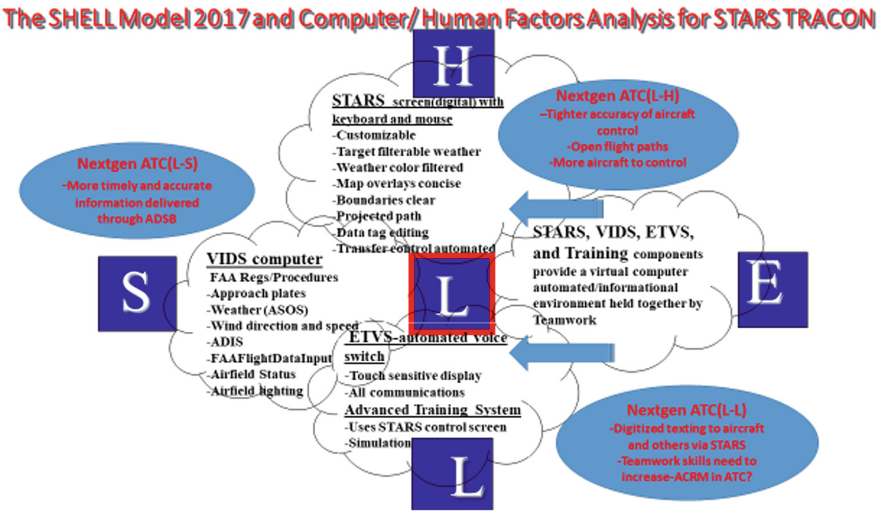

Fig. 2. The SHELL model 2017 adopted for the computer-automation/information of the STARS TRACON controller with predicted Nextgen ATC effects by Mark Miller in 2019.

interface ergonomically. The controller sets the brightness, the size of the screen and adjusts colors to their preference. They can also save the setting to reinstate it whenever they need to. To assist in the automation adjustments, the STARS display has a fully functioning computer keyboard and built in mouse. The target aircraft on the display screen can be filtered from the weather to become highly visible. Meanwhile, the software on the display screen can give the controller an accurate representation of weather intensity around aircraft by depicting it with six different colors. Airspaces and their boundaries are seen more accurately and can be enhanced. Map overlays are accurate. These efficiencies also come with gains in safety since operators can control aircraft more accurately with far less stress. Furthermore, the STARS controller has the aid of projected path software enhancements that allow them to see aircraft vectors in relation to other aircraft they are controlling. Software filters enhance margins of safety when activating low altitude warning and separation alerts. Wake turbulence distances have been greatly reduced. Perhaps one of the biggest improvements of the STARS system is the accuracy provided by an electronic Data Tag that appears with the aircraft as aircraft flight information. What was once a mounted paper flight strip identifying the flight and aircraft is replaced by information entered in electronic format directly into the computer scratch pad that is then digitally transformed next to the aircraft on the STARS screen. This digitized Data Tag of aircraft identification includes call sign, aircraft type, assigned altitude, airspeed, destination, service requested, airport and runway. The controller can update information on that Data Tag while controlling the aircraft through the STARS keyboard and mouse.

As the computer automation/information in the STARS digital display greatly enhances the interface between L-H, it accomplishes this through shifting automation and information from other interfaces. In the L-E interface the physical dark room remains dark to optimally use the STARS display. However, many aspects, like weather, have migrated to the STARS display or other computer automated/informational technologies in other SHELL interfaces. Managing the controllers' work and teamwork still remain strongly at play in the TRACON. Where the technological shift has affected TRACON operations the most is in the volume of traffic handled, the severity of weather around that traffic, and the types of aircraft being controlled for wake turbulence. The accuracy of the STARS display in visibly tracking aircraft and Data Tagging each aircraft along with the projected path automation and alerts means that a controller can efficiently increase the number of aircraft under their control. The same automation/information can add VFR aircraft to controller tasking along with IFR aircraft. The accurate weather environment depicted on the STARS controller's screen helps them see the most dangerous weather, differentiate the aircraft from the severe weather on the screen, and accurately vector the aircraft safely around the weather. This same accuracy also enabled reducing wake turbulence separation between aircraft as recently mandated by the FAA.

In the L-S environment, what was once a myriad of separate information resources of Software representing FAA ATC procedures, regulations, approach plates, weather, wind shear, ATIS and flight strip information is now placed in one computer source to the side of the controller via another computer screen called VIDS (Visual Information Display System). The VIDS displays many different icons to represent important areas of information now found in one computer information source. There are icons for FAA ATC procedures, regulations, approach plates, Automated Surface Observing System for weather, Wind Speed and Direction Indicator, ATIS, Airport Status Display, and the FAA Flight Data Input/Output (FDIO). Special attention needs to be given to the FAA FDIO icon as this is where the controller inputs the Flight Progress Strip data for the Data Tag on the STARS screen. VIDS brings many different sources of information to the controller in one automated location.

The L-L interface is now enhanced with automation in three major ways. First, through enhanced communications among all L-L participants by means of the automated communications suite called the Enhanced Terminal Voice Switch (ETVS). ETVS provides control of all frequencies, interphones, and landlines with touch-sensitive controls and displays instead of antiquated switches. Secondly, through what is the most significant feature of STARS computer automation enhancement, is its ability to complete the transfer of a tracked aircraft from one controller to another through an automated exchange. In receiving control of the transferred aircraft, the new controller sees the aircraft target flashing on their STARS control screen and clicks on it to accept control. The colors then change for the aircraft on both screens as both controllers receive indications of transfer of that aircraft. The third major way is through a training enhancement. Instead of classroom hours and on the job training with controllers, training controllers in the STARS systems is all about real world controlling via simulation. A STARS display is designated in the TRACON while other controllers are actually controlling real aircraft. Meanwhile, the trainee is in the same room doing simulated controls on an actual STARS display. This training is as close as a new controller can get to live operations without controlling real aircraft.

The shift in SHELL analysis from an era of controllers using analog/CRT radar displays with direct linkages shown in Fig. 1., as compared to that of the digital automated/informational displays used by the current controllers in Fig. 2., shows a clear trend toward adding significant levels of visual information to the controller enabled by computers. STARS, supported by VIDS and ETVS, clearly shows that the L-E direct linkage of the old TRACON is being outsourced and replaced by multiple computer automated/informational devices. The technology is creating a detailed virtual L-E for the STARS controller. However, the now indirect linkages of the L-H, L-S, and L-L replacing the L-E pose challenges for STARS TRACON controllers that invite human error. The depiction of the L-H, L-S, and L-L replacement of the L-E in Fig. 2. shows all these new connections as cognitive clouds overlapping each other. The new computer technologies are causing the indirect linkages of the STARS TRACON controller to become concatenated. This means that cognitive tasks are overlapping. To counterbalance the technology from overwhelming the STARS controller, training and teamwork are of utmost importance. Just as the modern commercial cockpit has turned to an Advanced Crew Resource Management culture that emphasizes teamwork skills integrated with new multiple technologies, the STARS TRACON should adopt more formal aspects of teamwork through the FAA to meet the challenges of the future. The STARS controllers seem to enjoy this technological configuration as a leap forward in efficiency, safety gains and confidence in operations. In terms of technologically integrating the STARS systems with NextGen, there is not a part of the ATC system better prepared to transition to the satellite-driven system than a STARS TRACON integrated with VIDS and ETVS. Yet as the new technologies seem to enhance their abilities, what will happen to STARS controller cognition when the current STARS model merges fully with NextGen?

6 NextGen Factors to Influence SHELL 2017

The SHELL 2017 STARS controller analysis, as depicted in Fig. 2. also has added to it in red NextGen effects for L-H, L-S, and L-L. With NextGen, the L-H interface of STARS gets an immediate boost from the constant satellite signal without interruptions. This makes controlling aircraft through STARS more accurate and the STARS controller gains more open flight paths for free flight. However, the biggest gain from this NextGen satellite accuracy is that the STARS controller will be able to efficiently, effectively and safely handle more aircraft. In the L-S interface the STARS controller quickly gains more accurate and up to date information from the VIDS that is now connected to an ADS-B system that is able to share that information with aircraft (ADS-B In screen). Perhaps the biggest potential human factors change affecting the STARS controller using the NextGen system will come in the form of digitized (texting) communications in the L-L interface. At some point STARS controllers will have the option to text other aircraft and the aircraft will be able to text reply back. This is currently being demonstrated through Datalink. In the future this might possibly be accomplished better ergonomically through modifying the Data Tags that currently allow for editing and also enable two-way digitized texting. The NextGen enhanced system will give STARS controllers an upgraded virtual environment from the L-E interface to the STARS, VIDS, and ETVS. Acknowledging the critical importance of approach and departure control in the ATC system, and that most aviation accidents occur on or near an airport, the NextGen upgrade added to the STARS controllers' arsenal will give promise to a safer, more efficient, path to future flight operations. In referencing the Avianca Flight 53 accident mentioned previously, it is inconceivable that this accident could occur in the STARS controlled NextGen satellite system. The aircraft would be controlled more effectively, but most importantly the inability of the Avianca crew to communicate a low fuel emergency would be negated with texting. Free flight accuracy would then line up the low fuel aircraft for an immediate landing. The fact that this new TRACON system could prevent accidents is noteworthy. However, with so many technologies converging to make the virtual environment more accurate, controller cognitive loading could be challenged.

7 Cognitive Loading in the STARS Environment

The authors have noted SHELL originally did not envision simultaneous, multi-dimensional interfaces with increased optical and cognitive loads. Consequently, the SHELL 2017 model was proposed to demonstrate cognitive load effects from overlapping interactions [3]. Cognitive load, for this study, refers to attentional or working memory resources dedicated to information processing. Evident in SHELL 2017 is clear evidence of concatenated cognitive tasks and neural loading that presents opportunity for capacity problems and competing resources. Figure 2 illustrates cognitive processing required for dynamic visual cues, icons, and text using multi-dimensional interfaces (screen, tablet, keyboard, and mouse). Cognitive loading effects with STARS require head shifts by operators, viewing separate screens displaying with disparate information, and processing that precipitates dynamic shifts in perceptual load, processing resources, and interface distractions.

Task load and workload are related, but not the same. Controllers may perceive changes in task load as a workload increase. In ATC, increasing the number of aircraft under control has affected cognitive workload negatively [4]. Likewise, the NextGen transition from audio communication to texting increases cognitive load. Controllers' responses to visual cues were found to be more accurate but slower than performance with auditory cues [5], suggesting controllers are more susceptible to overload with visual cues attributed to depletion of neural protein and working memory deficit [6].

With multiple STARS interfaces, image-processing considerations must be considered. Display density, target-background, and layout perspectives vary among interfaces used. Consequently, ergonomics issues for search time expended and compromised accuracy presume increased error rates [7]. As NextGen progresses, development may follow the progress of ATM in Europe which employs four-dimensional trajectories, extending the cognitive processing load. Among the tools used are automated systems electronic coordination and conflict detection for enroute traffic. Corver [8] found that in control centers using newer technology, the nature of cognitive error had changed. While effectively reducing cognitive errors related to detection, memory, and decisions, new tasks invited error in timely detection of relevant data. A shift from individual controller responses to a larger organizational framework may hold promise in addressing cognitive loading concerns. Examining SHELL interactions, Chang [9] found controllers were more influenced by organizational factors than individual differences which invites further study of team effects when changes occur in the STARS environment.

Transition has posed numerous challenges for the FAA, including the need to validate new requirements and provide automated tools for controllers, e.g., performance-based navigation, to merge and sequence aircraft [10]. Tasks for controllers have emphasized effective visual radar scanning, and a study of controllers performing monitoring tasks determined that effective visual scanning is their principal concern [11]. Results showed significant variation in visual scan patterns tied to particular tasks and which type of interface was used. The study identified that perceptual load effect required attentional control that restricted neural resource allocation for distractors.

Perceptual load (or, load theory) is based on models of dual-task information processing and indicates the extent of behavioral interference imposed by high rates of attentional demands. Perceptual resources are allocated first to task-relevant information and, if capacity remains, to less relevant information [12]. Controllers in the STARS environment, working with several interfaces of varying symbology, are subject to saturation from data and the need to interpret significance of display information, which invites the possibility of delayed controller comprehension. Selective attention assigns limited resources to significant information while filtering task-irrelevant ones and load theory suggests irrelevant stimuli are not processed under high perceptual load [13]. The problem for STARS controllers is that when irrelevant stimuli, e.g., a road crossing a runway, become relevant the attention may not be perceived cognitively since no neural resources are available for processing.

Distraction can impede our ability to detect and effectively process task-relevant stimuli in our environment. Cognitive load influences situation awareness (SA) and is affected adversely as demands increase [4]. Discussions about distraction involve a bottom-up response to unexpected stimuli and a top-down capture of attention using working memory to filter out what is not relevant. These two routes recruit different neural resources like when bottom-up stimuli activate the ventral frontoparietal network that computes relevance and suppresses response to items not relevant [14]. To accommodate overlapping cognitive load shown in Fig. 2., synchronous neural processing must flow freely. However, when disrupted by distractions or loss of capacity from rapid updating of working memory, there are notable losses of sustained attention, mental sequencing, and integrity of an associated cognitive map [15].

Attention is related to working memory in two ways. One affects memory load, the other influences content, and both relate to perceptual load and distractor processing. Evidence suggests that perceptual load reduces distractor interference and working memory load increases distractor processing. However, working memory load restricts resources to resolve distractor interference and largely depends on the mode of information. When a distractor is being held in working memory it will interfere with processing targets under high perceptual load [16]. Display clutter is closely tied to effective performance and has been linked to impaired performance. Both the number and density of display entities has been recognized as a concern and contributes to the overall problem of clutter. For STARS, the task relevance of added icons and identifying data in supplemental interfaces presents a potential for mode confusion. While an experienced controller may work efficiently with multiple screen representations, when cognitive workload approaches maximum capacity, novel situations or heightened task difficulty the opportunity for error and unintended actions (or inactions) is likely to increase [17]. Eye tracking and gaze duration are concerns, particularly when multiple interfaces are used and controllers must shift attention to different layouts and areas of interest (AOI) (see Fig. 2). While VIDS aides the controller by aggregating information, the shift to distractor AOIs for verifying information challenges integrity of the STARS cognitive map held by the controller. Issues related to the number of fixations, scan path ratio, and duration can be problematic when upper limits are exceeded [18]. STARS does not include an embedded function for digitized communication which currently must be provided on a separate display. This also invites added cognitive issues for the controller.

8 Controller Assessment of STARS Cognitive Loading

The authors conducted a program review with TRACON STARS controllers at a facility using the current technology. Controllers responded to questions (available upon request) about attention to displays, operating conditions, and potential distractions. Incidence of degraded cognitive performance was assessed with respect to selective and divided attention between displays having disparate three-dimensional cognitive maps, with attendant problem resolution and decision actions during operations. Available controllers choosing to participate were asked to respond to an electronic survey. Responses were categorized and evaluated to identify potential impaired action, error, or other influences. The results enabled a glimpse of human factors and cognitive performance challenges that may confront NextGen controllers operating in the near future. The results are shown in Table 1.

Table 1. Responses of STARS controllers in a TRACON environment.

Item	N	Never	Sometimes	Often
Head turn required for other displays	11	0	6	5
Displays viewed peripherally	11	1	1	9
Added time/effort to re-engage STARS	11	4	1	6
Supervisor called for STARS assist	11	7	4	0
Physical actions other than for STARS	11	2	1	8
Missed item of importance	11	6	5	0
Annoyed by intrusion	11	5	6	0
Uncertainty after distraction	11	7	4	0
Distracted by non-flight activity	11	7	4	0
Read status message more than once	11	6	5	0

Results showed a mean of 4.2 years as controller, 2.9 years at TRACON, and 2.0 years at the STARS location. Findings indicated that for more than half the controllers head turns or body movements were required to view other interface displays, inviting disorientation and vestibular interference. Nearly all the controllers acknowledged scanning displays peripherally which added time. For distractions, nearly half the controllers reported they missed important items, were annoyed, or were uncertain about aircraft status after viewing other screens, requiring reading messages twice.

9 Conclusion

Precautions and recommendations to address cognitive workload related to added digitized communication messaging and visual tasks must be integrated into the NextGen controllers work environment. This study provides evidence that increased cognitive load can lead to distraction and delay in responding. Further investigation for understanding cognitive limits, team interactions, and NextGen changes is needed.

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