DOT/FAA/TC-23/70

Federal Aviation Administration
William J. Hughes Technical Center
Atlantic City International Airport
New Jersey 08405

Human Factors Evaluation of Large Displays in the Air Traffic Control Environment

January 2024

Final Report

U.S. Department of Transportation
Federal Aviation Administrati

NOTICE

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No.
DOT/FAA/TC-23/70

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Human Factors Evaluation of Large Displays in the Air Traffic Control Environment

5. Report Date
January 2024

6. Performing Organization Code
ANG-E5B

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Federal Aviation Administration
Human-Systems Integration Branch
William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Air Traffic Organization (ATO) Program Management Office (PMO) and Human Factors Division, ANG-C1

13. Type of Report and Period Covered
Technical Report

14. Sponsoring Agency Code
PMO:AJM-131, ANG-C1

15. Supplementary Notes

16. Abstract
The Federal Aviation Administration (FAA) deployment of 43-inch en route air traffic control displays resulted in unexpected issues (e.g., headaches, nausea) for some air traffic controllers. We conducted this project to investigate the reasons for these problems to provide information to FAA Air Traffic Control (ATC) acquisition programs to guide the development of requirements, the criteria for product selection, and the evaluation of large displays. We evaluated five different large display technologies with 20 federal employees from the William J. Hughes Technical Center (WJHTC). The selected displays included two light emitting diode (LED) displays, a quantum dot LED (QLED), an organic LED (OLED), and the legacy 28-inch display under two different room lighting conditions (bright, dark) We examined eye movement data (eye blinks, eyelid openings) as potential metrics of visual fatigue, but did not find differences across displays. We collected subjective ratings of fatigue, discomfort, and other problems from participants while they used each display and from questionnaires. None of the participants reported experiencing greater than mild to moderate discomfort using any display. Participants who used the displays in darker room lighting conditions (similar to an approach control or en route control room) reported higher workload than did those who used the displays in brighter (low office lighting) conditions. However, the difference in the ratings was small, and the median workload rating for the darker room light condition was still rated "low." We found differences in ratings pertaining to display legibility and clarity; colors were rated easier to distinguish in brighter room light conditions than darker room light conditions. However, even in darker conditions, median responses were high (4 on a 5-point scale). Ratings made from the off-angle viewing position, simulating the Radar Associate (RA) position, were similar to center viewing; colors were easier to distinguish in brighter room light conditions; text in the checklists at the edges of the screen was easier to read. Many considerations must be made in selecting displays for use in the ATC environment, including balancing the brightness of the display with the background room illumination, display resolution, and off-angle viewing. Evaluating potential displays in simulated environments with a sample of intended users can help identify potential problems and determine which selection would be best.

17. Key Words
Air Traffic Control
Large Displays
Eye strain
Fatigue
Motion sickness

18. Distribution Statement
This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
61

22. Price

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Acronyms

Acronym	Definition
ATC	Air Traffic Control
AMOLED	Active-Matrix Organic Light Emitting Diode
ANOVA	Analysis of Variance
CFF	Critical Flicker Fusion
COTS	Commercial-off-the-Shelf
CVS	Computer Vision Syndrome
CVS-Q	Computer Vision Syndrome Questionnaire
DES	Digital Eye Strain
DESIREE	Distributed Environment for Simulation Rapid Engineering and Experimentation
FAA	Federal Aviation Administration
FOV	Field of View
IPS	In-Plane Switching
LCD	Liquid Crystal Display
LED	Light Emitting Diode
OLED	Organic Light Emitting Diode
mLED	microLED
QLED	Quantum Dot LED
PPI	Pixels Per Inch
PWM	Pulse Width Modulation
RA	Radar Associate
RDHFL	Research, Development, and Human Factors Laboratory
SSQ	Simulation Sickness Questionnaire
VA	Vertical Alignment
VIMS	Visually-Inducted Motion Sickness
VIMS-SQ	Visually-Inducted Motion Sickness Susceptibility Questionnaire
WAK	Workload Assessment Keypad
WJHTC	William J. Hughes Technical Center

Executive Summary

The Federal Aviation Administration (FAA) deployment of new 43-inch en route air traffic control workstation displays resulted in unexpected issues for some air traffic controllers who reported experiencing difficulties such as headaches, eyestrain, vertigo, and nausea. We conducted this project to investigate the reasons behind these problems, to provide guidance to FAA Air Traffic Control (ATC) acquisition programs in the development of requirements and criteria for product selection and the evaluation of large displays for use in the air traffic environment.

We evaluated five different display technologies: two 43-inch light emitting diode (LED) displays (EIZO, DELL), a 43-inch quantum dot LED (QLED) display (AORUS), a 48-inch organic LED (OLED) display (LG), and the legacy 28-inch display (BARCO) under two different room lighting conditions (bright, dark) with 20 federal employees from the William J. Hughes Technical Center (WJHTC). About half of the participants reported some prior experience with computer-related discomfort such as headaches and eyestrain. For the current study, the participants completed simple search tasks while viewing recordings from a previous en route air traffic control simulation using each display.

We collected eye movement data (eye blinks, eyelid openings) as potential metrics of visual fatigue, hypothesizing that more fatigue (more blinks, smaller eyelid openings) would be observed after participants used a display. However, we did not find differences in these eye metrics for any display. We also collected subjective ratings and comments of fatigue, discomfort, and other computer-related problems from the participants while they used each display and from questionnaires after they used each display. We found that no one experienced greater than mild to moderate discomfort using any of the displays.

We did find that participants who used the displays in darker room light conditions (similar to an approach control or en route control room) reported a higher level of workload than did those who used the displays in brighter room light (low office lighting) conditions. However, the difference in the ratings was small, and the median workload rating for the darker room light condition was still rated “low.”

We also found differences in some ratings pertaining to legibility and clarity of the displays, and that the participants rated the colors easier to distinguish in brighter room light conditions than darker room light conditions. However, even in the darker room light conditions, median responses were high (4 on a 5-point scale), indicating there was no real difficulty distinguishing between colors. Ratings made from the off-angle viewing position that simulated where the radar

associate (RA) would be positioned were similar to center viewing in that colors were rated easier to distinguish in brighter room light conditions. Additionally, the participants rated the text in the checklists at the edges of the screen easier to read off-angle under brighter room light conditions.

We did not find examples in our study of the types of symptoms reported by some en route controllers when they started using the newer 43-inch replacement displays. A critical difference between this study and field conditions is the duration of time the displays were used and the nature of the tasks performed. It is possible that a more extensive study with more difficult tasks would reveal differences and that display technologies play a more subtle role that this study did not uncover.

There are many considerations that must be made in selecting appropriate displays for use in the air traffic environment, including balancing the brightness of the display with the background room illumination, display resolution, and off-angle viewing. In very bright environments, reflections will be important to consider. Additional factors such as viewing distance, display flicker (even if imperceptible), and blue light as well as individual factors such as uncorrected vision problems, being susceptible to motion sickness, and eye accommodation and vergence problems also play a role.

The specific environment in which the displays are to be used is of utmost importance in selecting and configuring the displays. Evaluating potential displays in simulated environments with a sample of intended users can help identify potential problems and determine which selection would be best.

1 Introduction

Many Federal Aviation Administration (FAA) Air Traffic Control (ATC) programs are replacing their specialized legacy displays with less expensive and more readily available commercial-off-the-shelf (COTS) products such as liquid crystal displays (LCDs) or light-emitting diode (LED) displays. The trend has also been for programs to deploy new COTS displays that are larger than the legacy displays. For example, the en route domain has started replacing 28-inch legacy displays with 43-inch COTS displays. The COTS displays have different characteristics than the legacy displays including different aspect ratios (16:9 versus 1:1) and different resolutions that affect the appearance of the information presented.

The deployment of the new 43-inch en route displays resulted in unexpected issues for some air traffic controllers who reported experiencing problems such as headaches, eyestrain, vertigo, and nausea. They also reported problems viewing the new displays off-angle, increases in workload, and problems with attention being drawn to areas outside the sector—areas that were not previously visible on the smaller legacy displays. The Air Traffic Organization Program Management Office made some changes to the new displays, such as changing their maximum brightness, to attempt to mitigate these problems. However, those changes were not evaluated systematically, so it is not known whether such modifications effectively addressed the root causes of the reported problems.

Research is needed to understand the reasons behind these problems and to develop data-driven solutions to mitigate them. In this study, we seek to provide such information to FAA ATC acquisition programs that can guide requirements, selection criteria, and evaluation methods of large displays for use in the ATC environment.

1.1 Background

People report experiencing eye strain, headaches, and nausea when using computer displays of various sizes whether for work or personal use. In the air traffic environment, some controllers have recently reported experiencing such problems using new, large displays that have been deployed in the en route ATC domain. The new 43-inch rectangular displays are wider than they are long and have a 16:9 aspect ratio. They replace the existing 28-inch square displays that have a 1:1 aspect ratio.

A lot of research has been conducted on computer vision problems and cybersickness. These problems include computer-vision syndrome (CVS), digital eye strain (DES), and visually-induced motion sickness (VIMS). They differ from one another based on the types of symptoms experienced. However, there is relatively little research pertaining specifically to large displays and whether larger displays are associated with more problems than smaller displays. A recent study by Pakdee & Sengsoon (2021) found no difference in CVS symptoms between displays of different sizes, but the displays they tested were only 18.5 and 23-inches in size.

There are many anecdotal reports of problems with large displays found in online forums (e.g., (Blur buster forums, 2021). These typically describe difficulties someone is experiencing with a newly purchased large display, either for television viewing or desktop use (e.g., gaming, work). In these online forums, individuals describe the problems they are experiencing with a new display and others in the discussion then provide possible reasons for the problems and potential solutions for alleviating them. For example, a user might report a problem with vertigo when viewing a new television screen and a suggestion might be made to reduce this effect by adjusting the parameters for "motion blur." These types of anecdotal reports are easy to find, and they raise important issues that should be investigated. However, there is little published information available in the scientific literature that systematically examines these effects or the effectiveness of the potential mitigations.

1.2 Computer vision syndrome

CVS has been described and studied across many display sizes from handheld devices, including mobile phones and tablets (e.g., 5 - 13 inches), to large televisions (e.g., 40 – 60 inches), to very large panel displays (e.g., 80 – 100 inches) that are used in gathering spaces for multi-person viewing. Much of the CVS research focuses on the use of displays in 3-dimensional (3D) and virtual reality environments. The stimuli often include rapid, expansive visual scene shifts, rather than environments that are more reflective of the types of information presented in the ATC environment—text and icons, with limited, small-scale motion.

Much of the research on CVS has been conducted by optometrists and ophthalmologists. Coles-Brennan, Sulley, and Young (2019)summarized the literature on the causes of CVS and DES, describing these effects as "an emerging public health issue" and estimating that between 25 – 83 percent of screen users are affected by symptoms such as tearing, eye fatigue, blurry vision, burning and redness of the eyes, and double vision. The causes cited include uncorrected vision problems (e.g., astigmatism, presbyopia), lens accommodation problems due to the need to focus on near objects for extended periods of time, lags in pupil dilation after near-task work, and vergence problems in which the two eyes have difficulty fixating a single location to obtain a clear image of an object.

Coles-Brennan et al. (2019) also cite the effects of dry eye caused by reduced and incomplete blinking that often occurs with screen use. Dry eye is exacerbated by environmental conditions such as air conditioning, as well as by the need to squint because of glare or intense light. Contact lens wearers are especially susceptible to dry eye. Closer working distances and smaller font sizes also aggravate CVS. While the authors did not discuss nausea per se, diplopia (double vision) caused by vergence problems can contribute to this effect. Earlier work by Ebenholtz (1988; 1992) points to issues with vergence and lens accommodation as contributors to motion sickness in various environments including cars, simulators, and when viewing “large screen movies and television screens” (Ebenholtz, 1992, p. 2).

Display flicker also contributes to CVS and can cause eye fatigue and migraines. Display flicker occurs when the display lighting elements are turned on and off rapidly, typically 60 Hz or higher, to create the appearance of a steady image. Also known as pulse width modulation (PWM), this technique is often used to control display lighting. However, some manufacturers use continuous lighting at a lower, steady current level to eliminate flicker. Although manufacturers may advertise displays as having “no flicker” or as being “flicker free,” this can be misleading. These systems may still be using PWM at extremely high refresh rates that viewers would not perceive rather than using continuous current. Therefore, flicker is still present and still affects the visual system. Flicker is additionally affected by ambient lighting (Mertens, 2018) and is typically more noticeable in darker environments. Display flicker may be exacerbated by fluorescent lights that produce their own flicker. Sitting close to a display can make flicker more problematic because more information occupies the peripheral visual field which is more sensitive to flicker than central vision (Adams, Wu, & Shimojo, 2020).

Most people notice flicker when the refresh rate is about 60 Hz or lower, but this varies by individual (How flicker-free monitors contribute to eye health, 2020). Some researchers have examined the threshold at which viewers perceive flicker as a means of determining when CVS problems are likely to occur (Thomson & Saunders, 1997). Tools such as the Critical Flicker Fusion (CFF) test in which observers view stimuli at various flicker rates and indicate when a stimulus no longer appears to flicker or when it begins to flicker have been used to try to measure an individual’s sensitivity threshold. However, even when flicker is imperceptible to the viewer, its effects on the visual system remain because the pupil and lens must continue to make rapid, on-going adjustments. Benedetto, et al. (2013) compared visual fatigue and CFF between different electronic readers—electronic ink readers, which simulate reading on paper, and LCD readers—and found that while reported visual fatigue differed between the two devices, CFF did not. These authors cite work by others (Shen, Shieh, Chao, & Lee, 2009) who likewise did not find a relationship between visual fatigue and CFF. Therefore, CFF may not provide a reliable or complete measure of CVS.

In addition to flicker, the effect of blue (short wavelength) light has been found to contribute to CVS. Research by Jaadane, et al. (2015)reported on the effects of blue light emitted by LEDs on visual fatigue as well as on its damaging effects on cells in the cornea and retina that indicate the potential for more extensive and long-term problems from continued exposure. Simmers, Gray, and Wilkers (2001) identified that blue light can cause problems for lens accommodation, resulting in more micro fluctuations and making it more difficult to maintain visual focus. Research into the effectiveness of blue-blocking filters to remediate these problems has been mixed. Lin, et al. (2017) found that visual fatigue decreased for participants who wore high-blocking blue light lenses compared to low-blocking lenses or no lenses. However, Leung, Li, and Kee (2017) did not find such effects. Differences in the types of lenses used in these studies may have played a role. More research is needed to investigate the effectiveness of blue light blocking lenses to resolve this issue.

The use of electronic displays has been found to contribute to visual fatigue and false myopia and may involve blurred vision and difficulty focusing (Lee, Chiang, & Hsiao, 2021). These problems can be exacerbated by low-luminance contrast or other factors such as a close viewing distance (Lin, Chen, Lu, & Lin, 2008). Other research has supported these findings and found that font size, background color, screen brightness, ambient brightness, usage time, and contrast also have a role in visual fatigue (Lee, Chiang, & Hsiao, 2021) in addition to flicker (Kopyt & Narkiewicz, 2013).

Coles-Brennan et al. (2019) focus on mitigating CVS symptoms by correcting underlying vision problems and by periodically resting the eyes, suggesting that users look away from screens at more distant objects, and do exercises that encourage more frequent and sufficient blinking to keep the eyes sufficiently lubricated. As eye care professionals, these authors concentrate on the clinical aspects of computer vision problems. They provide only some general guidance on adjustments to the displays themselves and the work environment that can reduce symptoms. These include adjustments to room lighting, adjusting font sizes and display contrast, and, possibly, using anti-glare and blue light filters. Certainly, correcting any underlying visual issues is a necessary foundation for fully mitigating any negative effects of CVS. But we must also look at whether different display technologies affect these symptoms differently, as well as what display factors are most problematic and what modifications to those parameters may help mitigate symptoms.

1.3 Visually induced motion sickness and cybersickness

The symptoms of VIMS and cybersickness include nausea, eye strain, vertigo, disorientation, and postural instability (Van Emerick, de Vries, & Bos, 2010) and can occur with the use of many types of visual displays including desktop monitors and stereoscopic displays (Rebenitsch & Owen, 2016). VIMS and cybersickness are most often explained by the conflict that results when information processed by the visual system (the appearance of motion) does not match the input received by the vestibular system (the sense that the body is stationary).

There are several measures used to assess VIMS and cybersickness. Self-report questionnaires, such as the Simulator Sickness Questionnaire (SSQ), are widely used to assess subjective impressions about the severity and frequency of symptoms (Golding, Rafiq, & Keshavarz, 2021). Physiological measures have also been investigated as potential indicators. These include measures of postural instability obtained while a participant stands on a balance board and performs visual tasks, as well as measures of heart rate and blood pressure to assess stress while performing such tasks (Rebenitsch & Owen, 2016). Some preliminary research into electroencephalogram (EEG) measures has sought to identify and assess visual fatigue (Lee, Chiang, & Hsiao, 2021), as has research into hormone levels (Kennedy, Drexler, & Kennedy, 2010). Kennedy et al. evaluated saliva samples to determine biochemical levels of cortisol and melatonin pre and post exposure to a visual stimulus to identify drowsiness, often a first sign of VIMS. The results of the study were mixed. Whereas cortisol levels increased significantly after exposure to the stimulus, melatonin levels did not. Nevertheless, the study suggested that certain “endocrine determinants” may become potential tools to objectively evaluate VIMS.

Some research has indicated that large displays may be associated with more symptoms or more severe symptoms of VIMS than smaller displays. Harvey and Howarth (2007) found that VIMS was reported more often with larger fields of view than smaller fields of view. Their comparison involved scenes that ranged from 39-inch to greater than 70-inch diagonal in which the visual angle of the scenes subtended 27 × 21, 48 × 36, and 62 × 47 degrees for small, medium, and large scenes, respectively. In their study, the stimuli involved a high-motion video game in which the participants “drove” a vehicle around a track. Other research also found that larger fields of view resulted in more cybersickness than smaller fields of view (Rebenitsch & Owen, 2016; Van Emerick, de Vries, & Bos, 2010) . More of the peripheral visual system is occupied with larger fields of view, resulting in greater vection and higher reported levels of motion sickness (Mollenhauer, 2004) .

Emoto, Sugawara, and Nojiri (2008) found that displays with wider horizontal viewing angles resulted in more VIMS than displays with smaller horizontal viewing angles. This study also involved high-motion stimuli. VIMS has been found to generally increase with faster image speeds, but an optimal presentation rate has not been determined (Rebenitsch & Owen, 2016). Lin, Duh, Parker, Abi-Rached, and Furness (2002) found that larger fields of view (FOV) in simulators were associated with more motion sickness as measured by greater difficulty maintaining postural stability. Lin et al. reported that symptoms decreased on average when they presented a stable visual image, such as a grid pattern, over the motion scene. Symptoms were reduced most when bright, stationary grids were presented over low-frequency motion scenes. However, the researchers also noted that VIMS increased for some of the participants in these conditions, highlighting the important role of individual differences in the experience of VIMS.

In contrast to Lin et al. (2002), Keshavarz, Hecht, and Zschutschke (2011) found that the stationary environment surrounding the visual display contributed to VIMS. The participants in the Keshavarz study were seated and rested their heads on a chin rest to minimize motion while they viewed visual scenes. They used rating scales to report VIMS. Keshavarz et al. found that presenting a virtual-reality driving scene on a large projection wall display resulted in more reported VIMS than the same scene presented through head-mounted display goggles. This occurred even when the visual size of the images was the same, in contrast to what they expected based on earlier studies (Sharples, Cobb, Moody, & Wilson, 2008). Keshavarz et al. suggested that “intra-visual conflict” resulted when some information in the visual field indicated motion (the driving video) while other information indicated stability (the surrounding information beyond the edges of the display). When the researchers blocked visual access to areas beyond the edges of the display, VIMS decreased. Thus, they identified intra-visual conflict as a contributor to the experience of VIMS. It is possible that intra-visual conflict contributes to the reports of VIMS from air traffic controllers using the new displays. However, it is important to note that the type of displays used and the high-speed motion visual scenes in Keshavarz et al. and other studies are quite different from the displays and more static information used in ATC, which involve much smaller-scale movements of individual display elements. In addition, this does not explain why intra-visual conflict would occur or be more problematic for the 43-inch displays than the 28-inch displays. The surrounding visual background is present in both. We must look more closely at the relevant display technologies and the type of information presented to better understand the causes of and possible remedies to these problems.

Other factors, such a habituation to stimuli (adaptation and repeated exposure) have been found to minimize adverse effects of motion-sickness symptoms (Kennedy, Drexler, & Kennedy, 2010). Some research suggests that users should ease into daily, prolonged use of visual displays by working with them only every two to five days to start (Stanney & Kennedy, 1997; Rebenitsch & Owen, 2016). Other research found that providing intermittent five-to-fifteen-minute breaks for participants while they used large displays was helpful in reducing reported cybersickness (Singer, Ehrlich, & Allen, 1998; Rebenitsch & Owen, 2016). It would need to be determined how these types of mitigations, if helpful, could be implemented into training and familiarization in the air traffic environment.

The distance at which users sit from the display can exacerbate symptoms, including dizziness and nausea (Dramamine, 2021). When seated close to large displays, users must move their eyes and/or head over larger distances to view screen areas further from their central vision, and more of the peripheral visual field is occupied. As described earlier, the lens must accommodate to adjust for these distances and problems with vergence may result in unclear images. These issues may be especially problematic for those more susceptible to CVS or VIMS.

To use large displays at workstations, individuals must be seated within about 2-3 feet to ensure that they are able to reach keyboards and other controls such as the voice communication panel also located on the desktop. Recommended viewing distances for displays require consideration of the display's aspect ratio, resolution, and pixel density to help ensure image sharpness and clarity (Monitor size and viewing distance, 2021; Perfecting proximity, 2021). For a 43-inch display with a 16:9 aspect ratio, 3840x160 (4K) resolution, and 104 pixels per inch (ppi), the minimum recommended distance is 33" (84 cm) so that the individual pixels are not visible and the images appear sharp and clear. Displays with higher pixel densities can be viewed at closer distances; displays with lower pixel densities require further distances. Finding an appropriate distance to ensure display clarity while allowing users to reach controls may be challenging. In addition, determining an appropriate viewing distance must also consider how it affects body position and posture. Improper posture and positioning can also lead to fatigue and discomfort. The user must be seated in such a way that neck strain, back strain, and so forth are minimized.

1.4 Display technologies

We conducted a search of display technologies to determine which large displays to include in our evaluation. For each technology, we searched for commercially available displays that received high ratings in technical reviews (e.g., CNET & RTINGS) and from consumers for use as a desktop monitor, as well as for its contrast, color, and off-angle viewing quality and overall lifespan. The display technologies we researched included: liquid crystal display (LCD)/light emitting diode (LED), organic LED (OLED), active matrix OLED (AMOLED), miniLED, and microLED (mLED). We provide a brief description of the different technologies below, along with their pros and cons, and their current availability on the market in the size range most relevant to use in ATC.

Liquid crystal displays (LCDs) are the oldest technology still available in the market. When they were first implemented, LCDs used cathode ray tubes to provide backlighting that passed through filters to produce different colors and images. Current LCDs use light-emitting diodes (LED) to provide the backlight, so they are typically now referred to as LED displays. We will refer to them as LCD/LEDs to differentiate them from other display types because of their continued use of backlighting. LCD/LEDs are widely produced and are of relatively low cost compared to newer display technologies. Because backlight is always present, it is not possible to achieve true black with this technology, so contrast is not as good as it is for other display types.

There are two popular types of LCD/LED panels: in-plane switching (IPS) and vertical alignment (VA). A VA panel usually has a comparatively higher contrast ratio and narrower viewing angles. An IPS panel has comparatively lower contrast and wider viewing angles. For the most part, panel type does not affect other aspects of picture quality, such as peak brightness, color gamut, or color accuracy (Giovanni, 2021). QLED (Quantum-dot LED) displays are an extension of existing LED technology. QLEDs use a quantum dot color filter on an LCD panel along with an LED backlight to improve contrast and color vibrancy (Leger, 2021).

OLED (Organic Light Emitting Diode) displays use a different technology than LCD/LEDs. OLEDs use a carbon-based film between two conductors that emit their own light when an electric current is passed through. Unlike traditional LED displays, OLEDs do not use LED backlights since the pixels are self-emissive. OLEDs are less bright overall than LCD/LEDs but provide excellent contrast in comparison. They also have faster response rates. However, OLEDs can have problems with image burn-in and do not have as long a lifespan as LCD/LEDs. OLED colors can also degrade over time.

AMOLED displays use the same basic technology as OLED but have a thin film transistor (TFT) and capacitor attached to each LED that allow an activated pixel to maintain its charge between refresh cycles, resulting in faster and more precise pixel control. AMOLEDs provide deep blacks and good off-angle viewing. AMOLED displays can also be folded. Although the technology can be used in screens of any size, AMOLEDs are currently produced almost entirely for small devices such as cellphones rather than large displays. AMOLED displays do not perform well in bright conditions, so they would not be suitable for use in ATC towers which are exposed to natural daytime light.

MiniLED technology is similar to LCD/LED technology but uses much smaller LEDs that are about 1/5 the size of standard LEDs. These displays use thousands of miniature LED backlights to further improve local contrast, peak color vibrancy, and result in less “leakage” and “haloing” on the display. MiniLEDs offer images that are similar to OLEDs in quality but at a lower cost. MiniLED displays are currently used in some tablets and other small devices. They are used in some high-end monitors, but are currently only commercially available in 32” monitors or 55” and larger televisions.

Micro LED (mLED) technology is the newest display technology to emerge. The mLED displays use different chemicals and have different electroluminescent properties than OLEDs. They do not suffer from burn-in issues or color degradation as do OLEDs. The LEDs used in mLEDs are 1/100 the size of standard LEDs and are clustered in triplets (red, blue, green) in each pixel. Displays using mLED provide excellent color and a range of brightness levels that can be up to 5 times the luminance of OLEDs. mLED technology is currently not used in displays that are smaller than 88” due to manufacturing costs. The few displays that are currently on the market are extremely expensive.

Display technologies are continuously evolving. It is expected that AMOLED displays will soon be manufactured for larger displays and that mLED displays will be produced in smaller formats to make them more suitable (and affordable) for widespread use. Other technologies, such as electroluminescent displays are also on the horizon. Although these displays are expected to provide good wide-viewing angles and good contrast, at present, they are monochromatic.

2 Purpose

The purpose of this study was to systematically evaluate several large display technologies to determine whether they differed in the extent to which they induced symptoms and to identify potential mitigations.

3 Methodology

3.1 Participants

We recruited participants via an email sent to federal employees at the FAA William J. Hughes Technical Center (WJHTC) describing the study and asking for volunteers. Those wishing to volunteer coordinated with their supervisor to receive approval and then contacted the researchers to set up a mutually convenient time to participate.

Twenty participants completed the study. One participant completed the study at a time. The participants reported using digital screens of various sizes for work and/or personal use a median of 10 hours a day (range: 5 – 16). The median age of the participants was 41 (range: 23 – 64).

Fifteen of the participants reported wearing corrective lenses either for distance (9) or for both distance and reading (6). Fourteen participants wore glasses, and one wore contact lenses. Only one participant indicated using corrective lenses specifically for computer use. All the participants reported that their current vision was either “Pretty Good” or “Excellent.” Sixteen of the participants had had their vision checked within the last 3 months to 2 years.

Eleven participants indicated that they experience some problems when using digital displays outside of the study. They reported eyestrain, headaches, and dry eyes as the most common problems. They reported that taking breaks, adjusting room or screen lighting, or using blue-blocking glasses or filters as ways in which they typically try to relieve symptoms. Additional questionnaires we administered indicated that more of the participants had experienced these and other symptoms previously when using digital displays as we discuss below in Section 4.1.

3.2 Facilities and equipment

We conducted this study at the Research, Development, and Human Factors Laboratory (RDHFL) at the WJHTC. We positioned the displays in experiment room 3 (ER3; see Figure 1) for this evaluation.

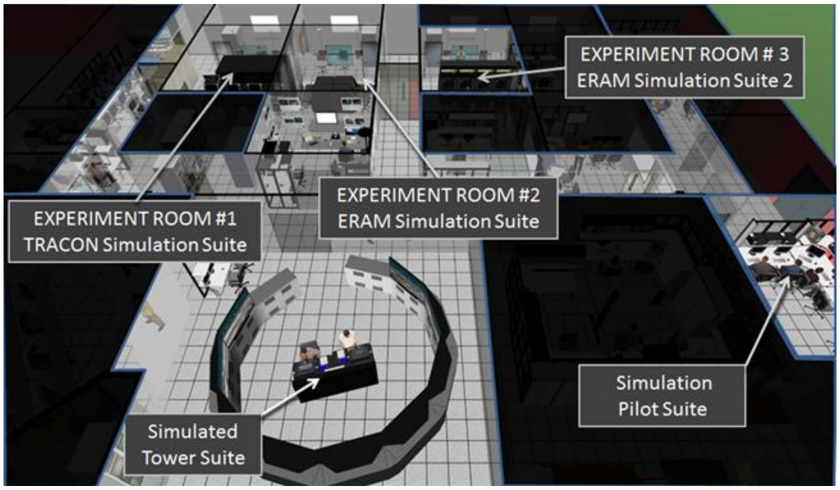

Figure 1. RDHFL layout

We also used ER2 to set up an eye tracker on a separate display from those used in the evaluation. We used the eye tracker to monitor and record eye data to obtain potential measures of visual fatigue.

3.2.1 Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE)

The Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE) is an ATC simulator that can mimic the En Route Automation Modernization (ERAM) system and Standard Terminal Automated Radar System (STARS). In this study, we used DESIREE to present video recordings of en route air traffic and to control which scenario and display was in use. A sample screen depicted on one of the displays is shown in Figure 2. We did not use DESIREE to collect workstation keyboard or trackball entries since the participants did not enter any ATC instructions into the system.

Figure 2. ATC video replay emulation

We used five similar but unique videos for this study, recorded from simulation scenarios involving the same airspace and traffic flows but with different aircraft call signs. Each video was randomly assigned to one display for each participant. The videos were recorded at a 4k resolution (3840 x 2160 pixels). They were displayed at the same resolution on each of the four widescreen displays. The legacy display is square resolution (2048 x 2048 pixels), so we made a cropped version of each video that presented only the central section of the videos and removed the outer (left, right, and a small section of the bottom) portions for that display.

3.2.2 Workload Assessment Keypad (WAK)

We also used DESIREE to provide prompts and record responses on the workload assessment keypad (WAK) device. In this study, we used the WAK device to enable participants to report their level of discomfort during the scenarios when prompted using a 10-point scale (low = 1; high = 10).

We instructed the participants to use the following scale to provide their ratings:

1 – 3: No – mild discomfort
4 – 6: Mild – moderate discomfort
7 – 9: Moderate – fairly strong discomfort
10: Too high to continue; Notify the researcher

We instructed participants the study would end if their discomfort went above a moderate level, and to verbally inform the researcher if this occurred. . None of the participants indicated discomfort above a moderate level at any point during this study.

3.2.3 Eye tracker

We used the Smart Eye Pro System to collect eye data and used the number of blinks and the size of the eyelid openings to assess visual fatigue. The Smart Eye Pro does not require participants to wear head-mounted gear, thus allowing them to move freely. The system creates a three dimensional (3D) model of a participant's head and tracks both head and eye movements in real time. Figure 3 shows the SmartEye Pro System configured for a simulation involving an en route workstation. The system uses four cameras to capture the participant's head as a 3D object at up to 120Hz. It then determines the location of the eyes and eyelids using infrared technology, the intensity of which is about one thirtieth of the intensity expected while walking outside on a sunny day. The device is not reported to cause any discomfort or health risk.

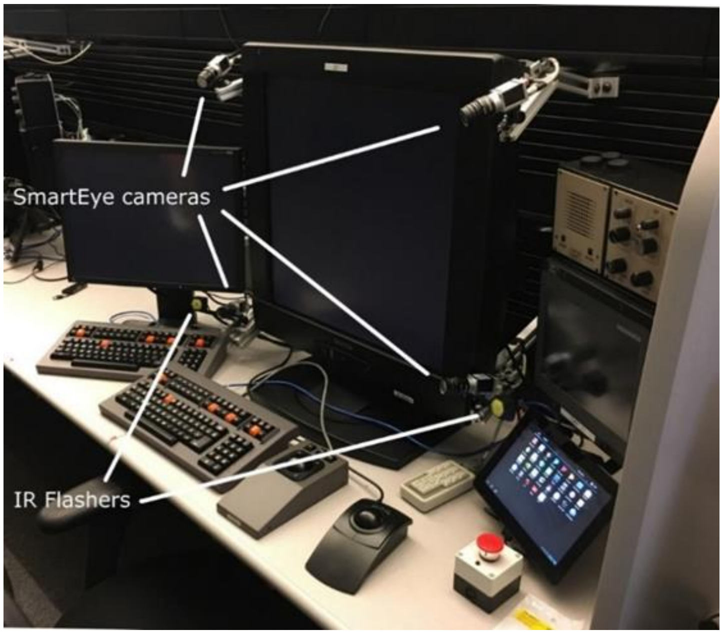

Figure 3. SmartEye Pro eye trackers set up at an en route R-side position

We used the SmartEye Pro to measure the participant's eye data before and after using each display and used the difference as an objective measure of eye fatigue (Lee, Park, Whang, & Min, 2009; Lee, Heo, & Park, 2010; Bang, Heo, Choi, & Park, 2014; Kim & Lee, 2020), a methodology that has been used in previous studies (Bang, Heo, Choi, & Park, 2014; Luo, et al., 2016) .

We measured the number of blinks and average eyelid opening size while participants read a short passage of text for three minutes on a separate monitor in ER2 before and after working with each display. The pre- and post-test procedure was chosen to mitigate the potential effect of scenario order. Eye fatigue was expected to be higher towards the end of the full study, but the pre-test/post-test methodology took this into account.

3.2.4 Displays

After researching and reviewing the different display technologies, we selected displays from three available technology categories to evaluate in this study: LCD/LED, QLED, and OLED. We selected displays that were at or about 43-inches in size diagonally (with 16:9 aspect ratios) to reflect the display sizes recently chosen for use in some ATC environments. We did not include ultra-wide or curved displays because these would not work well on desktops when more than one user is involved as in some air traffic work configurations. The displays were positioned in ER3 adjacent to one another as shown in Figure 4.

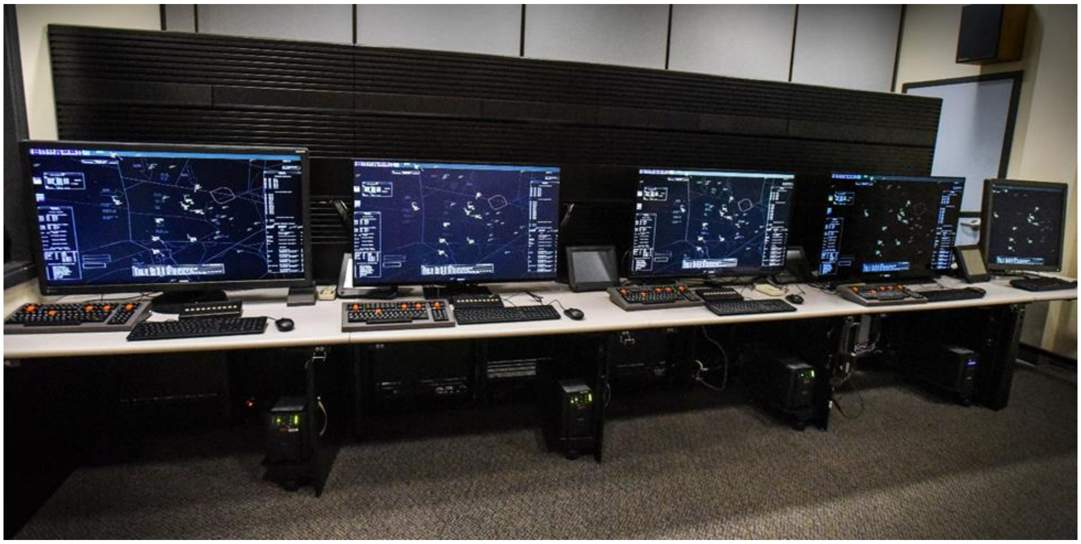

Figure 4. Displays evaluated (left to right): LED (VA), LED (IPS), QLED, OLED, legacy

We included the four displays listed in Table 1 in this study. Each one represents a different type of currently available technology. We also included the legacy 2K display (BARCO, 2,048 x

2,048) to gather data about the effects of eye fatigue, nausea, etc. from participants who did not have ATC experience or familiarity with this type of display. This allowed us to determine whether participants experienced different symptoms with the square display compared with the widescreen displays. The characteristics of each display were measured with a spectroradiometer (Photo Research, SpectraScan 740) before the study began. Each display was iteratively calibrated so the overall brightness of each color value was similar. We provide a full table of the measured values in Appendix F.

Table 1. COTS displays selected for the evaluation.

Technology	Manufacturer & Display	Display Size	Basic Information	Pros	Cons
LCD/LED	EIZO 4325	43-inch	Configuration: VA Supports resolution scaling for each video input (i.e. any non-native resolution can be displayed in actual size or scaled proportionally) Luminance Range: 25-500 cd/m^2	Good contrast (4000:1); internal backlight sensor to stabilize brightness level	Poor off-angle viewing, fewer display colors available compared to other displays (16.77 million)
LCD/LED	DELL Ultrasharp U4320Q	43-inch	Configuration: IPS Resolution is 3840 x 2160 @ 60 Hz Luminance Range: 350 cd/m^2 (typical)	Good color quality (supports 1.06 billion colors); blue light filter; anti-glare treatment; flicker free	Low refresh rate (60 Hz), lower contrast ratio than other options (1000:1)
QLED	AORUS FV43U	43-inch	Configuration: VA Refresh Rate: 144 Hz. Max resolution is 3840 x 2160 Luminance: 1000 cd/m^2 (peak)	High contrast ratio (4000:1) Extremely low response time (1ms)	One of the more expensive displays we considered Image may appear washed out at an angle
OLED	LG OLED48C1PUB	48” (no 43-inch available)	Refresh Rate: Resolution is 3,840 x 2,160 @ 120 Hz	“Screen shift” feature to minimize burn-in; high refresh rate (120 Hz); good color quality and perfect black	Potential for glare; needs a filter

3.3 Materials

The participants first read and signed the informed consent statement (Appendix A). Next, they completed the background questionnaire (Appendix B) to provide basic demographic data and then the pre-test questionnaire (Appendix C) to report any symptoms they experienced using digital displays in the past. The pre-test questionnaire included the CVS questionnaire (CVS-Q) developed by Seguí, et al. (2015) and the VIMS Susceptibility questionnaire - short version (VIMSSQ-short) developed by Golding, Rafiq, and Keshavarz (2021). After each experimental scenario, the participants completed the Post-Scenario questionnaire (Appendix D) that included a modified version of the Simulation Sickness questionnaire (SSQ) developed by Kennedy, Berbaum, and Lilienthal (1993) to assess symptoms related to CVS and VIMS and that included additional items pertaining to the usability and legibility of the display. A final exit questionnaire was administered at the end of the study that asked the participants to rank the displays according to preference (Appendix E).

3.4 Procedure

Each study session began with the participant reading and signing the informed consent statement (Appendix A) that described the purpose of the study and the procedures. The informed consent statement also described that negative effects, such as eye strain and headaches could occur, and it explained the procedures to be followed should the participants experience any of them.

Each participant then completed the background questionnaire (Appendix B) to provide basic demographic information followed by the pre-test questionnaire (Appendix C) to provide information about previous experiences with display-related illnesses. The participant then began the first of five study scenarios, each one with a different display. A timeline of events for each scenario is shown in Figure 5.

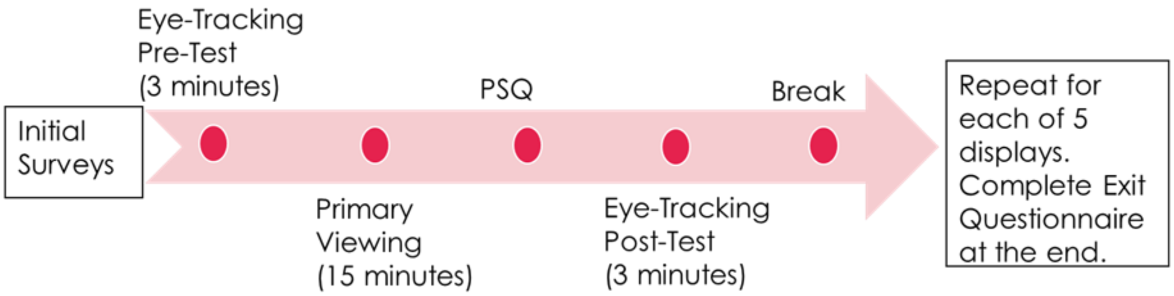

Figure 5. Timeline of study events

Before and after the participants used each display, we collected participant eye movement data (number of blinks; size of eyelid openings) to obtain potential metrics of eye fatigue. We had the participants read text from a PDF version of a book (The Design of Everyday Things by Donald Norman) for three minutes on a separate lab display in ER2, as described in section 2.2, while monitoring and recording their eye data. We examined the difference in the number of blinks and size of eyelid openings obtained before and after working with each of the test displays. We hypothesized that more visual fatigue should be observed by a greater number of blinks and smaller eyelid openings.

We counterbalanced the order in which we tested each of the displays across participants to mitigate order effects. When using each test display, the participant viewed video recordings of en route ATC obtained from a previous simulation performed by the RDHFL (Zingale, Woroch, Dworsky, & Willems, 2021). That simulation presented a high volume of aircraft in New York Center (ZNY) airspace.

Each participant viewed one of the video replays for 15 minutes while using each display. They also performed a series of tasks while viewing the video, which required the participants to scan the full display in a similar way controllers would when controlling air-traffic. The tasks did not require the participants to have any prior background or familiarity with air traffic control. For each scenario, the participants performed two simultaneous counting tasks. One task was to count items, such as specific numbers, in the "checklists" in the periphery of the screen that remained static throughout the scenario. The second task was to count something about the aircraft that updated dynamically during the scenario. The potential tasks to be performed were explained in a pre-experiment briefing. The complete list of tasks can be found in Table 2, the tasks were randomly assigned without replacement to a video and display for each participant. The participant was told just before the video started which two tasks to perform. They were prompted to report their final counts at the end of the scenario to ensure attention. For the smaller legacy display, there were no "checklists," so a fifth task was developed that all the participants performed.

Table 2. Sample task instructions and prompts.

	Task 1	**Task 2**
1	Count the number of the letters "R" in the checklist at the edge of the Display, upper and lowercase.	Count the number of aircraft that reach altitude 220 exactly at any point during the video.
2	Count the number of the letters "N" in the checklist at the edge of the Display, upper and lowercase.	Count the number of aircraft that reach altitude 240 exactly at any point during the video.
3	Count the number of the number "3" in the checklist at the edge of the Display.	Count the number of aircraft that have an up or down altitude arrow in the datablock at any point during the video.
4	Count the number of the letter "5" in the checklist at the edge of the Display	Count the number of aircraft that receive a conflict probe at any point during the video.
5	Count any "2" or "A" (upper or lowercase) that appears in any part of the display such as map elements: datablocks, menus, etc.	

The participant began seated at the Radar position (center) to complete the primary set of tasks for a display. Every 5 minutes, the WAK prompted to provide a numerical rating (1= low; 10=high) of their discomfort via the keypad. After using each display, each participant completed a post-scenario questionnaire (PSQ; Appendix D) to provide reports about any symptoms experienced during the scenario and to provide ratings about the technical aspects of the display, such as visibility, legibility, and color accuracy. Each participant first evaluated the display from the Radar position, then from an off-angle position to simulate the viewing angle of the Radar Associate position, which is more than 30 degrees from the center-line. Following the PSQ, the participants performed the post-test eye-tracking evaluation, which was the same as the pretest with the participants beginning the text where they left off during the pre-test. The participants were given a break after completing each scenario. This break was a minimum of 5 minutes, but was as long as the participants requested. After finishing 5 experiment scenarios, the participants completed the exit questionnaire (see Appendix E) which included a ranking of the 5 displays.

Due to the nature of this study and the potential for participants to experience some negative effects, the participants were instructed to immediately inform the researchers if they experienced any discomfort that was above a moderate level. The experimenter also monitored participant responses to the WAK and PSQ throughout the study. If reported discomfort levels were more than moderate, the experiment would be terminated and the circumstances documented. The participants would followed a health and safety protocol before leaving the RDHFL and any events would have been reported to the IRB. None of the participants experienced any such events, and all participants completed the study in its entirety.

3.5 Experimental design

Display type served as the primary independent variable for this study. Our dependent variables included subjective survey measures of physiological symptoms caused by using each display such as eye strain, nausea, and headache. Participants also rated the usability (e.g., picture quality, legibility) of each display. We included the objective measures of eye fatigue (number of blinks and average size of eyelid opening) before and after each scenario to determine whether different levels of eye fatigue were found for different display types.

We also included two levels of ambient lighting as an independent variable. Ambient lighting was set to reflect a typical room lighting level for an air traffic control TRACON or ARTCC (low light level) or a typical lighting level in an office environment (high light level). We set the light levels at 2.5 lux for the low light, “Dark,” condition and 35 lux for the high light, “Bright,” condition. We compared the data obtained across conditions to determine whether differences in the eye data or reported fatigue/illness levels across different display types or had an interactive effect with display type.

To minimize the effect of test order, we counterbalanced the sequence in which participants worked with the displays. Half of the participants worked with the displays under the Dark conditions and half worked with the displays in the same test order under the Bright condition. The test orders and lighting conditions for the 20 participants are shown in Table 3. We used a mixed between-subjects (lighting condition) and within-subjects (display) experimental design in our analysis. Using a within-subjects design helps to control variability in the data and can increase statistical power.

Table 3. Display orders and room lighting conditions for each participant

P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**
Dark	Bright	Dark	Bright	Dark	Bright	Dark	Bright	Dark	Bright
1	1	2	2	3	3	4	4	5	5
2	2	5	5	1	1	1	1	4	4
3	3	1	1	5	5	3	3	3	3
4	4	4	4	2	2	5	5	2	2
5	5	3	3	4	4	2	2	1	1
P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
Dark	Bright	Dark	Bright	Dark	Bright	Dark	Bright	Dark	Bright
1	1	4	4	3	3	5	5	2	2
4	4	2	2	4	4	2	2	1	1
2	2	3	3	5	5	4	4	5	5
3	3	5	5	1	1	1	1	3	3
5	5	1	1	2	2	3	3	4	4

We positioned the participants in front of each display so that they were able to comfortably reach the keyboard, although they were not asked to make any keyboard entries. The literature is mixed regarding the optimal distance to sit from a display. Display aspect ratio, resolution, and pixel density must be considered in determining an appropriate distance as described earlier in Section 1.3. Lee, Heo, & Park (Lee, Heo, & Park, 2010) found that eyestrain was lower when participants sat 90 cm (about 35 in) from the display compared with 60 cm (about 24 in). Rempel, et al. (2007) found increases in blurred vision, dry or irritated eyes, and headache at a distance of 46 cm (about 18 inches) compared to 66 cm (about 26 in) and 86 cm (about 34 in). They found no effect of those 3 distances on eyestrain or eye fatigue. However, both studies used much smaller monitors (21-inches and 18-inches respectively) and some different display technologies than those used in this study. A 43-inch widescreen display can have a very large field of view (FOV), depending on the distance of the viewer. When viewed at a distance of 24 inches (about 60 cm), a 43-inch display subtends about 60 degrees of the user's visual angle whereas an 18-inch and 21-inch monitor subtend approximately 37 and 41 degrees respectively. A large FOV has been associated with motion sickness in virtual reality (Lin, Duh, Parker, Abi-Rached, & Furness, 2002) and head-mounted displays (Arthur, 1996).

We designed the experiment to enable us to complete the study in about 3.5 hours. This allowed us to accommodate participant schedules while meeting the needs of the study. Each participant used each display for about 15 minutes. We based this duration on the work of Kim and Lee (2020) who found that relatively short durations (16 min) were enough to elicit changes in pupil dilation and constriction (speed was slower), blink frequency (higher), and duration of eye closures (greater) when certain display characteristics (gamma, temperature, and/or brightness) differed from the nominal display setting values. They reported that the number of blinks and the duration of eye closures increased in response to "tiredness" and "dryness" of the eyes. Most of the other studies we reviewed had participants view displays for about 30 minutes or more to obtain visual fatigue indicators (Lee, Park, Whang, & Min, 2009; Lee, Heo, & Park, 2010; Bang, Heo, Choi, & Park, 2014; Abdulin & Komogortsev, 2015; Luo, et al., 2016; Wang, et al., 2018). Given that we had learned that reports from air traffic controllers in the field suggested that they began to experience difficulties using the 43-inch displays after a relatively short time, we chose a 15-minute usage time to meet the needs of the study.

Reports by eye care professionals indicate that people typically blink an average of 15 times per minute, but blink rates may be one third to one half of that when people use computer displays (https://advancedeyecaremd.net/blinking-matters/). There would appear to be a time during digital display viewing in which blink rates and completeness of blinks are low inducing the problematic affects and then a time at which a rebound effect emerges when participants attempt to alleviate their symptoms by blinking more frequently and more completely. We therefore measured the blink rate for each participant before and after they worked with each display and used the difference between these measures as the metric of visual fatigue. We also included the size of the eyelid opening as a potential metric of fatigue, as eyelids would be more closed after using a display if they were more fatigued at that time.

We statistically compared the dependent measures across conditions (eye metrics and subjective data) to determine whether there were significant differences in these measures between the display types and between lighting conditions. We also summarized the comments that participants made about using each of the displays and any fatigue or discomfort they experienced.

4 Results

4.1 Participant background questionnaire ratings

Prior to beginning the scenarios the participants completed two questionnaires, the CVS and the VIMS-SQ to rate their prior experience with various symptoms when using digital displays. The summaries for the CVS questionnaire responses are shown in Table 4.

Table 4. CVS-Q responses: Number of participants reporting symptoms and intensity

Symptom	**Frequency**			**Intensity**	
	NEVER	OCCASIONALLY	OFTEN OR ALWAYS	MODERATE	INTENSE
1. Burning	16	4	-	4	-
2. Itching	13	7	-	7	-
3. Feeling of a foreign body	16	4	-	4	-
4. Tearing	11	8	1	9	-
5. Excessive blinking	8	10	2	12	-
6. Eye redness	15	3	2	4	1
7. Eye pain	15	5	-	5	-
8. Heavy eyelids	13	6	1	7	-
9. Dryness	11	3	6	7	2
10. Blurred vision	10	10	-	9	1
11. Double vision	18	2	-	2	-
12. Difficulty focusing for near vision	14	6	-	6	-
13. Increased sensitivity to light	14	5	1	5	1
14. Colored halos around objects	16	4	-	4	-
15. Feeling that sight is worsening	16	3	1	4	-
16. Headache	9	10	1	10	1

The five most frequently reported symptoms were headaches, blurred vision, dryness, tearing, and excessive blinking. Most of the reported symptoms were indicated as being of moderate intensity, but headache, increased sensitivity to light, blurred vision, dryness, and eye redness received a few ratings of “intense.” A total score for each participant is generated by summing all frequency values multiplied by intensity values. According to Segui et al. (2015) a score of six or higher indicates that the participant “is considered to suffer Computer Vision Syndrome.” This score is not intended as a medical diagnosis, but was used by the researchers as an additional independent variable during exploratory data analysis. Eight of the 20 participants had a total score of six or greater and are considered to suffer computer vision syndrome.

We provide the summaries for the VIMS questionnaire responses in Table 5. This questionnaire shared items with the CVS, but also included items for fatigue, dizziness, and nausea as well as questions about whether symptoms affected continued use of the device(s) and which devices were affected.

Table 5. VIMS questionnaire results

Symptom	**Frequency**			
	Never	Rarely	Sometimes	Often
Nausea	16	4		
Headache	10	6	3	1
Dizziness	15	4	1	
Fatigue	8	7	5	
Eyestrain	8	5	5	2
Have any of these symptoms stopped you using any of these devices or made you avoid viewing such displays?				
	11	6	3	
If you have answered stopped or avoided, please list the devices or displays that you avoid: Poorly configured displays Computer monitors; cellphones Larger, brighter screens (TVs, large monitors) temporarily Head-mounted displays VR glasses Cellphone Television VR goggles avoided OLED television with video game				

4.2 Eye-tracking data

We collected data on the number of blinks and the average eyelid opening size before and after the participants used each display (pre & post). We expected that fatigue would result in more blinks and smaller eyelid openings after the participants used the displays than before. We analyzed these two eye measures separately using a mixed regression model with Lighting condition as the between-subjects factor and Time (pre & post) & Display type as within-subject repeated measure factors. We implemented the mixed model regressions in R software with the lme4 package (Bates, Mächler, Bolker, & Walker , 2015). This analysis approach is more powerful than a standard ANOVA because the error term is reduced by adding the additional explanatory variable (between-subjects Lighting) to the regression model.

Blink rate did not increase after monitor use as hypothesized; there was a measured decrease. We found a mean of 30.58 (*SD* = 27.47) blinks during the pre-test and 27.82 (*SD* = 25.99) blinks during the post-test. There was large variability in the amount of blinking between participants (range 0 - 99 blinks per 3 minutes). This measured decrease from pre to post was not statistically significant ($F(1,170) = 3.056$, $p = 0.082$). Neither Display type nor Lighting condition had an effect on the change in blink rate from pre to post, as indicated by the interaction terms of the mixed model (both $p > 0.05$).

We found no difference in eyelid opening between pre-test ($M = 7.98$mm, $SD = 2.53$) and post-test ($M = 8.12$mm, $SD = 2.34$). Nor did we find significant effects of Lighting or Display type on eyelid opening (all $p > 0.05$).

As an exploratory analysis we looked at whether CVS scores were predictive of overall blink rate. We separated the participant's data into two groups, those with CVS (a score of 6 or greater) and those without CVS. We found no significant differences in blink rate between the groups ($p = 0.357$).

4.3 Post-scenario questionnaires

We analyzed the data from the PSQ using Multiple Ordinal Regression. The logic of this analysis and outputs are analogous to an Analysis Of Variance (ANOVA) but the statistical assumptions of the underlying models differ. The questionnaire data in this study used 4-point and 5-pont Likert scale ratings that are not normally distributed, thus violating the normality assumptions required for a typical ANOVA model. Ordinal regression is a non-parametric approach that takes advantage of the fact that the dependent variable is ordinal and cumulatively distributed. We tested the significance of the effects of independent variables with an analysis of deviance approach which is analogous to ANOVA. We implemented the ordinal regression in R software with a Cumulative Link Model (Christensen, 2015; Mangiafico, 2016). The model included 2 factors: 1) The ambient Lighting level of the room (Dark or Bright), and 2) the Display evaluated (5 types). The dependent variables were the responses to the survey question item that used Likert scale ratings from low to high.

We analyzed the data for the PSQ items obtained from the participants when they were seated directly in front of the displays as controllers would be when working the R-side position as well when the participants were seated off-angle as controllers would be when working the RA-position. We did not find any significant effects of the Lighting condition for any of the physiological discomfort, illness, etc. questionnaire items in Part 1 of the PSQ. However, we did find significant differences between the Lighting conditions for some of the items in Part 2 of the PSQ. Table 6 summarizes the results for these items. Median response, quartiles, and ranges are presented. The participants rated each of the items listed significantly higher for the Bright room lighting condition.

Table 6. PSQ response medians, ranges, and quartiles for significant differences (Part 2 items)

Centered Viewing Position	Median rating (ranges)		
	Bright	Dark	X^2 (1), p = * <.05; ** <.01; *** <.001
1. The information on the display is easy to read.	5 (2-5) Q1: 4; Q3: 5	4 (1-5) Q1: 3.25; Q3: 5	X^2 = 5.36 *
3. The colors are easy to distinguish from one another.	5 (3-5) Q1: 4; Q3: 5	4 (1-5) Q1: 1; Q3: 5	X^2 = 7.105 **
6. It is easy to locate information in the datablocks for each aircraft.	5 (2-5) Q1: 4; Q3: 5	4 (1-5) Q1: 4; Q3: 5	X^2 = 6.021 *
7. It was easy to perform the tasks required using this display.	5 (2-5) Q1: 4; Q3: 5	4 (1-5) Q1: 3; Q3: 5	X^2 = 12.446 ***
Off-Angle Viewing Position			
Angle Q3. The colors are easy to distinguish from one another.	5 (1-5) Q1: 4; Q3: 5	4 (1-5) Q1: 4; Q3: 5	X^2 = 7.105 **
Angle Q5. It is easy to read the text in the checklists at the edges of the display.	4 (1-5) Q1: 3; Q3: 4.25	3 (1-5) Q1:2; Q3: 4	X^2 = 4.557 *

These results suggest some differences in the legibility and clarity of the displays under the two lighting conditions. However, even in the Dark room light condition, most median ratings were still quite high (4 on 5-point scale).

We also found significant differences for some of the PSQ item ratings across the Display conditions. Table 7 shows the PSQ questions for which we found a significant effect of Display type. Post-hoc tests (Tukey) indicated that the AORUS display differed either from all or from some other displays at $p < 0.05$. Comparisons not listed were not statistically significant.

Table 7. PSQ Items with a main effect of display type.

Centered Viewing Position	X^2 **(1),** p **= * <.05; ** <.01; *** <.001**	**Post-hoc Results at** $p < 0.05$
1. The information on the display is easy to read.	X2 = 19.42 ***	AORUS rated lower than all others.
2. The objects on the display look clear and sharp.	X2 = 20.88 ***	AORUS rated lower than all others.
4. Objects and text look hazy or cloudy.	X2 = 21.19 ***	AORUS rated higher than all others.
5. It is easy to read the text in the checklists at the edges of the display.	X2 = 16.13 **	AORUS rated lower than all others.
7. It was easy to perform the tasks required using this display.	X2 = 12.21 *	AORUS rated lower than LG_OLED and EIZO
Off-Angle Viewing Position		
Angle 5. It is easy to read the text in the checklists at the edges of the display.	X2 = 9.21*	AORUS rated lower than EIZO

4.4 WAK discomfort ratings

We used the WAK as a way for participants to rate their current discomfort levels. The WAK took 3 measurements during the use of each monitor, at 5, 10, and 15 minutes into the video replay. The data from the WAK was analyzed similarly to the eye-movement data. We analyzed this data set using a mixed regression model with Lighting condition as a between-subjects factor and Time (5, 10, & 15 minutes) & Display type as within-subject repeated-measure factors. We implemented the mixed model regressions in R software with the lme4 package (Bates, Mächler, Bolker, & Walker , 2015).

The maximum discomfort rating for the study was 6, with an overall mean of 1.92 (*SD* = 1.06). The ratings increased over time from 5 to 10 to 15 minutes ($F(2,266) = 15.709$, $p < 0.001$). However, the mean rating at 15 minutes was only 2.14 (*SD* = 1.22) indicating “no to mild” discomfort. There was no significant effect of Display type or Lighting conditions on the ratings ($p = 0.09$, $p = 0.56$ respectively).

4.5 Exit questionnaire and comments

We asked the participants to rank order displays from best (1) to worst (5) and to provide the reasons for their choices. The ratings for the displays are shown in Table 8.

Table 8. Number of participants ranking the displays from best (1) to worst (5)

Display	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 5**
QLED (AORUS)	1	2	1	6	10
Legacy (BARCO)	2	5	4	4	5
LED-IPS (DELL)	1	6	4	6	3
LED-VA (EIZO)	7	2	8	3	0
OLED (LG)	9	5	3	1	2

We conducted a Chi-square test to determine whether the rankings for the best displays differed from what would be expected by chance. Chance would mean that the number of people rating each display “best” should be the evenly distributed across the displays (4 each). We found that the ratings differed significantly, X^2 (4, N = 20) = 14, $p = 0.0073$, indicated some displays were preferred more than others. The LG and EIZO received the highest number of “1” rankings. The comments for the LG and EIZO displays are provided in Table 9.

Table 9. Comments about the OLED (LG) and LED-VA (EIZO) displays when rated "best"

LG
Vivid color and brightness which makes text stand out
Crisp, clear text
At all angles, the LG screen provided sharp resolution that did not degrade quality at any angle viewed
Max contrast and legibility from all angles
Most clear display with easy to read text
The black is darker than all the others giving more contrast
Best display at all angles, darkest "blacks", best colors, best readability
The best contrast and not much eye strain w/ good picture resolution
The framing, clearness, sharpness, and color all seemed to display the best on this monitor
EIZO
Crisp text, good color
Best screen overall. Few or no strain symptoms.
Sharp, least glare, good viewing angle
Larger display, crisp foreground, background and text. Just the right brightness
No reflection, no blur, closest to what I'm used to in the labs
Clear w/ less glare
The screen had practically no glare or mat like grayness to it. It also maintained clarity and darker feeling black.

We conducted a Chi-square test to determine whether the rankings for the worst displays differed from what would be expected by chance and found that the ratings did differ significantly, X^2 (4, $N = 20$) = 14.5, $p = 0.006$. The AORUS received the greatest number of low ("5") ratings. The comments provided for these ratings are shown in Table 10. The participants found this display had glare and that the images were less sharp and clear on this display than on the others.

Table 10. Comments about the QLED (AORUS) display when rated "worst

AORUS
Large amounts of glare. Difficult to focus. Sickness feeling increased quickly.
Fuzzy text
Far edges clipped text until moving head side to side; least sharp text and outline
Poor text, not clear and crisp; dull display
Blurred text
Resolution was okay, but corners/sides were terrible, text was often cut off at the sides and had to be guessed or viewed at weird angles
Too reflective
Text is blurry (pixelated)
Text was unclear and hard to see letters and numbers
The screen had the most glare and the glare became distracting at times

5 Conclusions

Some reports from air traffic controllers in the field indicated that they had experienced problems such as headaches, eyestrain, nausea, and increased workload when they began using the new 43-inch display (EIZO 4325) that replaced the 28-inch legacy display (BARCO) at the workstations. This study sought to systematically evaluate the effects of different display technologies on visual fatigue and other digital display problems to better understand the potential causes of these issues.

We evaluated five displays under two different room lighting conditions (bright, dark). Four of the displays were large, measuring 43-inch or 48” diagonal: LCD/LED with VA pixel alignment, LCD/LED with IPS pixel alignment, QLED with VA pixel alignment, and OLED. The fifth display was the legacy 28-inch square display. We configured the displays so that they approximated the display characteristics of the EIZO display (LCD/LED VA) that is deployed to the field.

We sought an objective measure of visual fatigue by examining eye metrics that included the number of blinks and the size of the eyelid openings. We expected to find more blinks and narrower eyelid openings after participants used the displays when they were presumably more fatigued. We used relatively short viewing durations (15 minutes/display) because prior research indicated that studies with similarly short viewing durations (16 minutes) found evidence of eye fatigue and because some reports of symptoms by air traffic controllers were reported to have started after only a short time on position. However, we found no statistically significant difference in these eye metrics before and after the participants used each display.

We collected subjective ratings of fatigue, discomfort, and other computer-related problems from the participants through feedback they provided at 5-minute intervals while using each display and via questionnaires they completed after using each display.

The ratings indicated while using the displays, no participant experienced greater than mild to moderate discomfort. Although discomfort ratings increased slightly as the scenarios progressed, ratings were still very low even at the end of each scenario. The ratings the participants provided on the questionnaire after they used each display did not reveal any significant differences in computer-related problems. The majority of the ratings indicated that they did not experience any problems.

We did find an effect of room lighting level on workload participant ratings. The participants who used the displays in darker room light conditions (similar to an approach control or en route control room) reported a higher level of workload than did those who used the displays in brighter room light (low office lighting) conditions. But the difference in the ratings was small, and the median workload rating for the darker room light condition was still “low.” This result has implications for whether increasing the light levels at the facilities may be beneficial. However, the full work context and the range of effects of any change in ambient lighting conditions must be considered before being made.

We found differences in some of the questionnaire ratings pertaining to legibility and clarity of the displays, and we found that room light levels affected how participants rated the colors. The participants rated the colors easier to distinguish in brighter room light conditions than darker room light conditions. The participants also rated that it was easier to locate information in the data blocks and perform the tasks required in this study in the brighter room light conditions than the darker room light conditions. However, even in the darker room light conditions, median responses were high (4 on a 5-point scale). Small differences though they are, these results highlight the findings of previous studies that emphasized the importance of appropriate display brightness and room lighting in configuring displays effectively.

Regarding the displays, we found that the participants reported more difficulties with the AORUS display compared to the others. Participants found this display more difficult to read, had poorer visibility/legibility at the edges of the display, and that objects on the display looked hazier than on the other displays. The participants also reported that it was more difficult to perform tasks using the AORUS display than two of the others (EIZO and LG). However, we cannot conclude that the issues experienced were due to QLED technology specifically and that all QLED displays would be rated similarly. Other models and brands of QLEDs would need to be tested. We were unable to purchase the original QLED display we had intended to evaluate because it became unavailable at the time required for this study.

The participants indicated preferences for which displays provided better and worse viewing experiences. Sixteen of the twenty participants rated either the LG or the EIZO the “best” display of the five evaluated, citing the good resolution and contrast of these displays among the reasons for their choice. Ten of the participants rated the AORUS display the worst of the five, citing blurry text and dullness among the reasons for their choice.

Ratings made from the off-angle viewing position, that simulated where the RA would be positioned, were similar to center viewing in that colors were easier to distinguish in brighter room light conditions. Additionally, the text in the checklists at the edge of the screen was easier to read at an angle under brighter room light conditions. The text in the checklists at the edge of the screen was most difficult to read at an angle on the AORUS display.

Our participant group was a diverse cross-section of WJHTC employees. About half (8/20) of the participants in this study reported some prior experience with computer-related discomfort and problems such as headaches and eyestrain during their normal computer use. However, we did not find any differences in our eye fatigue measures for participants reporting computer-related symptoms compared to those who did not.

We did not find examples in our study of the types of physiological symptoms reported by some en route controllers when using the new large replacement displays. A critical difference between this study and field conditions is the duration of time the displays were used and the nature of the tasks performed. The participants in our study used each display for 15 minutes to complete simplistic tasks that did not involve high levels of attention and decision-making. The increased cognitive demands of controlling air traffic are likely contributing factors in the issues reported. It is possible that a more extensive study with more difficult tasks would find differences and that display technologies play a more subtle role that this study did not uncover.

There are many considerations that must be made in selecting appropriate displays for use in the ATC environment, among them balancing the brightness of the display with the background room illumination, resolution, and off-angle viewing. In very bright environments, glare will be a very important consideration. It is also important to consider additional factors that affect digital display discomfort that we identified in the comprehensive literature review we conducted in preparation for this study. Factors such as viewing distance, display flicker (even if imperceptible), and blue light have been implicated. Individual factors also play a role, including uncorrected vision problems, being susceptible to motion sickness, and vergence problems in which the two eyes have difficulty focusing on a single location and which can be exacerbated by the need to make large eye movements to focus on objects in the periphery as would be needed when viewing large displays. The specific environment in which the displays are to be used is of utmost importance in selecting and configuring the displays. Evaluating potential displays in simulated environments can help identify potential problems and determine which selection would be best.

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A Informed consent statement

Informed Consent to Participate in Research Study:
Human Factors Impacts of Large Air Traffic Control Displays

Principal Investigator (PI): Carolina M. Zingale, Ph.D., FAA ANG-E5B

Co-investigator: Brion Woroch, Ph.D., Diakon, supporting ANG-E5B

Sponsors: Air Traffic Organization (ATO) Program Management Office (PMO); Human Factors Division, FAA ANG-C1

Invitation to Participate in Research Study

Carolina Zingale, FAA ANG-E5B, invites you to participate in a research study investigating the causes and potential mitigations of eye strain, headaches, nausea, and other such problems that may result from the use of digital display monitors. The study will evaluate whether differences in these problems are found across various large display technologies, including Liquid Crystal Display (LCD)/Light Emitting Diode (LED), Organic LED (OLED), Quantum-dot LED (QLED), and a legacy air traffic control display. This research was initiated due to reports that some air traffic controllers experienced such problems when large (43-inch), commercial-off-the-shelf (COTS) displays replaced the existing (29”) displays at workstations in the en route domain. The causes of these reports are unknown. The research will take place at the Research, Development, and Human Factors Laboratory (RDHFL, Bldg. 28) at the William J. Hughes Technical Center (WJHTC) and is sponsored by the Air Traffic Organization (ATO) Program Management Office (PMO), AJM-1, and funded by the NextGen Human Factors Division, ANG-C1.

- We are recruiting 20 employees at the WJHTC between the ages of 18 – 56 who use digital displays of any size (handheld to wall-mounted) for work or personal reasons. We are seeking individuals who have experienced problems such as eye fatigue, headaches, nausea, etc. when using computer displays, as well as individuals who have not experienced such problems.
- The research is planned for two phases. Both phases will use the protocol described below. The first phase will investigate the causes of the problems, and the second phase will investigate potential mitigation strategies. Participants are encouraged to

complete both phases but may complete only one if necessary. The second phase is planned to be conducted approximately one month after completion of the first phase.

- The purpose of the study is to provide data-driven information to FAA ATC acquisition programs that can be used when developing requirements, selecting products, or conducting tests of large ATC displays.
- This study will take place in person at the RDHFL, Bldg. 28. All research personnel and participants must be compliant with COVID-19 protocols and agency requirements for access to the research site and safety and health procedures in effect at the time of the study.

Conflict of Interest Statement: The researchers have no conflict of interest associated with this study.

Description of participant involvement

- Each participant will spend about 3 hours at the RDHFL for each phase of the study. The participants will view recorded air traffic scenarios and complete simple tasks such as reporting which aircraft are at a designated altitude while using each of 5 displays. The displays vary in size from 29” to 48” diagonal and represent different display technologies (LED, QLED, OLED).
- No air traffic control experience is needed.
- Participants will:
    - complete preliminary questionnaires before beginning the study to provide basic information such as their age, whether they wear corrective lenses, the frequency and duration with which they use digital displays, and whether they have experienced any negative effects (e.g., eyestrain, headaches) while using them.
    - view each display under different room lighting levels or under different display configurations (e.g., contrast adjustments) depending on the experimental conditions.
    - read short text passages at a separate workstation while their eye movements are monitored and recorded before and after working with each of the displays. Eye movements will be monitored using the SmartEye Pro System to to assess potential measures of visual fatigue.

  - complete questionnaires after using each display and at the conclusion of the study.
- No audio/video recordings will be made other than eye movement recordings.
- No names or identities will be associated with the data or released in any reports, briefings, or presentations. All data (questionnaires, task responses) will be coded and stored only by participant number.
- One participant will complete the study at a time.

Potential Benefits

You will not directly benefit from your participation in this study. The only benefit to you is that your data and feedback will help inform FAA decisions regarding the development of requirements, testing, and selection of air traffic controller workstation displays.

Risks and discomforts

The discomfort and risks associated with this study are similar to the discomfort and risks associated with regular office computer work or personal computer use. There is the possibility that you may experience problems such as eyestrain, headaches, nausea, or other symptoms which are occasionally reported by some individuals working with computer displays. Estimates as to how often these problems occur range widely (from 20% to 80% of users). Should you experience any problems that go beyond a moderate level, you will inform one of the researchers immediately. We will end your participation in the study and ensure that you are able to rest and recover before leaving the laboratory. We will report any of these events to the IRB as required.

We will use the SmartEye Pro eye tracking system to measure eye movements before and after using each type of display to obtain potential measures of eye fatigue. The system uses cameras located at the edges of a computer display and infra-red light at up to 120Hz to determine the location of the participants' eyes and head. The intensity of the infrared illumination is about one thirtieth of the intensity expected while walking outside on a sunny day and, therefore, does not present any additional risks.

Participant's Rights

You will not lose any legal claims, rights, or remedies by signing this form and your participation in this research study. The local FAA Institutional Review Board has reviewed this research project under expedited review and found it to be acceptable, according to applicable state and federal regulations designed to protect the rights and welfare of subjects in research.

Cost to Participant

You will not incur any costs for participating in the research study.

Confidentiality

The data collected in this study are stored only by code number, not by name. No names or identities will be released in any research reports, publications, or presentations resulting from this work. Electronic data will be maintained on secure FAA computers and websites that are accessible only by research team members. Any data collected on paper (e.g., questionnaires) will be secured in a locked file cabinet accessible only by research team members. The anonymized data from the study may be made available to other researchers for related studies. We will keep your participation in this research study confidential to the extent permitted by law.

Injury

In the event of any injury incurred while participating in this study, medical treatment will be provided by emergency responders, local hospitals, or clinics. Notify one of the researchers immediately if medical attention is needed. It is the policy of this institution to provide neither financial compensation nor free medical treatment in the event of such injury. You should contact Carolina Zingale, Carolina.zingale@faa.gov, 609-485-8629 to report any injury.

Voluntary Nature of Participation and Withdrawal

Your participation in this study is completely voluntary and it is your choice whether to participate or not. You may decline or withdraw your participation in the study at any time. The choice to decline or withdraw from the study will not cause any penalty or loss of any benefit to which you are entitled. During the study, the principal investigator or research team member will share any new information that develops that may affect your decision to continue to participate. The PI or research team may also terminate your participation in the study at any time if they determine this to be in your best interest.

Contact Information

If you have questions about the study, please ask them before signing this form. You can ask any questions that you have about this study at any time, or after your participation concludes.

For questions, concerns, or complaints about this study, please contact the principal investigator, Carolina Zingale at 609-485-8629. If you feel that you have been treated unfairly, or you have questions regarding your rights as a research participant you may contact the FAA IRB at (405) 954-2700.

Signature and Consent to be in the research study

I have been informed about the purpose, procedures, possible benefits and risks of this research study. I have read (or someone has read to me) this form, and I have received a copy of it. I have had the opportunity to ask questions and to discuss the study with an investigator. My questions have been answered to my satisfaction. I have been told that I can ask other questions any time. I voluntarily agree to participate in this study. I am free to withdraw from this study at any time without penalty and without the need to justify my decision. The withdrawal will not in any way affect any benefits to which I am otherwise entitled. I agree to cooperate with the principal investigator and the research staff and to inform them immediately if I experience any unexpected or unusual symptoms.

Below, I have indicated my decision about being contacted after this study to provide additional information about my experience such as further describing any negative effects I encountered and my recovery, by placing an “X” next to my choice:

___ Yes, I agree that you may contact me after my participation in this study to ask further questions.

___ No, please DO NOT contact me after my participation in this study to ask further questions.

Below, I have indicated my decision about being re-contacted for related studies in the future by placing an “X” next to my choice:

___ Yes, you may contact me about related studies.

___ No, please DO NOT contact me about related studies.

Participant: By signing this consent form, you indicate that you are voluntarily choosing to take part in this research.

____

Printed Name of Participant

____________________________________ ________________

Signature of Participant Date

Investigator

I have fully explained this study to the subject to the best of my ability. As a representative of this study, I have explained the purpose, the procedures, the possible benefits and risks that are involved in this research study. I have answered the subject's questions to his/her satisfaction before requesting the signature(s) above. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily. There are no blanks in this document. A copy of this form has been given to the subject.

____

Printed name of Principal Investigator

________________________________ _______________ ___________

Signature of Principal Investigator Date Time

B Background questionnaire

1. Age _____

2. Occupation ______________________

3. Number of hours using computer, tablet, phone, etc. on a typical day: _________

4. Do you experience any problems such as eyestrain, headaches or nausea when using displays, including computer screens, tablets, smartphones, etc.?

   Yes No

   4a. If yes, what type(s) of problems do you experience:

   ____

5. Do you wear corrective lenses? Yes No

   5a. If yes, do you wear:
   ___ glasses
   ___single vision
   ___ bifocal
   ___ contact lenses

   5b. Do you wear corrective lenses for: ____distance ____reading

   5c. Do you wear lenses specifically for computer use? Yes No

6. Rate your vision currently, as it pertains to your computer use:

   ___ very poor ___ somewhat poor ___ pretty good ___ excellent

7. Approximate date of last eye exam:

   ___ within the last 3 months
   ___ 3 months to 6 months ago
   ___ 6 months to 1 year ago
   ___ 1 – 2 years ago
   ___ > 2 years ago

C Pre-test questionnaire

Computer Vision Syndrome – Questionnaire (CVS-Q)

Indicate whether you experience any of the following symptoms during the time you use the computer at work. For each symptom, mark with an **X**:

a. First, the <u>frequency</u>, that is, how often the symptom occurs,

considering that:

NEVER = the symptom does not occur at all

OCCASIONALLY = sporadic episodes or once a week

OFTEN OR ALWAYS = 2 or 3 times a week or almost every day

b. Second, the <u>intensity</u> of the symptom:
If you indicated NEVER for frequency, you should not mark anything for intensity.

	a. Frequency			**b.** Intensity	
	NEVER	OCCASIONALLY	OFTEN OR ALWAYS	MODERATE	INTENSE
1 Burning					
2 Itching					
3 Feeling of a foreign body					
4 Tearing					
5 Excessive blinking					
6 Eye redness					
7 Eye pain					
8 Heavy eyelids					
9 Dryness					

10 Blurred vision					
11 Double vision					
12 Difficulty focusing for near vision					
13 Increased sensitivity to light					
14 Coloured halos around objects					
15 Feeling that sight is worsening					
16 Headache					

Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ)

Modified:

This questionnaire is designed to measure your experience with different visual display or entertainment devices and if they ever caused discomfort. Visual display or entertainment devices include: Movie Theatre or Cinema screens, Smartphones, Tablets, Video games, Virtual Reality Glasses or Head Mounted Displays, Simulators, Large Public MovingDisplay Advertising or Information Screens

Please answer these questions solely with respect to your experiences during adulthood (older than 18 years) and ignore childhood experiences.

Q1. How often have you experienced each of the following symptoms with any of these devices? (circle your response)

Nausea	*Never*	*Rarely*	*Sometimes*	*Often*
Headache	*Never*	*Rarely*	*Sometimes*	*Often*
Dizziness	*Never*	*Rarely*	*Sometimes*	*Often*
Fatigue	*Never*	*Rarely*	*Sometimes*	*Often*
Eye-strain	*Never*	*Rarely*	*Sometimes*	*Often*

Q2. Have any of these symptoms stopped you using any of these devices or made you avoid viewing such displays? (circle your response)

Never *Rarely* *Sometimes* *Often*

Q3. If you have answered stopped or avoided, please list the devices or displays that you avoid:

D Post-test questionnaire

Simulation Sickness Questionnaire (SSQ)

Part 1:

For each item listed below, please rate your symptoms by circling the appropriate number (First 16 items are based on Kennedy, 1993)

Symptom	**None**	**Low**	**Medium**	**High**
General discomfort	0	1	2	3
Fatigue	0	1	2	3
Headache	0	1	2	3
Eyestrain	0	1	2	3
Difficulty focusing	0	1	2	3
Increased salivation	0	1	2	3
Sweating	0	1	2	3
Nausea	0	1	2	3
Difficulty concentrating	0	1	2	3
Fullness of head	0	1	2	3
Blurred vision	0	1	2	3
Dizzy (eyes open)	0	1	2	3
Dizzy (eyes closed)	0	1	2	3
Vertigo	0	1	2	3
Stomach awareness	0	1	2	3
Burping	0	1	2	3
Workload	0	1	2	3
Dry eye	0	1	2	3
Add any other symptoms you experienced below and provide a rating for each:				
	0	1	2	3
	0	1	2	3
	0	1	2	3

Part 2: While seated **in front** of the display, provide a rating for each statement below by circling or filling the appropriate number.

1. The information on the display is easy to read.	**Not at All**	**➀ ➁ ➂ ➃ ➄**	**Almost Always**
2. The objects on the display look clear and sharp.	Not at All	① ② ③ ④ ⑤	**Almost Always**
3. The colors are easy to distinguish from one another.	Not at All	① ② ③ ④ ⑤	Almost Always
4. Objects and text look hazy or cloudy.	Not at All	① ② ③ ④ ⑤	Almost Always
5. It is easy to read the text in the checklists at the edges of the display.	Not at All	① ② ③ ④ ⑤	Almost Always
6. It is easy to locate information in the datablocks for each aircraft.	Not at All	① ② ③ ④ ⑤	Almost Always
7. It was easy to perform the tasks required using this display.	Not at All	① ② ③ ④ ⑤	Almost Always

With **your chair positioned to the right (or left)** of the display as designated, evaluate the display from this angle. Provide a rating for each statement below by circling or filling the appropriate number.

1. The information on the display is easy to read.	**Not at All**	**➀ ➁ ➂ ➃ ➄**	**Almost Always**
2. The objects on the display look clear and sharp.	Not at All	① ② ③ ④ ⑤	Almost Always
3. The colors are easy to distinguish from one another.	Not at All	① ② ③ ④ ⑤	Almost Always
4. Objects and text look hazy or cloudy.	Not at All	① ② ③ ④ ⑤	Almost Always
5. It is easy to read the text in the checklists at the edges of the display.	Not at All	① ② ③ ④ ⑤	Almost Always
6. It is easy to locate information in the datablocks for each aircraft.	Not at All	① ② ③ ④ ⑤	Almost Always

Positive aspects of using this display:

Negative aspects of using this display:

Other comments about your use of this display.

E Exit questionnaire

Please rank order the displays from 1 to 5 in which 1 is the best display you worked with / caused the fewest problems and 5 is the worst display you worked with / caused the most problems.

Left to right: EIZO DELL AORUS LG BARCO (square)

1. ____________________
2. ____________________
3. ____________________
4. ____________________
5. ____________________

Please provide your reasons for your # 1 choice:

____

Please provide your reasons for your # 5 choice:

____

Please provide any additional comments about any of the displays or about the study:

F Spectroradiometer characteristics

Monitor	Color	R	G	B	u'	v'	Y
AORUS	Red	255	0	0	0.4665	0.5248	28.7253
AORUS	Green	0	255	0	0.1248	0.563	91.2709
AORUS	Blue	0	0	255	0.167	0.1866	12.3073
AORUS	Black	0	0	0	0.2147	0.4638	0.0762
BARCO	Red	255	0	0	0.4665	0.5253	24.5402
BARCO	Green	0	255	0	0.119	0.5672	100.1872
BARCO	Blue	0	0	255	0.1885	0.1057	6.1354
BARCO	Black	0	0	0	0.2178	0.4742	0.2824
DELL	Red	255	0	0	0.4481	0.5226	30.0551
DELL	Green	0	255	0	0.1216	0.567	94.5767
DELL	Blue	0	0	255	0.1828	0.1484	10.3582
DELL	Black	0	0	0	0.222	0.4548	0.4015
EIZO	Red	255	0	0	0.461	0.5273	28.9447
EIZO	Green	0	255	0	0.1222	0.5672	94.4813
EIZO	Blue	0	0	255	0.1827	0.1379	9.3321
EIZO	Black	0	0	0	0.1995	0.4537	0.1221
LG	Red	255	0	0	0.4488	0.5207	26.194
LG	Green	0	255	0	0.1297	0.5613	96.2678
LG	Blue	0	0	255	0.1744	0.1641	10.4966
LG	Black	0	0	0	0.2001	0.4523	0.3141