



The impact of out-the-window size on air traffic controllers' visual behaviours and response time on digital tower operations

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ABSTRACT

Digital tower using video-panorama display permits the provision of air traffic services remotely without the need for a local physical tower. The recent growth of visual science has demonstrated the popular concept in respect of the size of display “bigger is better”. The aim of this research is to examine the sizes of Out-the-Window (OTW) panoramic displays and how they affect controller's visual behaviours, response time and workload. There are two validated OTW (43-inch vs 55-inch) which can potentially be implemented in the digital tower module. It is critical to investigate air traffic controllers' cognitive demand and monitoring performance while interacting with different sizes of OTW in the digital tower module. This research recruited 15 qualified controllers working at a European regional airport. The results demonstrated that a 43-inch display was a better human-computer interaction in target identification than a 55-inch OTW panorama display. The subjective and objective approaches revealed that controllers' visual behaviours and response times were difference while interacting with different sizes of OTW, but controllers' workload did not show difference. The bigger screen presents bigger stimuli which are easier spotted by ATCOs, but it induces bigger amplitude of head and eye movements, bigger distortion on both edges of screen and longer response time on target identifications. System designers should be aware of the effects of peripheral vision and visual distortion on panorama displays while designing digital tower modules for the provision of future air traffic services.

1. Introduction

Air navigation service providers (ANSPs) and airport operators around the world are facing increasing financial pressure from significantly reducing revenues due to effects of the COVID-19 pandemic. It is a challenging task to increase efficiency, while at the same time reduce costs and meet performance, safety, and regulatory requirements. There are some benefits associated with digital tower operations including improved air traffic controllers (ATCO's) SA in adverse weather conditions and at night; optimised shift planning due to cross-training and licensing; reduced costs; maintenance of ATCO's proficiency; airport security and harmonised air traffic management (ATM) infrastructure pooled in one centre (Van Schaik et al., 2016). There are 75% of Europe's regional small airports which have lower than one million passengers making a financial loss. The application of augmented video-panorama technologies has been demonstrated to increase

ATCO's monitoring abilities and situation awareness (SA) on digital tower operations (Ziegler, 2017). ATCO's visual properties to monitor aircraft for landing and manoeuvring on the airfield are critical to the maintenance of safe operations (Papenfuss and Friedrich, 2016). The reconstruction of the far view aircraft via pan-tilt-zoom (PTZ) cameras provides augmented visualization on the out-of-window (OTW) on digital tower module to reduce ATCO's head-down time. However, the design of human-computer interactions (HCI) for panoramic displays on digital tower may induce safety concerns due to image compression and display screen resolution in the digital tower (Fürstenau and Schmidt, 2016). Therefore, the augmented visualization displays of video-panorama cameras has to be taken into account when considering a human operator's cognitive demands and performance (Friedrich and Mohlenbrink, 2013).

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2. Related works

The application of PTZ cameras providing an out-the-window view to ATCOs is extremely beneficial, however the calibration of PTZ cameras for radial distortion and zoom are still challenging to human operator's visual perception (Galego et al., 2012). Distortion in panoramic images created by parallel motion stitching which is shown by lines appearing to converge but which are actually parallel. The effects of 360-degree panoramic images do not provide a good visual cue on a large field (Goncalves et al., 2015). The application of PTZ cameras creates the distortion issue which can make the straight-line of a runway look like a curved banana shape (Fig. 1) on the OTW displays (Kearney and Li., 2018). ATCOs' monitoring performance was based on the alteration of temporal and spatial analysis of ocular indices (Kang and Landry, 2015). The design of OTW panorama displays must provide the optimum field of view to ensure all critical information is available to ATCOs. There are benefits of physically larger displays with fixed retinal image size for several performance tasks (Moore et al., 2004). In visual psychophysics, the term "better" usually pertains to an improvement in performance in a visual task. This type of approach is seen in the use of visual displays where human performance measures are central to the HCI investigation (Robertson et al., 2005).

2.1. Characteristics of displays affecting operator's visual behaviours

The effect of display sizes could impact visual search and reaction time (RT) when the target/distractor discriminations are relatively difficult to be identified (Reynolds and Miller, 2009). Hancock et al. (2015) examined the effects of screen size on performance and found that performance decrement and workload elevation were significant only with the smallest screen size. The feature integration theory (FIT) developed in the visual search context proposed that the size of objects is an influential factor related to visual attention and performance (Treisman and Gelade, 1980). Operator's visual attention was guided in the search for conjunction characteristics such as size and colour which can be processed in parallel (Wolfe et al., 1989; Cavanagh et al., 1990). Whilst ATCOs searching for objects amongst different sizes of distractors, such as searching for the large target of a commercial aircraft amongst small distractors of single engine aircraft, can be efficient because objects could be processed in parallel. Increasing an object's

size could increase search performance in favour of the larger object. FIT suggested that the size of a target could impact visual search performance on the operational environment (Proulx and Egeth, 2008). Is this FIT in line with the innovative digital tower operation? When ATCO search objects on an interface display, the size of an object was determined in terms of the characteristics of panoramic displays on the digital tower module (Li et al., 2018).

The effects of information presentation on displays have been investigated with respect to the impact on human performance and HCI design as Fitts's Law has indicated the size and distance of displays effecting operator's response time (MacKenzie, 1992; Fitts, 1954). The size of OTW panoramic displays may have influenced ATCO's information processing and decision-making. Stimulus sizes may vary significantly between different types of displays, with technologies crossing from 70 ft. large-scale cinema screens, to small mobile displays and even fully immersive virtual reality headsets (Chapiro et al., 2018). Other research proposed that the screen size did not affect hazard surveillance or visual search, as pilots were adaptive in changing scanning patterns in response to the enlargement of the displays (Stelzer and Wickens, 2006). Although a general conclusion suggested human monitoring performance is better with large displays than with small displays. Screen size is an important factor and needs to be considered in the design of information presentation, as operators tend to use the larger screen for searching information to make relevant decisions compared to the small screen (Sweeney and Crestani, 2006). However, the evidence is inconclusive. Research investigating the impact of screen size on target detection task found no significant differences in terms of accuracy and response time between two different sizes of displays (Bush et al., 2020).

2.2. The attribute of multitasks on digital tower operations

Air traffic controller's visual behaviours are reflecting cognitive processes while providing air traffic services (ATS) at a controller working position (CWP). Therefore, an ATCO's visual parameters moving amongst different area-of-interests (AOIs) reveal human information processing (HIP) related to their monitoring performance and response time (Wickens and Hollands, 2000; Henderson, 2003). The provision of human-centred design on the digital tower module may have significant effects on human performance and cognitive processes



Fig. 1. The visual effects of distortions (shadowed by red) on both edges of OTW on digital tower module. The straight-line runway has been distorted to curved-shape due to the visual presentation of pan-tilt-zoom camera and panoramic displays.

(Tobaruela et al., 2014), with increasing challenges to monitor multitask tasks (Wickens and Hollands, 2000; Gutzwiller et al., 2016). ATCOs operating digital tower must constantly shift attention between air movements and ground movements on the airfield to monitor aircraft, vehicles, and ramp operators' activities. Furthermore, the multiple digital tower operations had been certified and will be implemented in the near future (Papenfuss and Friedrich, 2016). The challenge of multitasking in real world operations involves either concurrent task performance, which is not applicable in overload scenarios due to limited cognitive resources; or sequential task performance where operators choose one task to perform at a time (Wickens et al., 2008).

The concurrent multitasking model is impossible to be accepted in high workload scenarios, for example simultaneously operating two international airports using digital tower which will result in a serious event if ATCOs' workload breaks down their monitoring performance (Wickens et al., 2015). ATCOs' visual activities are based on the OTW therefore the interface design of OTW display impacts on ATCOs' cognitive loads and monitoring performance while multitasking (Peterson and Pinska, 2006). The characteristics of OTW superimposed traffic, information and the operational environment through enhanced visualization system on the PTZ can effectively reduce ATCO's cognitive demands and head-down issues (Peterson and Pinska, 2006; Schmidt et al., 2006). It has been demonstrated that the digital reconstruction of the far view of the local tower by means of high-resolution panorama cameras with augmented visualization technology will be able to provide the same quality of ATS in a lower financial cost (Van Schaik et al., 2016). However, the augmented vision element may increase ATCO's cognitive demands by processing more visual information in a multitask scenario, therefore, it will eventually increase ATCO's perceived workload (Bos et al., 2017).

2.3. Visual parameters related to monitoring performance

The operational concept of a digital tower is using high-resolution video-panorama cameras to replace the direct view of local tower at regional small/medium airports (Papenfuss and Möhlenbrink, 2016). To provide effective air traffic services by digital tower, ATCOs must constantly scan the dynamic movements of aircraft in the air and vehicles on the ground by interacting with different interface displays. Therefore, an effective approach to detect ATCO's attention shifts and visual behaviours is the use of an eye tracking device (Robinski and Stein, 2013). Recently, more research has adopted eye-tracking in various contexts of aviation, such as flight deck design (Yu et al., 2016), synthetic vision system display (Thomas and Wickens, 2004), pilot's attention distributions (Zelinsky, 2008), remote tower system design (Möhlenbrink and Papenfuß, 2014), and training and simulation (Korek et al., 2020). Studies suggest eye tracking research, such as scan path and visual parameters, are promising in understanding human operators' visual search patterns and cognitive information processing (Argyle et al., 2020; Jankovics and Kale, 2019). The application of an eye tracker seems promising for analysing ATCOs' visual behaviours on target identification and response times related to perceived workload (Papenfuss and Möhlenbrink, 2016).

The remote tower operation is characterized by the visual reproduction and enhancement by OTW panorama display. The detection, recognition, and spatial perception of the visual cues are significant cognitive tasks for ATCOs performing remote tower operations (Ellis and Liston, 2016). In the cognitive process, visual attention is a precursor in attention distribution, situation awareness, and real-time decision-making (Lavine et al., 2002). The duration of visual scanning is related to processing complex information, as much more time is spent in eye fixation durations than in saccades (Robinski and Stein, 2013). Observing ATCOs' eye movement reveals that pupil dilation is significantly bigger after an alert activation due to higher demanding challenges (Friedrich et al., 2020). Saccades, which are defined as rapid movements between fixations, may reflect the operators' direction of an

attention shift (Kowler, 2011). However, saccade can be measured in multiple ways including amplitude, duration, and velocity. Research suggested that saccade amplitude would be less affected by the viewing area, task time, and blink effects compared with saccade velocity (McGregor and Stern, 1996). Furthermore, a linear relationship was found between saccade amplitude and saccade duration (Baloh et al., 1975). Pupil dilation increases along with cognitive workload (Ahlinstrom and Friedman-Berg, 2006). Distribution of fixations is defined as a period of time watching a stimulus in a specific area of interest and is highly related to how the operators allocated their attentions (Henderson, 2003; Ognjanovic et al., 2019). Inappropriate system design of digital towers may present many disadvantages and risks leading to accident/incidents, including loss of SA, and placing the human operators outside of the system control loop (Durso et al., 1998; Endsley, 1995). The PTZ cameras in a digital tower module could generate the issue of visual distortion while compacting a 360-degree field-of-view into a 220-degree configuration of OTW (Kearney et al., 2020). Therefore, it is critical to understand ATCOs' visual parameters such as eye fixation durations, eye fixation numbers, saccade amplitude, pupil dilation, and response on target identifications while interacting with different sizes of panoramic displays (Ellis and Liston, 2016; Robinski and Stein, 2013).

2.4. Information presentation related to workload

Workload is a self-evaluated and reflects the individuals perception related to mental and physical effort, frustration, and time restrictions to complete the objectives (Fernandes and Braarud, 2015). Although there are many different interpretations of cognitive workload published in different domains of literatures, the commonality of workload has consisted across several dimensions related to diversity of challenge on task performance (Evans and Fendley, 2017). One of the most frequently used subjective methods is the NASA-TLX which includes mental demand, physical demand, temporal demand, performance, effort, and frustration (Hart and Staveland, 1988). PTZ cameras providing dynamic information using augmented visualization cues may be able to increase ATCO's situation awareness. However, ATCOs' perceived workload may be affected by the way the information is presented (Leitner and Oehme, 2016). The display system in a digital tower module has been proved to increase ATCOs' physical demand and mental demand compared with local physical tower operations because there are too much monitoring tasks simultaneously on digital tower operations (Aricò et al., 2019).

Air traffic management at an airport is constantly changing with dynamic situations. Therefore, ATCOs must deal with unexpected events that could cause a significant increase in their workload. Appropriate interface design at the CWP can discharge the ATCOs cognitive loads and enhance their SA by ensuring a better match between cognitive resources and task demands (Kaber et al., 2006). The application of eye tracker seems promising for analysing ATCOs' pupil dilation on target identification is also related to perceived workload (Papenfuss and Möhlenbrink, 2016). The panorama display integrated with augmented visualization design will be an effective component of information presentation in the digital tower operations (Barfield and Caudell, 2001). By analysing the required information presentation, digital tower system design must also consider how to reduce ATCOs' workload (Fürstenau and Schmidt, 2016). Hopefully, the application of advanced optical technologies will reduce controller's perceived workload. Therefore, various options for digital tower design and human performance certification would have to be examined in detail in laboratory and operational tests before implementation.

2.5. Motivation

The recent growth of visual science has demonstrated that the popular notion that the bigger the size of display, the better is normally correct (Silvera et al., 2002; Robertson et al., 2005). There are a number

of problems with this argument including distance of view, spatial resolution of the visual system, and user's experience (Troscianko et al., 2012). The large display was linked to higher levels of artefact interaction and more integrative behaviour in terms of manipulating the digital content (Zagermann et al., 2016). However, other research proposed that larger-sized interfaces went along with reduced interactions amongst participants, and the size of the display impacted collaborative processes (Mateescu et al., 2021). The visual reproduction OTW screens on digital tower modules provides critical information for ATCOs conducting target identification and conflict resolution. There are two OTW screens (43-inch vs 55-inch) proposed by manufacturers but these need to be evaluated by the operators (Frequentis, 2016). It is critical to investigate ATCOs' monitoring performance related to perceptual thresholds while interacting with different sizes of OTW displays (Ellis and Liston, 2016). Therefore, there are three research questions to be examined as follows:

- Research question 1: What is the difference in ATCO's visual behaviours while interacting with 43-inch OTW versus 55-inch OTW?
- Research question 2: What is the difference in ATCO's response time on target identification while interacting with 43-inch OTW versus 55-inch OTW?
- Research question 3: What is the difference in ATCO's workload while interacting with 43-inch OTW versus 55-inch OTW?

3. Method

3.1. Participants

This research recruited 15 qualified ATCOs (60%) from the population of 25 ATCOs working at a European regional airport. The ages of participants ranged between 31 and 58 years old ($M = 42.07$, $SD = 8.13$) with working experience ranging between 2 years and 39 years ($M = 16.33$, $SD = 10.99$). A research proposal was submitted to the research institute ethics committee for approval before conducting the experiment (CURES2471/2017). All participants were informed that the research related to OTW design on the digital tower module for future remote tower operations. Participants were guaranteed the right to

withdraw from the research at any stage. All collected data is only available to the research team and stored in accordance with the United Kingdom Ethical Code and the Data Protection Act.

3.2. Apparatus

3.2.1. Eye tracker

The Pupil Labs eye tracker used in this research consisted of an eye camera and world camera fixed in a plastic frame worn like glasses. It is composed of a light-weight headset, high resolution cameras for eye movement parameters and a graphical user interface for video visualization. The world camera was fixed on the outside part of the frame, in front of the forehead. It captured the field of view of the participant, following head movements as the frame moved with it (Fig. 2). The visual angle error could be estimated by the spatial difference between the actual gaze position and gaze position (Wang et al., 2017). As the visual angle error is random, when a fixation point on the boundary of an AOI is detected by the eye tracker, the focus that a participant is actually looking at would be in a circle with a radius of 0.6° and centered at the fixation point. In other words, the actual fixation point could be either outside or inside the AOI. The random visual angle error will be cancelled out in statistical analysis when comparing the means amongst groups such as *t*-test (Hooge et al., 2019). Therefore, the analysis on eye movement parameters used the predefined AOI without adjusting the boundary.

In the present study, eye fixation is defined as consecutive gaze points that fall into a circle with a radius of 1.5° and a duration longer than 150 ms. Based on this definition, gaze duration refers to the duration of a gaze point. And the eye fixation duration is calculated by aggregating the gaze durations for an eye fixation. The resolution was 1280×720 pixels for a sample rate of 60 frames per second. The eye camera was fixed on the side of the frame, below the participant's right eye. It was meant to capture the participant's pupil and its movements (top on left-corner, Fig. 2). To detect the pupil dilation, it was equipped with an infrared illumination and an infrared detector (Kassner et al., 2014). A saccade refers to the fast eye movement between two gaze points, which is measured in terms of saccade amplitude in degree in the AOI. This is because saccade amplitude is a relatively stable and

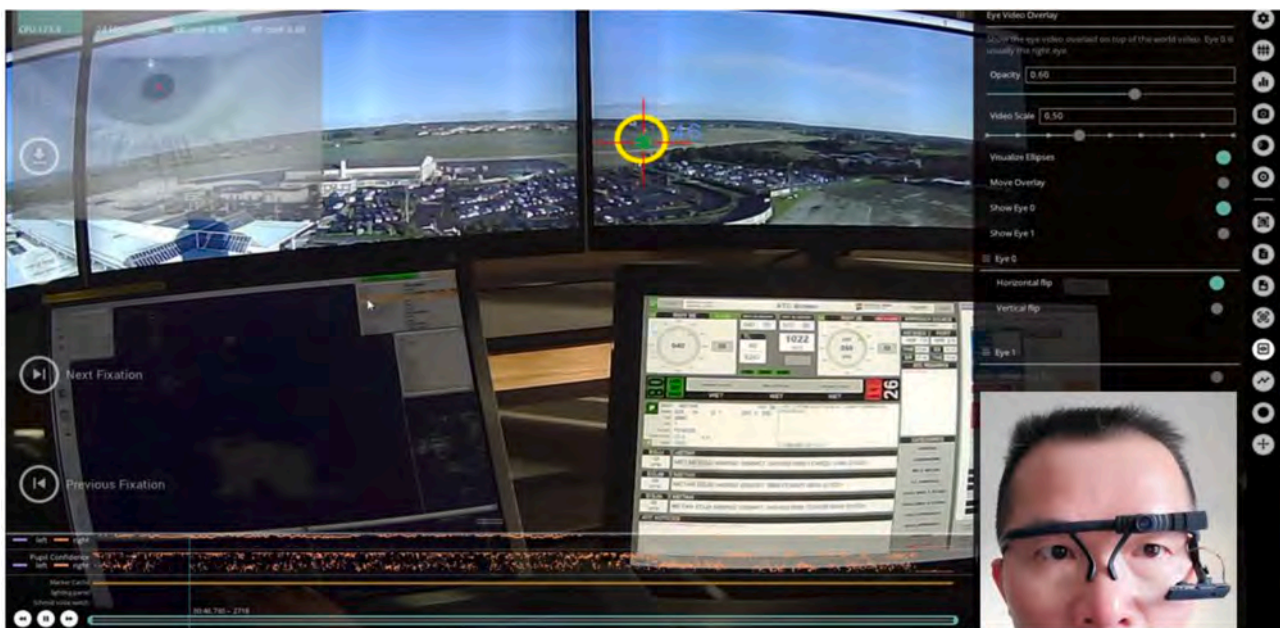


Fig. 2. The field of view on eye tracker and participant's fixation shown as red-cross with yellow-circle on the touchdown area of runway (target-12) on OTW of Digital Tower module captured by world camera; participant's pupil image (top on left-corner) superimposed on the screen captured by eye camera of Pupil Labs Eye Tracker (bottom on right-corner).

normalized measurement reflecting cognitive process and perceived workload, and less influenced by viewing area and blink effects (McGregor and Stern, 1996). Therefore, visual parameters including eye fixation numbers, eye fixation durations, saccade amplitude and pupil dilation were analysed while ATCOs performed visual searches on the OTW.

3.2.2. Digital tower module

The layout of the digital tower (Fig. 3), which consists of seven different components, is exactly the same as that of the current physical tower. The seven components are a Lighting panel; Voice Switch Panel; Electric flight strip (EFS); Radar display; Automated weather observation system (AWOS); Pan-tilted-zoom cameras display (PTZ); and OTW. Given the design of the visual presentation on the interface displays is the substantial factor to be considered for human-computer interactions in digital tower operations, we focused on the area of interest (AOI-OTW), which is the critical component to replicate the out of window view on the physical tower.

Two different sizes of OTW using three screens (43-inch vs 55-inch) were being considered for implementation in the digital tower module. This research is to investigate which size of display is the best OTW in the digital tower module from an HMI perspective. Although there are seven components in the digital tower module, this research only focuses on ATCOs' visual parameters on OTW (AOI-OTW), perceived workload, and response time on target identifications between the 43-inch and 55-inch of display. There are 14 selected targets which are critical references to ATCOs' monitoring tasks presenting to participants as followings, (1) JAL Hangar; (2) ATR on Stand 6; (3) C310 on Stand 20; (4) Met-Site on North Boundary; (5) Runway 08 Glidepath Aerial; (6) Rescue 6; (7) Met-Office Observation Balcony; (8) 737 on Stand 18; (9) RWY 08 Threshold, (10) Arrivals Building Entrance; (11) Runway 26 Threshold; (12) Runway 26 Touchdown Zone; (13) Jersey Airfield Radar & (14) Met-Observation Tree in St John (Fig. 4).

3.2.3. NASA-TLX workload measurement

The NASA Task Load Index is a popular technique for measuring subjective perceived workload and is composed of six sub-scales, mental demand, physical demand, temporal demand, performance, effort, and frustration. The participant must rate the sub-scales with a score that can range from low (0) to high (100). NASA-TLX was applied to assess participants' perceived workload while interacting with the 43-inch OTW compared with the 55-inch OTW screens. Participants were presented with the 43-inch OTW and 55-inch OTW randomly to

counterbalance practice effects; and were required to mark their perceived workload whilst identifying 14 dispersed targets on the airfield after interacting with these two different sizes of OTW in the digital tower module.

3.3. Procedures

Participants were briefing that the experiment involved wearing an eye tracker to identify the scattered targets in the airfield and manoeuvring areas presented on the OTW. The procedures for all participants were as follows, (1) complete the demographical variables including age, gender, qualifications, and working experiences by years as qualified air traffic controllers (five minutes); (2) a briefing regarding the purpose of the study and consent form as following: 'This research is to investigate the potential impacts to ATCO's monitoring performance by implementation of Digital Tower. There are two different sizes of OTW screens (43-inches vs 55-inches), which will be assessed related to ATCO's response time on target identification. You are invited to identify 14 targets scattered around the airfield with five seconds of interval using the laser-point pen as soon as you heard the target from audio recorder' (10 min); (3) participant sat on the controller working position to calibrate the eye tracker (five minutes); (4) randomly assigned the first scenario and the second scenario (43-inch OTW or 55-inch OTW) to each participant with pre-recorded audio consisting of 14 targets with five seconds intervals between targets. Participants were advised to identify each target by using red-colour laser pointer placed on top of the named target to measure the response time (10 min); (5) mark the NASA-TLX scores immediately after completing each scenario (ten minutes); (6) de-briefing the participants and asking their comments regarding the best OTW design in digital tower module (five minutes). It took approximately 45 min for each participant to complete the experiment.

3.4. Research design

Participants partook in two sessions of trials for target identification around the airfield interacting with both 43-inch and 55-inch OTW to measure ATCOs' responses. A random table for those visual targets was generated to counterbalance the practice effects on participants. Furthermore, visual parameters including eye fixation durations, eye fixation numbers, saccade amplitude and pupil dilation were collected by Pupil Labs eye tracker (Kassner et al., 2014). Several statistical methods were adopted to answer the research questions. Goodness-of-fit



Fig. 3. The layout of digital tower module including seven components. The panorama displays (AOI-OTW) consisted with three screens to accommodate stitching images from 13 cameras for 240° filed-of-view on the airfield. The other six displays below OTW are exactly the same with physical tower module.



Fig. 4. The image of panorama display scattered 14 targets in the airfield and manoeuvring areas on two different sizes of OTW video-panorama display for trials.

analysis based on chi-square is used to examine whether the ATCOs' preference is different. The paired t -test, a statistical analysis for repeated measure, is used to test whether the difference between two conditions. Afterward, the effect size for a paired t -test is measured in terms of Cohen's d . In summary, paired t -test is applied to analyse visual parameters including eye fixation numbers, eye fixation durations, saccade amplitude, and pupil dilation; perceived workload on NSAT-TLX including mental demand, physical demand, temporal demand, performance, effort, and frustration; and response time.

4. Results

4.1. Sample characteristics

There were 15 qualified air traffic controllers participated this trial. The results of goodness of fit tests suggested no significant difference on the preference of participants, $\chi^2(1) = 0.067, p > .05$. The paired samples for comparison are from the same participant, satisfying the equal variance and independence. The assumption of normality is verified by Shapiro-Wilk tests ($p > .05$). The results demonstrated that there were significant differences on ATCOs' eye fixation numbers, eye fixation durations, saccade amplitude, and response time. However, there was no significance on both pupil dilation and perceived workload. The detailed t -test results of four eye-tracking variables, response time of 14 targets, and six dimensions of perceived workload by NASA-TLX are presented in Figs. 5, 6, 7 and 8 respectively. Furthermore, eight ATCOs preferred the big OTW (55-inch) while the other seven ATCOs preferred the smaller OTW (43-inch). The accuracy rate of target identification is 100%, all ATCOs correctly identified 14 targets on the airfield with different response times on different sizes of OTW.

4.2. ATCOs' visual behaviours on target identifications

There is a significant difference in eye fixation numbers when ATCOs interact with the big (55-inch) and small (43-inch) size of OTW, $t = 2.97, d = 0.77, p = .010$. ATCOs tend to fixate more on the smaller OTW than on the bigger. There is a significant difference in eye fixation duration between the big (55-inch) and small (43-inch) size of OTW, $t = 2.26, d = 0.58, p = .040$. Evidence suggested that ATCOs are inclined to fixate on the big size OTW longer than the small size OTW. There is no significant difference on pupil dilation between the big (55-inch) and small (43-inch) size of OTW, $t = 1.56, d = 0.40, p = .140$. Furthermore, there is a significant difference on saccade amplitude between the big (55-inch) and small (43-inch) size OTW, $t = 2.24, d = 0.58, p = .040$. The result suggested that ATCOs have a larger saccade amplitude on the big size OTW than on the small size OTW (Fig. 5).

4.3. ATCOs' response time on target identifications

There is a significant difference on ATCOs' average response time while interacting with the big (55-inch) and small (43-inch) size of OTW, $t(14) = 2.55, p = .02, d = 0.66$. Evidence suggested that the participants are inclined to respond quickly while interacting with small size of OTW. The average response time is calculated based on 14 targets (five centred targets and nine side targets) scattered around airfield. For five centred targets, there is no significant difference of ATCOs' response time when interacting with the big (55-inch) and small (43-inch) size of OTW (Fig. 6), $p > .05$. However, ATCOs' response time of all nine side targets are influences significantly by the sizes on big (55-inch) and small (43-inch) OTW (figure). Eight out of nine side targets show consistent effects, which suggest the smaller size of OTW could lead to quicker response times from ATCOs': target 1, $t(14) = 2.38, p = .032, d = 0.62$; target 2, $t(14) = 2.52, p = .024, d = 0.65$; target 5, $t(14) = 2.28, p = .038, d = 0.59$; target 8, $t(14) = 3.84, p = .002, d = 0.99$; target 9, t

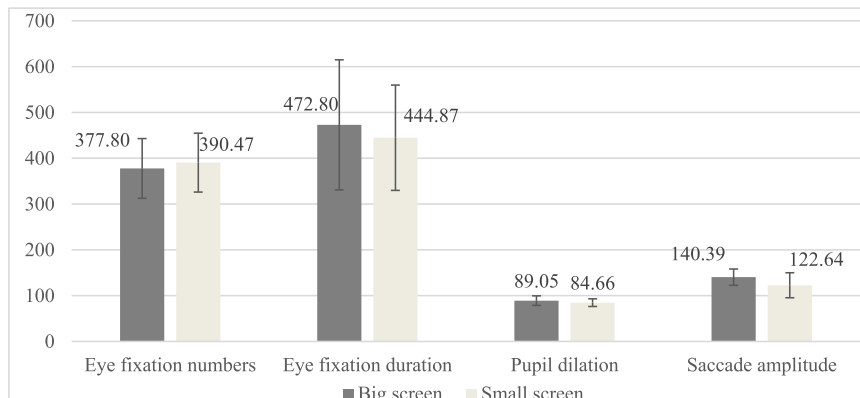


Fig. 5. The differences of ATCOs' visual behaviours by eye tracking parameters while interacting with big OTW (55-inch) and small OTW (43-inch).

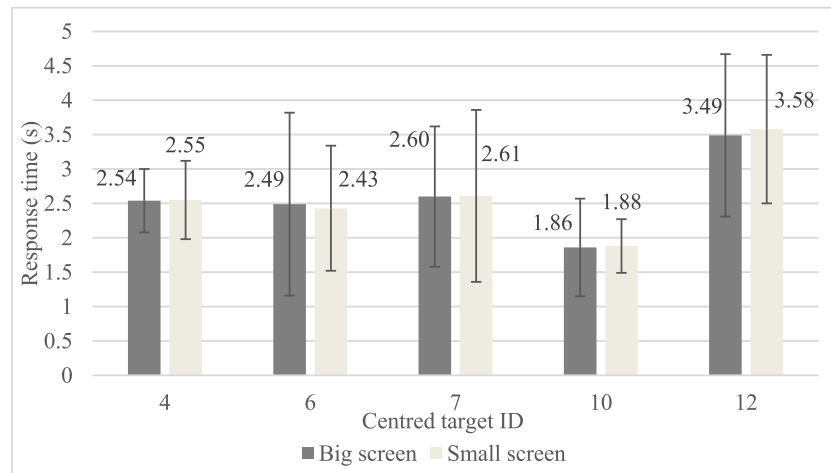


Fig. 6. The differences of response time on five centred target identifications scattered in airfield while interacting with big OTW (55-inch) and small OTW (43-inch).

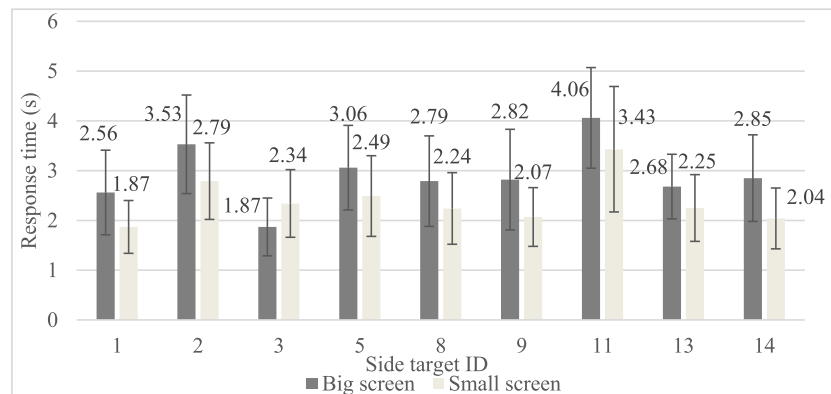


Fig. 7. The differences of ATCOs' response time on side target identifications scattered in airfield (seven on left-hand side and two on right-hand side) while interacting with big OTW (55-inch) and small OTW (43-inch).

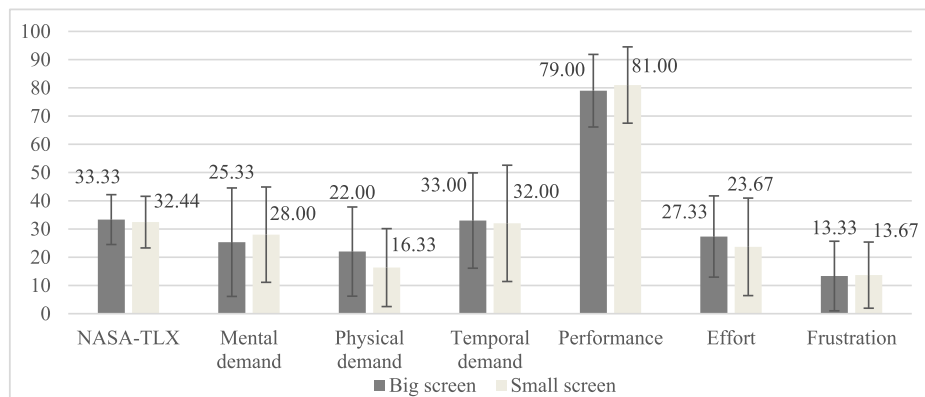


Fig. 8. The differences of ATCO's perceived workload on six sub-dimensions of NASA-TLX while interacting with big OTW (55-inch) and small OTW (43-inch).

(14) = 2.90, $p = .012$, $d = 0.75$; target 11, $t(14) = 2.38$, $p = .032$, $d = 0.62$; target 13, $t(14) = 2.22$, $p = .043$, $d = 0.57$; target 14, $t(14) = 3.16$, $p = .007$, $d = 0.82$. However, there is one inconsistency where the ATCOs' response time is significantly quicker on the big OTW than small OTW on target 3 (C310 on Stand 20), $t(14) = -2.37$, $p = .032$, $d = -0.61$.

4.4. ATCOs' perceived workload

The NASA-TLX scores demonstrated that there is no significant difference while ATCOs interacting with the big (55-inch) and small (43-inch) OTW, $t(14) = 0.70$, $p = .49$, $d = 0.18$. Due to workload consisted with several dimensions of challenging on task performance, it is necessary to specify ATCOs' perceived workload in detail. There are six sub-dimensions on NASA-TLX including mental demand, physical demand, temporal demand, performance, effort, and frustration. ATCOs'

perceived workload on six sub-dimensions of NASA-TLX either show no significant differences when interacting the big (55-inch) and small (43-inch) OTW, $p > .05$ (Fig. 8).

5. Discussion

The development of digital towers must comply with an ANSP's certification processes and should enhance safety, capacity, human performance, and cost-efficiency (Kearney and Li, 2018). ATCOs may perform both ongoing tasks (OT) such as clearing an aircraft to land and interrupting tasks (IT) such as responding to a runway incursion in high-workload and high-tempo environment (Wickens et al., 2016). Technological developments allow more flexibility in the use of the available ATCO resources and the European Union Aviation Safety Agency (EASA) aims to fully exploit the current regulatory framework to accommodate new technologies and operational concepts, while maintaining a high level of safety (EASA, 2019). amongst various factors that influence visual search performance, OTW and PTZ are the fundamental displays related to ATCO's monitoring performance and SA that should be considered while designing a panoramic display for digital tower operations. The design of the panorama OTW displays which impact ATCO's visual behaviours, response time on target identification and perceived workload need to be prudently investigated before implementation.

5.1. ATCO's distinct visual behaviours on different sizes of displays

Eye tracking technology offers detailed measurements on operators' attentional distribution, response time, SA and perceived workload. Visual behaviours can provide guidance to optimize system designs to enhance HCI performance and reduce response time (Ahlstrom, 2010). Therefore, visual parameters are crucial and can be regarded as direct measurements of ATCOs' attention distributions related to cognitive information processing and workload (Ahlstrom and Friedman-Berg, 2006). In this research, we investigated the effects of sizes of panorama OTW displays based on ATCOs' visual parameters, including eye fixation numbers, eye fixation durations, pupil dilation, and saccade amplitude. It is found that ATCOs' visual parameters on monitoring panoramic displays are distinct. Specifically, we found ATCOs have more numbers of fixation and shorter eye fixation durations while interacting with a smaller sized panoramic display. When ATCOs interacted with a bigger sized screen they were inclined to fixate at fewer locations and spent more time on target identification. Furthermore, a high negative correlation between eye fixation numbers and eye fixation durations on both the big screen ($\gamma = -.837, p < 0.01^{**}$) and the small screen ($\gamma = -.952, p < 0.001^{***}$) was found, suggesting the pattern is consistent across different size of displays. These results could be interpreted from a visual search perspective in which the task is to search a specific object amongst objects in a dynamic scenario (Chapman and Underwood, 1998), such as searching an aircraft landing at an airport. The visual searching behaviour is a complicated cognitive process which involved perception (visual stimulus and location in the airfield) and pattern matching between targets. While conducting target identifications on a small size of panoramic display, it might be difficult if the target is too small to be identified (such as target 3). Therefore, ATCOs would integrate more information from various sources on a small size OTW, resulting in more eye fixation numbers and shorter eye fixation durations with smaller saccade amplitude. The gathered evidence from visual parameters demonstrated that the ATCOs are identifying the target by cross-checking more visual references on a small size OTW display. In summary, the eye fixation numbers and eye fixation durations could reveal the distinct pattern of ATCOs' interactions with different size of OTW displays. This is consistent with the finding that visual behaviours based measures are relevant to operators' situation awareness in aviation contexts (Van De Merwe et al., 2012). In general, the bigger displays are more impressive and therefore operators are more engaged on

monitoring tasks and bigger screens should be better on reflecting a stimulus to a bigger object (Hancock et al., 2015). However, the result of this research demonstrates: 'the smaller the better on ATCOs' target identification while interacting with panoramic OTW displays on digital tower module.'

5.2. ATCOs' response time on panoramic displays for target identification

The application of PTZ cameras and panorama displays on digital tower modules has created mixed effects for visual searching which are related to foveal, parafoveal and peripheral vision in conducting target identifications (Stewart et al., 2020). The result demonstrated that ATCOs must turn their heads and move their eyes dramatically during target identifications with 55-inch displays compared to the 43-inch displays. Therefore, ATCOs' response time has significantly increased using the larger OTW on eight targets (1, 2, 5, 8, 9, 11, 13 & 14) compared to the smaller screen (Fig. 7). The differences in ATCOs' response time may be associated with scanning the larger scope of the 55-inch screen from right-hand side to left-hand side compared with the 43-inch OTW (Fig. 9). If targets are allocated beyond foveal and near peripheral vision, ATCOs must move their heads and eyes to search and identify targets. The fovea is responsible for sharp central vision which is important for primary visual activities such as reading and driving. The Blue frame OTW (43-inch screen on Fig. 9) required a smaller degree of head movement on both left-hand side targets (1, 2, 5, 8, 9 & 13) and right-hand side targets (11 & 14) compared to the red frame OTW (55-inch superimposed 43-inch OTW on Fig. 9). The 55-inch screen is nearly 1.6 times larger than the 43-inch screen which can significantly magnify the visual stimulus on OTW displays to facilitate ATCO's monitoring performance. Furthermore, the effects of visual image distortion on both the right-hand side and left-hand side are more significant than on the centre of the panorama display. The bigger the screen the bigger the visual distortion on both the left-edge and right-edge of the screen. The straight line of the runway looks like a curved line on panorama displays (Fig. 1 & 10). Therefore, it is necessary to consider that magnifying objects to a suitable size for visual scanning.

There are no significant differences in response time amongst targets 4, 6, 7, 10 and 12 which are all allocated near the central of field of view (Red-colour section on the Fig. 10). Interestingly, one target shows an inconsistency where ATCO's response time is significantly faster on the large OTW compared to small OTW, this is target 3 (C310 on Stand 20). It may be that the small C310 aircraft presents a tiny stimulus on the retina, and this is difficult to identify on the small display. ATCOs must scan using a pattern matching strategy which took a longer time compared to the bigger OTW. This research is also in line with previous research that foveal vision allows human operator view shapes, colours, and details that are right in front of them (Schotter et al., 2012). The effects of magnification, peripheral vision and visual distortion on panorama displays should be considered when designing OTW for digital towers to improve ATCOs' response time and accuracy during monitoring tasks. In summary, although the bigger screen could be an important factor and preferable to human operator's visual search strategies, the positive effects may depend on different scenarios or tasks. ATCOs' response times are quicker while interacting with smaller displays (43-inch) compared with bigger displays (55-inch) on digital tower operations.

5.3. Subjective and objective perceived workload measurements

An ideal human-centred design for a digital tower would minimise ATCOs' cognitive workload and maximise their SA and monitoring performance. The aim of workload assessment is to evaluate the effect of cognitive and physical demands related to tasks placed on the human operator (Ayaz et al., 2010). Pupil dilation, an eye tracking based objective measurement, is known to quickly respond to cognitive workload while performing a visual task (Pomplun and Sunkara, 2003).

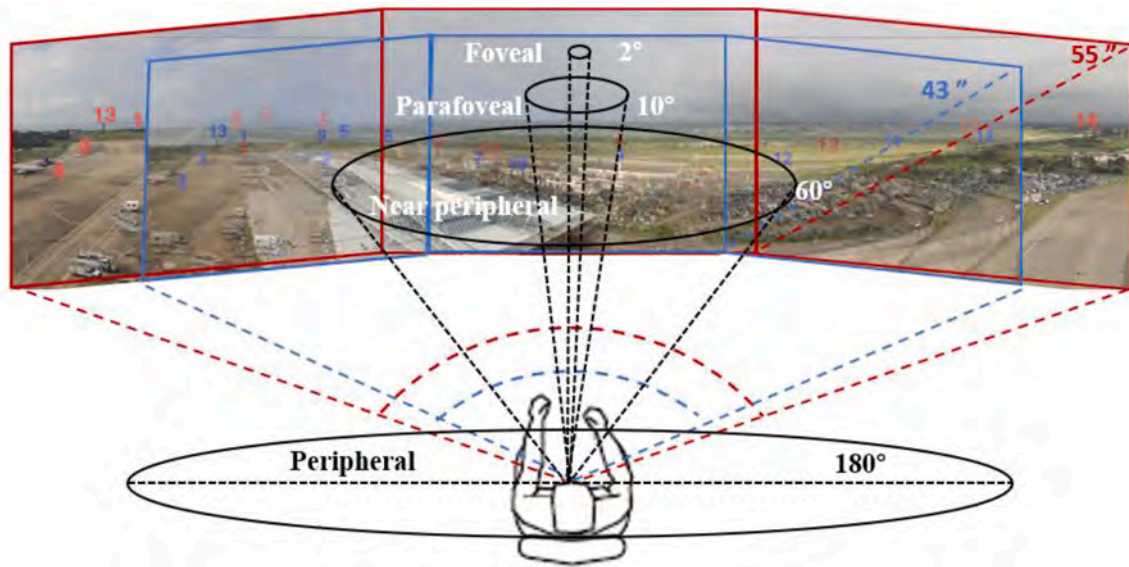


Fig. 9. The overlapped images to make comparison on 14 targets scattered in the airfield on panorama displays between 55-inch OTW (targets numbering in RED colour) and 43-inch OTW (targets numbering in BLUE colour) related to ATCOs' visual angles and range of head and eye movements on the digital tower module.



Fig. 10. ATCO's response time to identify targets shown significant differences only allocated on both left-edge and right-edge panoramic displays between 55-inch and 43-inch OTW, but the targets on the central field of view shown no significant differences (red-colour section).

An increasing pupil size correlates with increasing mental workload (Iqbal et al., 2005; Ahlstrom and Friedman-Berg, 2006). Therefore, pupil dilation is an effective indicator of mental workload under conditions of controlled illumination. In this study, we evaluated ATCOs' workload both objectively (pupil dilation) and subjectively (NASA-TLX). Subjective measurement on perceived workload is further broken-down to six sub-dimensions, including mental demand, physical demand, temporal demand, performance, effort, and frustration. The results suggested no significant difference on ATCOs' pupil dilation between the small and big size screens under the same illumination conditions in the digital tower control centre. On the other hand, ATCOs interacted with two different sizes of screen for target identifications tasks and showed no differences in perceived workload. Furthermore, the summary on participants' subjective opinions revealed that eight ATCOs preferred the big OTW while the other seven ATCOs preferred the smaller OTW. Both objective measurement of pupillary response and subjective measurement of NASA-TLX on perceived workload were consistent. A Possible interpretation could be that the workload of such monitoring tasks could be influenced by many factors, in which the ATCOs' attentional effort are always required when interacting with a screen for safety in providing air traffic services. There is a dilemma on the size of panorama display, the bigger screen presents bigger stimuli which are easier spotted by ATCOs, but it induces bigger amplitude of head and eye movements, bigger distortion on both edges of screen and longer

response time on target identifications.

5.4. Limitations

There are some limitations in the process of this research which are necessary to specify related to data collection. Firstly, the challenge in measuring subjective perceived workload is that it was assessed using the NASA-TLX questionnaire after the monitoring task has completed. The nature of presented information held in ATCO's working memory for a considerable period of time may affect their responses on subjective workload assessment (Slater, 2004). Secondly, the target identification is a very simple monitoring task to a professional air traffic controller. It does not involve any real-time decision-making in remote tower operations, though the research design is relevant to HCI in digital tower operations. To increase ecological validity, future studies could collect ATCOs' data involved in real time operations. Thirdly, the size of ATCO's pupil dilation detected by the eye camera on the eye tracker is a confounding variable which could be affected by brightness of OTW panoramic displays. Lastly, there were only 15 professional ATCOs in this research from the European regional airport. The results derived from a small number of participants may reduce statistical power. Authors have suggested to collect more data in the future to validate the finding on current research.

6. Conclusion

ATCOs' monitoring tasks and perceived workload are likely to change from time to time depending on the dynamic nature of the traffic on the ground and in the air. The subjective and objective approaches to evaluating ATCOs' visual behaviours, workload assessments, and response times related to HCI designs are critical to the certification processes in digital tower operations. To achieve these ambitious goals, ANSPs and airport operators must explore new operational concepts, integrating the principles of human-centred design in the digital tower module. The application of PTZ cameras and panoramic displays OTW in the digital tower has been proven to increase ATCOs' SA, capacity, and organisational cost-efficiency. The size of OTW panorama displays has a significant impact on ATCOs' visual behaviours and response times in target identification. Bigger is not always the better solution for the panorama OTW display. The bigger screen presents bigger stimuli which are easier spotted by ATCOs, but it induces bigger amplitude of head and eye movements, bigger distortion on both edges of the screen and longer response time on target identification. System designers should be aware of the effects of peripheral vision and visual distortion on panorama displays when designing digital tower modules for the provision of future air traffic services.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.ijhcs.2022.102880](https://doi.org/10.1016/j.ijhcs.2022.102880).

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