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The Impact of Alerting Designs on Air Traffic Controller's Eye Movement Patterns and Situation Awareness

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Abstract

This research investigated controller' situation awareness by comparing COOPANS's acoustic alerts with newly designed semantic alerts. The results demonstrate that ATCOs' visual scan patterns had significant differences between acoustic and semantic designs. ATCOs established different eye movement patterns on fixations number, fixation duration and saccade velocity. Effective decision support systems require human-centred design with effective stimuli to direct ATCO's attention to critical events. It is necessary to provide ATCOs with specific alerting information to reflect the nature of of the critical situation in order to minimize the side-effects of startle and inattentional deafness. Consequently, the design of a semantic alert can significantly reduce ATCOs' response time, therefore providing valuable extra time in a time-limited situation to formulate and execute resolution strategies in critical air safety events. The findings of this research indicate that the context-specified design of semantic alerts could improve ATCO's situational awareness and significantly reduce response time in the event of Short Term Conflict Alert activation which alerts to two aircraft having less than the required lateral or vertical separation.

Keywords: Air Traffic Management, Alerting Design, Eye Movement Patterns, Situation Awareness, Visual Attention

Practitioner Summary

Eye movements are closely linked with visual attention and can be analysed to explore shifting attention whilst performing monitoring tasks. This research has found that context-specific designed semantic alerts facilitated improved ATCO cognitive processing by integrating visual and auditory resources. Semantic designs have been demonstrated to be superior to acoustic design by directing the operator's attention more quickly to critical situations.

1. Introduction

The majority of alert activations in the COOPANS Air Traffic Management (ATM) system are Short Term Conflict Alert (STCA: A warning system designed to support air traffic controllers in preventing collision between aircraft.) which represent 61% of all activated alerts and include 12% of false alerts (Irish Aviation Authority, 2016). The COOPANS system is deployed in five countries within Europe: Ireland, Denmark, Sweden, Austria and Croatia. ATCOs across these five countries operate a harmonized system which offers three critical alerts using the same acoustic alerting schema in support of the Single European Sky (Eurocontrol, 2015). The COOPANS system provides three kinds of alerts which are designed to support air traffic controller's (ATCO) decision-making during critical situations such as conflict between aircraft (STCA), conflict between aircraft and terrain (Minimum Safe Altitude Warning - MSAW), and conflict between aircraft and airspace where airspace activities which are a risk to civil aviation exist (Area Proximity Warning - APW). Activation of any of these three alerts, signaled by a simple acoustic-designed alert (Beep-Beep-Beep-Beep) indicates either a potential conflict of two aircraft (STCA), conflict between aircraft and prohibited airspace (APW) or conflict between aircraft and terrain (MSAW). The ATCO is then expected to judge and resolve the potential conflict as quickly as possible to prevent an incident or accident (Kearney, Li, & Lin, 2016). The activation of the STCA alert on the COOPANS system provides a 90-second warning, that unless appropriate action is taken by ATCOs to resolve the conflict, significant risk of collision between aircraft exists. If the

ATCO does not detect this alert and does not issue control instructions to flight crew to resolve the conflict, there is a risk of aircraft collision. In the current COOPANS ATM system an activation of a STCA alert might be misinterpreted as another alert such as APW or MSAW due to the same acoustic stimulus (Beep-Beep-Beep-Beep). This may delay an ATCO's problem identification thereby weakening ATC safety barriers. Therefore, the auditory alarms should be easily distinguishable from one another by varying frequencies and modulation (Ahlstrom, 2003a).

In Air Traffic Management, a STCA represents a critical event which might lead to a significant air safety event. The mid-air collision that occurred at Überlingen in 2002 involving a B757 and TU154M aircraft was a STCA-related major accident that resulted in 71 fatalities. It occurred in part because an imminent separation infringement was not noticed by an ATCO in time (German Federal Bureau of Aircraft Accidents Investigation, 2004). Previous research found that fixation trajectory could be a key component to situation awareness (SA) (Ratwani, McCurry, & Trafton, 2010); the number of fixations might be associated with the process of SA recovery from interruption (Gartenberg, Breslow, McCurry, & Trafton, 2014); fixation duration could be an indicator of cognitive process related to task performance (Moore & Gugerty, 2010) and shorter fixation duration indicated higher workload and increased temporal pressure (Causse, Imbert, Giraudet, Jouffrais & Tremblay, 2016). Hence, visual monitoring and storage of aircraft information is an important task for an air traffic controller. This requires prompt and accurate responses by the ATCO to resolve the potential risks under time pressure.

2. Literature Review

A salient alert might be excellent at attracting operator's attention; however, it may divert an ATCO's attentional resources away by inducing startle. ATCO's cognitive resources may be allocated from the decision-making process to monitoring the flow of time as part of a coping strategy under time limited situations (Zakay, 1993). Furthermore, time pressure might cause the screening phase of problem identification to become less systematic. Therefore, inappropriate alerting design presents many disadvantages and creates potential risks which can lead to accident/incidents, including startle, loss of situation awareness, and switching the human operators outside system control loop (Durso, Truitt, Hackworth, Crutchfield, & Manning, 1998). A number of safety concerns have been identified in ATM systems including a lack of uniqueness of alarms, frequent false alarms, alarms that are not intuitive, annoying alarms which increase workload (Ahlstrom, 2003b; Newman & Allendoerfer, 2000). In addition, inattentional deafness is promoted by cognitive load which might impact ocular measurements, and the key factor of inattentional deafness was generated by the mental calculation of heading or by the numerous tasks required to manage an ATC sector (Causse et al, 2016). These issues can lead to human operators switching from proactive monitoring to reactive controlling such as checking or diagnosis of the risks, potentially resulting in delays to responding to a time critical situation (Dorner, 1993). Therefore, it is necessary to acquire visual information efficiently into the cognitive process via the monitoring work of ATCO. Eye movements can reflect monitoring behaviours (Bruder, Eißfeldt, Maschke, & Hasse, 2014).

2.1 Eye Movement Patterns and Situational Awareness

Aviation human factors experts have defined situation awareness (SA) as a state of the individual, and situation assessment as the process by which the state of awareness is achieved in order to conduct timely decision-making (Li, Harris, & Yu, 2008; Sarter &

Woods, 1994). Furthermore, Endsley (1997) developed a situation awareness and decision-making framework which is based on the information-processing model, and defined SA as 'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the future' to perform appropriate decision-making. Managing complex ATM systems including minimising response time to critical alerts such as STCA is not only an issue of technical skill, but also of a real-time decision-making involving situation awareness under time pressure. More recently, an analysis of military aviation accidents found perceptual errors and loss of situation awareness were involved in many aviation accidents (Diehl, 1991; Li, Li, Harris, & Hsu, 2014). However, the definition of SA has lots of important differences in what constitutes SA compared with Endsley's SA framework. Dekker and Hollnagel (2004) proposed that SA has the characteristics of a folk model with no explanatory power. There is a magnitude of discrepancy between Endsley's reported 88% of accidents/incidents attributed to SA problems and 1.4% identified SA issues based on the Aviation Safety Reporting System (ASRS) (Vaitkunas-Kalita, Landry, & Yoo, 2011). There are lots of arguments on the 'construct of situational awareness' and the 'meaning of loss of situational awareness' in the domain of Human Performance (Dekker, 2001; Dekker & Hollnagel, 2004; Stanton et al., 2006; Stanton, Salmon, Walker, Salas, & Hancock, 2017). How information is presented is highly critical to its readability, understandability, and accessibility, thus impacting on human perception, cognition and performance. There is a continuing need to conduct objective research on Endsley's model of SA, as some of the disagreements result probably by misconception and misunderstandings of the model of SA (Endsley, 2015).

Eye movements are closely linked with visual attention and can be analysed to explore how much effort and shifting attention occurred whilst performing visual tasks (Kowler, 2011). Previous studies indicate that human's fixations are not attracted by salient objects, but rather the meaningful places for the task that is being undertaken (Henderson, 2003). Fixation duration comes from deliberate consideration and induces more fixation points for acquiring more detailed information (Schulte-Mecklenbeck, Kuhberger, & Ranyard, 2011). Saccade is defined as fast eye movement and generally it declines as a function of increased mental workload, while the pupil diameter increases as a function of cognitive demand (Ahlstrom & Friedman-Berg, 2006). Saccadic eye movements are controlled by top-down visual processes, which are coordinated closely with perceptual attention (Zhao, Gersch, Schnitzer, Dosher, & Kowler, 2012). This indicates that saccadic paths are intentional and meaningful, and are based on the requirements of the task and trajectory prediction in the future (Kowler, 2011). The path of saccades is associated with selective attention and accurate judgments for perceptual targets (Henderson, 2003). ATCOs not only have to distribute their attention to detect potential conflicts among aircraft both in the air and on the ground, but also have to resolve unexpected events under time pressure through radio telephony communications with pilots. SA may be achievable without knowing what to do in some situations; however, understanding can require awareness of an event prospect including outcomes and preconditions of action (Lundberg, 2015). Therefore, visual attention is a precursor to initiating the cognitive process involved in attention distribution, situation awareness, and real-time decision-making (Lavine, Sibert, Gokturk, & Dickens, 2002).

2.2 Alerting Designs Impacted to Attention Distribution

The definition of conflict in ATM is 'an event in which two or more aircraft experience a loss of minimum separation, the distance between aircraft violates a criterion of 5 miles lateral distance or 1,000 feet of vertical distance'. The goal of decision support systems for conflict detection and resolution is to present warning messages to ATCOs predicting a conflict in sufficient time to respond and prevent any erosion of safety standards. Conflict detection can be assumed as the process of deciding when action should be taken, and conflict resolution involved in determining what actions should be performed. Therefore, an ATCO can have more time to conduct problem-solving in advance (Kuchar & Yang, 2000). However, the current COOPANS ATM system has a simple acoustic design (Beep-Beep-Beep-Beep) which signifies one of three different critical hazards: STCA for conflict; MSAW for terrain; and APW for airspace. This design had induced ATCO's into startle and also into misinterpreting the type of critical alerts being presented, and in the worst circumstance, the ATCO's response may be to solely silence the acoustic alert due to distraction. Better designed acoustic alerts are not necessarily the answer. Whilst they may be outstanding at seizing the ATCO's attention, the alert may immediately divert the ATCO's attentional resources away from the ongoing task, incurring other issues such as startle and operational error by distraction (Imbert et al., 2014).

The term of SA has been criticized as poorly defined and extremely debatable as a folk model, e.g. deficient SA was a causal factor resulting in accidents (Billings, 1995; Dekker & Hollnagel, 2004; Stanton et al., 2006). Furthermore, the prevailing notions of SA are overgeneralized such that those related perceptual factors, e.g. experience and workload, impacting SA performance are easily ignored. In addition to audio intensity warning, the semantic content of an auditory alert conveying the specific risk is the central component to alleviate time pressure and promote more effective decision-making (Edworthy & Hellier, 2006). Appropriate design of decision support tools in ATM systems can assist in moderating ATCO workload and improving SA by facilitating a better match between task demand and cognitive resource (Kaber, Perry, Segall, McClernon, & Prinzel, 2006). Designing decision support systems for ATCO's requires an understanding of principles of cognitive system engineering and allocation of function and team adaptation. It is a holistic approach of distributed cognition coordination to rapidly changing situations (Langan-Fox, Canty, & Sankey, 2009). Future human-centred designs of ATM systems must be based on a strategic, collaborative and automated concept of operations, as high performance in monitoring tasks has the potential to increase both airspace efficiency and the safety of aviation (Schuster & Ochieng, 2014). As detailed in the proposed paper the use of decision support systems "for conflict detection" is to provide advanced notice of a real, unsafe situation should the ATCO not intervene or take actions. ATM system functionalities such as Medium-Term Conflict Detection (MTCD), STCA and Trajectory Prediction (TP) belong to a suite of COOPANS tools called "safety nets". As detailed in the ATM master plan safety net enhancements will "maximise the future ATM system's contribution to aviation safety and minimise its contribution to the risk of accident". The deployment of a semantic alert for STCA events for example would reduce ATCO cognitive workload as it is argued that ATCOs will process the alert faster than the generic Beep Beep Beep acoustic alert.

2.3 Visual Behaviours Reflecting Information Processing

Human-centered design can improve an ATCO's performance and reduce their cognitive workload (Laois & Giannacourou, 1995), giving the ATCO increased cognitive capability to perform complex tasks (Tobaruela et al., 2014; Wickens & Hollands, 2000). If a controller over-relies on automated systems, it might result in poor SA (Orasanu, 2005). The concurrence of excessive fixations, long fixation duration and less saccade duration is the precursor of tunneled attention (Johnson & Proctor, 2004). ATCO's visual behaviours provide an opportunity to investigate the relationship between eye movement patterns and information processing. Eye scan pattern is one of the most powerful methods for assessing human beings' cognitive processes in Human–Computer Interaction (Ahlstrom & Friedman-Berg, 2006). Visual activity is the objective method for assessing an ATCO's cognitive process related to real-time decision-making (Ayaz et al., 2010). Based on accident investigation, 75% of aviation accidents involved poor perceptual encoding on the flight deck (Jones & Endsley, 1996). This phenomenon highlights how interface design impacts operator's attention distribution, cognitive activities, situation awareness and decision-making. Authors' previous research has found that effective context-specified design of alerts, where the warning signal is more than a mere stimulus, where the alert has been integrated to the ATCO's cognitive system and where the alert provides meaningful information can significantly speed up ATCO's response (Kearney & Li, 2015; Kearney et al., 2016).

Patterns of eye movement is one of the methods for assessing ATCO's cognitive processes based on real-time physiological measures (Henderson, 2003). Auditory alerts can attract an operator's visual attention regardless of where their visual attention is directed, if the alert is presented at an effective level. However, a side-effect of auditory alerts can be that poorly deployed alerting systems can induce startle and lead to the operator suffering tunnel vision at the cost of all other operations they are engaged in. Semantically designed verbal warnings tailored to specific hazard situations may improve hazard-matching capabilities without a substantial trade-off in perceived annoyance (Baldwin, 2011). ATCOs' visual search for maintaining SA is affected by the surrounding environment and interface designs. The factors manipulating visual attention include how information is presented, the complexity of the interface design, and the operating environment. These arguments provide a compelling explanation that eye movement is highly correlated with attention, indicating a substantial correlation between attention shifts and maintaining SA to support decision-making. The research objectives are to investigate how alerting design impacted ATCOs' visual behaviours and situation awareness by comparing their response to acoustic alerts versus a newly designed semantic alert, using the COOPANS ATM system.

3. Method

3.1 Subjects

Twenty-six qualified air traffic controllers from the Irish Aviation Authority (IAA) participated in this research. Participants' ages ranged between 24 and 47 years old (M=35.15, SD=6.11); professional experience ranged between 1 and 25 years (M=8.56, SD=6.81). Approval of the Science and Engineering Research Ethics Committee of Cranfield University was granted in advance of the research taking place (CURES/1506/2016). All collected data were only available to the research team and were stored in accordance to the University's Ethical Code and the Data Protection Act.

3.2 Apparatus

3.2.1 Training simulator: The contingency and validation platform of IAA was used to develop the STCA exercise. This training simulator reflects the same layout with the COOPANS Air Traffic Management System supplied by THALES. The software used was THALES-B2.1 for the configuration of acoustic alert (Beep-Beep-Beep-Beep). The COOPANS Air Traffic Management System is the system which is being used currently in the IAA for air traffic control (Figure 1). The semantic alert was developed by an IAA engineer and installed in the training simulator to support this experiment. The semantic alert design philosophy drew on previously established research from industry including airborne conflict detection and alerting systems such as TCAS/ACAS. The alerts were validated on the Technical and Training Facility prior to introduction and were designed as an integrated

WAV file which triggered based on system derived criterion for each specific alert under assessment.

[Insert Figure 1 Here]

3.2.2 Eye Tracking Device: A mobile head-mounted eye tracker (ASL Series 4000) was used to collect ATCO's eye movement data. The sampling rates are between 30 and 60 Hz. The eye tracker is portable and weighs only 76g. Air Traffic Controllers can move their head without any limitations during the experiment. Visual and cognitive science research typically analyse eye movements in terms of fixations (pauses over informative regions of interest), fixation duration (the sum of all durations on fixating an AOI), pupil size (indicator of cognitive load) and saccades (rapid movements between fixations). Therefore, the analysis metrics of this research include parameters of the following visual behaviours, fixation counted, percentage of fixations, fixation duration, pupil size, saccade duration, and saccade velocity.

[Insert Figures 2a and 2b Here]

3.2.3 Scenarios: The STCA scenario was developed to ensure consistent levels of air traffic reflective of day to day air traffic management within Irish airspace. The simulation included air crew initiated climbs and descents to present crossing traffic and initiate STCA activation, where climb and descent rates were deliberately inconsistent. The timing of which was randomised and introduced by the instructor. The airspace sector used represented an approach sector, with the radar range set to 40 nm and traffic arriving to and departing from an aerodrome in the centre of the display. A total of 18 aircraft were present in the airspace sector displayed. A target airspace environment representing a busy international airport approach sector was selected as a representative airspace configuration for the experiment. On this basis 1,000ft vertical and five miles lateral separation standard applied as per the airspace requirements. The STCA is triggered by positional conflicts within a given airspace for all eligible system track pairs whose separation is expected to be lower than the defined minimum separation requirement of 1,000 feet vertical separation and five nautical miles lateral separation. A pair of tracks in conflict means that the vertical and/or horizontal separations are infringed. The visual representation of the STCA is shown as figure 2a and 2b a pop-up flashing red boarder activates. Additionally the Radar Position Indicator and flight information also turns red. Conflicting aircraft are tagged with a red ball beside the highlighted callsign on the screen. A standard air traffic control training scenario was modified to contain an unanticipated STCA event. To standardize the processes of data analysis, it was necessary to standardize the time of ATCO's eye movement due to the varied time frames in performing the air controlling task between 650 and 1035 seconds. Considering the criticality of STCA alerts and their relative occurrence (61% of alerts), two alerting designs (semantic design vs acoustic design) were assessed using an STCA scenario.

3.3 Research Design

All subjects undertook the following procedure: (1) briefing about the objectives and procedures of the experiment (10 minutes); (2) calibration of the eye tracking device by using three points distributed over the ATM screen and control panels (5-10 minutes); (3) participants performed the STCA scenario either by acoustic alert or semantic alert randomly (10-20 minutes); (4) debrief of subject's feedback and comments (5-10 minutes). Each participant took around 50 minutes to complete the experiment. The audio alert presented to the Air Traffic Controllers in trial-A was the acoustic alert that is available within the COOPANS system (Beep-Beep-Beep-Beep). The experiment was conducted within the context of a mature, operational system and aims to explore how a relatively simple change to the alert can provide additional information and speed up decision making. As such, the semantic alert of Trial-B consisted of a new semantic audio alert (Beep-Conflict-Conflict-Beep). All participants were advised that the trials were in relation to operating the COOPANS Air Traffic Control System and were presented randomly with either the acoustic alert or the semantic alert. Participants' operational behaviours such as silencing the alert while STCA warning activated will be recorded for further analysis. A two-way mixed-design ANOVA with ATCOs' eye movement parameters including fixation numbers, fixation duration, saccade duration, saccade length, and pupil size was conducted. Alerting design (acoustic alert vs. semantic alert) is between-subject factors. For each subject, 60 seconds of ATCOs' eye movement data were analysed - 30 seconds before and 30 seconds after the activated alerts. Those two sessions of eye movement parameters (before and after alert activation) capture the most critical phases in terms of cognitive processes related to monitoring performance based on IAA senior instructors' professional experience. This data was used to compare the characteristics of ATCO's visual attention distribution and situation awareness to different types of alerting designs. The adjusted degree of freedom was based on the result of Mauchly's test. Significance level was set at $\alpha = .05$ for all analysis. No Bonferroni tests were performed to identify pairwise differences for factors, as there are no more than two levels of independent variables. Partial eta-square ($\eta2\rho$) is a measure of effect size in current study.

4. Results

The demographic information of the subjects' age, gender, and working experience are shown as table 1. A two-way mixed design ANOVA was applied to analyse five eye movement parameters as dependent variables (fixation count, fixation duration, saccade duration, saccade velocity and pupil size) by two independent factors; the first factor is between-subjects of alerting designs (acoustic design vs semantic design), and the second factor is within-subjects of alerting phases (before alert vs after alert).

[Insert Table 1 Here]

4.1 Fixation counts

There is a significant main effect of alerting designs on fixation counts (table 2), F (1, 24) = 31.35, $p < .001$, partial $\eta^2 = .193$, the result demonstrated that the semantic design had significantly more fixation counts (M = 46.25, SD = 6.19) compared with the acoustic design (M=39.80, SD = 11.16). Also, there is a significant main effect of alerting phases (table 3), F (1, 24) = 42.5, $p < .001$, partial $\eta^2 = .639$, before alert activation had significantly more fixation counts (M = 47.38, SD =6.95) compared with after alert activation (M = 40.15, SD = 9.34). Furthermore, there is a significant interaction on fixation counts between alerting designs and alerting phases, F (1, 24) = 5.15, $p < .05$, partial $\eta^2 = .177$. The pattern of interaction shown as table 4 and figure 3a. Further application of simple main effect analysis revealed there is a significant effect of alerting designs on fixation counts after alert activatation, F (1, 48) = 9.47, $p < .01$, partial $\eta^2 = .189$, showing the semantic design significantly increased fixation counts (*M* = 43.69, *SD* = 5.31) compared with acoustic design (*M* = 34.50, *SD* = 11.73) after alert activation. However, there is no significant simple main effect of alerting designs on fixation counts before alert activation, *F* (1, 48) = 1.54, *p* = .22, partial η^2 = .037.

[Insert Table 2 Here]

[Insert Table 3 Here]

[Insert Table 4 Here]

4.2 Fixation duration

There is no significant main effect of alerting design on fixation duration (table 2), *F* (1, 24) = .883, *p* = .357, partial η^2 = .035, the result demonstrated that the semantic design (*M* = 430.25, *SD* = 91.44) had no significant difference on fixation duration compared with the acoustic design (*M* = 392.50, *SD* = 136.62). Also, there is no significant main effect of alerting phases (table 3), *F* (1, 24) = 2.6, *p* = .120, partial η^2 = .098, the result shows no significant difference on fixation duration between before alert (*M* = 396.46, *SD* = 84.40) and after-alert (*M* = 435, *SD* = 131.75). However, there is a significant interaction of fixation duration between alerting designs and alerting phases, *F* (1, 24) = 4.623, *p* < .05, partial η^2 = .162. The pattern of interaction shown as figure 3b and table 4. Further application of simple main effect analysis revealed there is no significant effect of alerting designs on fixation duration after alert activation, *F* (1, 48) = 3.216, *p* = .079, partial η^2 = .075. Also, there is no significant simple main effect of alerting design on fixation duration before-alert activation, *F* (1, 48) = .001, *p* = .972, partial η^2 = .000.

4.3 Saccade duration

There is a significant main effect of alerting design on saccade duration (table 2), *F* (1, 24) = 4.973, *p* < .05, partial η^2 = .172, the result demonstrated that the semantic design (*M* = 231.78, *SD* = 105.85) had significantly less saccade duration compared with the acoustic design (*M* = 442.55, *SD* = 431.50). Also, there is a significant main effect of alerting phases (table 3), *F* (1, 24) = 12.515, *p* < .005, partial η^2 = .343, the result shown before alert (*M* = 247.65, *SD* = 135.69) had significantly less saccade duration than after alert (*M* = 378.04, *SD* = 387.32). Furthermore, there is a significant interaction of saccade duration between alerting designs and alerting phases, *F* (1, 24) = 12.395, *p* < .005, partial η^2 = .341. The pattern of interaction shown as figure 3c and table 4. Further application of simple main effect analysis revealed there is a significant effect of alerting design on saccade duration after alert activation, *F* (1, 48) = 13.54, *p* < .001, partial η^2 = .262, showing semantic design (*M* = 232.19, *SD* = 127.08) significantly decreased saccade duration compared with acoustic design (*M* = 611.40, *SD* = 539.88) after alert activation. However, there is no significant simple main effect of alerting designs before alert activated, *F* (1, 48) = .017, *p* = .683, partial η^2 = .004.

4.4 Saccade velocity

There is no significant main effect of alerting design on saccade velocity (table 2), *F* (1, 24) = 1.676, *p* = .208, partial η^2 = .065, the result demonstrated that the semantic design (*M* = 499.12, *SD* = 186.78) had no significant difference on saccade velocity compared with the acoustic design (*M* = 407.75, *SD* = 217.78). However, there is a significant main effect of alerting phases on saccade velocity (table 3), *F* (1, 24) = 9.806, *p* < .01, partial η^2 = .290, the result shown before alert (*M* = 506.50, *SD* = 197.45) had significantly faster saccade velocity than after alert (*M* = 421.46, *SD* = 201.66). Furthermore, there is a significant interaction of saccade velocity between alerting designs and alerting phases, *F* (1, 24) = 6.393, *p* < .05, partial η^2 = .210. The pattern of interaction shown as figure 3d and table 4. Further application of simple main effect analysis revealed there is a significant effect of alerting design on saccade velocity after alert activation, *F* (1, 48) = 5.35, *p* < .05, partial η^2 = .120, showing that the semantic design (*M* = 489.06, *SD* = 202.20) significantly increased saccade velocity compared with the acoustic design (*M* = 313.30, *SD* = 153.94) after alert activation. However, there is no significant simple main effect of alerting design on saccade velocity before alert activated, *F* (1, 48) = .01, *p* = .927, partial η^2 = .000.

[Insert Figures 3a, 3b, 3c & 3d Here]

4.5 Pupil dilation

There is no significant main effect of alerting design on pupil dilation (table 2), *F* (1, 24) = 0.585, *p* = .452, partial η^2 = .024, the result demonstrated that the semantic design (*M* = 26905.84, *SD* = 7075.31) had no significant difference on pupil size compared with the acoustic design (*M* = 24577.95, *SD* = 8290.91). However, there is a significant main effect of alerting phases on pupil size (table 3), *F* (1, 24) = 14.28, *p* < .005, partial η^2 = .373, the result shows that an ATCO's pupil dilation (*M* = 26972.31, *SD* = 7386.84) is significantly bigger than before alert activation (*M* = 25048.69, *SD* = 7777.82). There is no significant interaction of pupil size between alerting design and alerting phase, *F* (1, 24) = 0.108, *p* = .746, partial η^2 = .004 . The pattern of interaction shown as figure 4 and table 4.

[Insert Figure 4 Here]

5. DISCUSSION

Human operators play a critical role across operations, training, design, regulations and safety management. An understanding of human information processing is evidently demonstrated by reduction of human error in the systems (Chang, Yang, & Hsiao, 2016; Honn, Satterfield, McCauley, Caldwell, & Dongen, 2016). The organization of information for effective decision-making is an emergent theme of human-computer interactions between internal resources and external representations (Hollan, Hutchins, & Kirsh, 2000). The match between internal and external factors is a key prerequisite of monitoring performance. Therefore, an alerting design has to convey specific information to reflect external events in order to improve ATCO's SA and optimize ATCO's decision-making (Schuster & Ochieng, 2014). When information is complex, the corresponding eye movement will be different, such as increased fixation duration and reduced saccade distance (Hoffman & Subramaniam, 1995). Evaluating ATCOs' monitoring behaviours by using dynamic simulations and based on eye movements is an innovation which enables the development of new approaches for assessing selection profiles (Bruder et al, 2014). The results of current research has demonstrated that ATCOs' eye movement patterns had significant differences depending on the phases of alert activated and types of alerting designs.

5.1 Semantic Design Effect on ATCO's Situation Awareness

The results revealed no difference on fixation counts before-alerts between acoustic design and semantic design. Interestingly, the semantic design increased significantly the fixation counts compared with the acoustic design after alert activation (figure 3a). Furthermore, there is no difference of fixation duration before alert activation between acoustic design and semantic design. However, the semantic design increased significantly the fixation duration compared to the acoustic design after alert activation (figure 3b). This implies that the semantic design promotes ATCO's SA by increasing fixation numbers, allowing the ATCO to collect more critical information, and to conduct deliberate cognitive thinking by cumulative fixation duration which is related to problem-solving and therefore to developing conflict resolution strategies. It is reasonable that there are no significant differences between acoustic design and semantic design before alert activation, as an ATCO's cognitive processes are only triggered by the activation of alerts. The results of this research support previous findings that fixation duration reflects the concentration degree in extracting information, and fixation numbers reveal that critical information is processed by ATCO's to gain SA (Kotval & Goldberg, 1998). Theoretically, SA is a key component in human information processing, and is the basis for a proper decision-making (Wickens & Hollands, 2000). Despite SA being highlighted in the aviation domain as an essential prerequisite for safe operations, Sarter and Woods (1991) have challenged the SA technique needed to freeze a simulation of the primary task for probing the operator's situation awareness which clearly does not reflect real world operations. The results indicate that ATCOs have to sustain substantial attention to avoid mis-judging the trajectory of a moving target among lots of dynamic information (Li, Yu, Braithwaite, & Greaves, 2016). In summary, an ATCO's decision-making can be divided as situation awareness (conflict detection) and action choice (conflict resolution). Situation awareness is the starting point for an ATCO's problem-solving in critical situations, as the ATCO cannot solve a problem unless he/she recognizes there is a problem and understands the nature of the problem (Orasanu & Davison, 2001; Bruder et al, 2014). ATCO's eye movement patterns demonstrated that the semantic alert design is superior to the acoustic design to promote SA for monitoring performance (table 4).

The significant difference in ATCO's saccade duration was observed between acoustic design and semantic design after alert activation (table 4). ATCOs saccade duration is significantly decreased by using the semantic design compared to acoustic design (figure 3c). This illustrates that the ATCO shifts fixations with shorter time to search for critical information to make appropriate decisions in time-limited situation (90 seconds or less). Furthermore, the results reveal that the semantic design significantly increases saccade velocity after alert activation (figure 3d). ATCO's response time is primarily influenced by the design of alerting schemata, as the design of the semantic alert facilitated the ATCO's information processing and provided them with specific knowledge in the form of a mental model. The semantic alert has demonstrated improved ATCO's SA by providing a warning signal and characteristics of risk (level-1 and level-2 of SA), and assisting the projection of future status (level-3 SA), thus significantly off-loading ATCO's working memory and efficiently directing cognitive processes to problem solving (Kearney et al., 2016).

5.2 The Design of Context-specified Alert Directing Visual Attention

It has been proposed that semantic memory can have a positive impact on task performance (Gobet, 1998). Before the alert activates, the results show no differences between acoustic and semantic designs, as participants did not receive any stimuli from the ATM system. However, there are significant differences on fixation counts, fixation duration, saccade duration and saccade velocity between acoustic and semantic designs after alert activation (figures 4a, 4b, 4c & 4d). This is the evidence which ATCO's internal information process is significantly influenced by the representation of the alerting design. Based on the recording, eight participants silenced the acoustic alert first when it activated, then moved to resolve the issue. The reason they silenced the acoustic alert is that the auditory warning is annoying and distracts them from their task performance, as ATCOs can't concentrate on logical thinking to develop strategies for conflict resolution due to interruption of the acoustic alert. On the other hand, only two participants silenced the semantic alert - both participants expressed a concern of distraction by the auditory stimulus and they claimed they were already aware of the nature of the problem. ATCO's fixation shifting demonstrated that visual scan patterns related to alerting designs. In addition, before distributing saccades to the STCA conflict, auditory alert attracts ATCO's attention is the bottom-up cognitive process (the perception level of SA). Efficient alert design plays a very important role to activate ATCO's top-down knowledge-based visual process using saccades to survey correctly the potential at risk aircraft and subsequently interact with the visual ATM interface (the comprehension level of SA) and resolve the possible conflicts (the projection level of SA). Therefore, auditory alert design is associated with visual detection which should avoid inducing the occurrence of inattentional deafness (Macdonald & Lavie, 2011; Dehais et al, 2014).

In terms of the long debate on SA term, Parasuraman, Sheridan, and Wickens (2008) recognized the phenomenon of overgeneralizing SA. To avoid overgeneralizing SA, studies associated with SA should apply high fidelity simulators and design the experimental scenario to reflect and comply with real world operations. As systems become more complex and technology-driven, this raises important questions around situation awareness and how best to support it across individuals, teams, organizations and entire systems (Sarter & Woods, 1991; Stanton et al., 2006; Stanton, Salmon, Walker, Salas, & Hancock, 2017). Eye-tracking devices have been applied to human-computer interaction domains for a long time, such as flight deck design, controller working position design, and design of control rooms for nuclear power plants (Ahlstrom & Friedman-Berg, 2006; Ha, Kim, Lee, & Seong, 2006; Tvaryanas, 2004). Quick saccade velocity with the semantic design promotes quick attention distribution when searching for critical information after alert activation in order to enhance situational awareness. Based on the results of saccade duration and saccade velocity, the ATCO's attention, SA and decision-making process are influenced by alerting design within an ATM system. Real-time decision support requires reliable visualization to evaluate temporal information (dynamic aircraft movement) promptly to predict future status. Therefore, it is important to provide context-specified decision supports for dynamic situations (Ltifi, Kolski, & Ben Ayed, 2015). The semantic design can increase ATCO's cognitive ability by integrating visual resources and auditory signals to direct attention, to improve SA, expand working memory, and to enhance the recognition of patterns compared to the acoustic design. The effective design to improve monitoring performance must take the ATCO's cognitive process into account. The design of the semantic alert directly affects comprehension, as recognition is enhanced when stimuli are processed in a semantically meaningful way (Greve, van Rossum, & Donaldson, 2007).

5.3 The Path of Fixations Reflected to ATCO’s Information Processing

Saccade is defined as a quick eye movement between two phases of fixation in the same direction. Fixation shifts demonstrate the attention distribution and scan path of operators (Ratwani et al., 2010). Saccade duration is the total time taken to make a saccade, which is recognized as one of the indexes to assess operator’s workload. Saccade velocity is how fast the eyes move between fixations, which are associated with rapid deployment of attention. Therefore, saccades can be an effective indicator of situation awareness (Rognin, Grimaud, Hoffman, & Zeghal, 2004; Gartenberg et al, 2014). ATCO’s are constantly scanning the progress of aircraft in their sector in order to provide a safe and expeditious service. Observing ATCOs’ eye movement patterns reveals that pupil dilation after alert activation is significantly bigger than before alert activation. It may be a side-effect of startle induced by an annoying auditory stimulus. However, there is no significant interaction between alerting design and alerting phase on pupil dilation. To develop an effective ATM system, the HCI design must integrate two factors, auditory semantic factors which convey a stimulus of alert and specify the nature of the event; and visual representation factors which include salient colours, shape, texture, and flashing to direct the attention to the source of the event. Cognitive processing of aural and visual information involves stimulation, perception, recognition, memory and comprehension which all together facilitate effective decision-making. Air Traffic Controller’s cognitive processes for monitoring, identifying and solving potential conflicts require internal cognitive resources and external representation of objects, artefacts and interface designs (Ltifi et al., 2015). There are significant differences between ATCO’s fixations, fixation duration, saccade duration and saccade velocity depending on whether the ATM system presents an acoustic or semantic audio alert (table 4). The information-rich design of a semantic alert not only has significantly increased fixation numbers, but also increased fixation duration after an alert activates (figures 4a & 4b). Furthermore, it not only reduces the time to make a saccade, but it also speeds up the fixation shifts (figures 4c & 4d) compared with a simple acoustic design. These findings of saccadic activity of eye movement can further explain our previous findings of why semantic designed alerts significantly reduce ATCO’s response time to critical system alerts such as STCA, APW and MSAW (Kearney et al., 2016).

ATCOs tend to spend more time looking at interesting objects in the interface displays, as their fixations are roving over the critical visual stimuli on the screens. The length of fixation duration can reflect difficulty in extracting information, and the number of fixations indicates the importance of the areas of interest (Kotval & Goldberg, 1998). Also, the phenomenon of tunneled attention can be observed by the concurrence of an excessively long fixation duration dwelling on a specific area, reduced saccades, and decreased scanning frequency on the interfaces (Kowler, 2011). According to cognitive fit theory (Vessey, 1991), the most important factor in improving ATCO’s task performance is designing the semantic aural alert integrating visual representation which corresponds to the mental model of the ATCO. The initial auditory BEEP on semantic alert attracts air traffic controllers’ attention following by specific the nature of the alert i.e. Conflict, Airspace or Altitude. The ATCO will not be startled by the activation of the audio warning and no further cognitive load in evaluating the forthcoming threats is required. ATCO can immediately begin to develop conflict resolution strategies. Therefore, semantic design provides crucial extra time to support ATCO real-time decision-making to deploy the most appropriate response to specific critical event.

6. Future Application

Under high demand of monitoring, planning and controlling large numbers of aircraft, ATCOs not only have to communicate with pilots, but also have to deal with unexpected situations to maintain safe, orderly and expeditious flows of air traffic. The natural limitations of human cognitive processes and the vast number of parallel monitoring tasks are the reason for providing decision support tools in an ATM system, especially as air traffic continues to increase. HCI design should be able to provide an effective alert which facilitates the ATCO's attention being alerted without startle, and directed to the conflict being presented with coincident knowledge to support ATCO's decision-making to solve the conflict. The semantic alert demonstrated good matching between external events and ATCO's internal resources by facilitating cognitive processes to integrate auditory stimuli and directing visual attention, hence promoting effective ATCO's decision-making and speeding up ATCO response time to STCA. Automated aids are designed to improve ATCO's performance with more timely perception and precise comprehension of visual and auditory information. The findings could be applied to improve the alerting design of the COOPANS Air Traffic Management system, and in developing controllers' training syllabi to increase ATCO's situation awareness.

The design of decision support systems for use in dynamic environments must efficiently integrate with the characteristics of human cognitive processing. It is necessary to provide air traffic controllers with context-specified semantic stimuli which are appropriately salient and which provide specific information to reflect the nature of critical situations in order to minimize the side-effect of startle. The results of this research demonstrate that semantic alerts provide not only level-1 SA, detecting the conflict by increasing fixation numbers and fixation duration to STCA, but also promote level-2 SA in assisting ATCOs understanding of the nature of critical events denoted by quick saccade duration and saccade velocity developing quicker strategies for conflict resolution. Consequently, the design of a semantic alert can significantly reduce ATCOs' response time, therefore providing valuable extra time in a time-limited situation, to formulate and execute resolution strategies. The findings of this research indicate that the context-specified design of semantic alerts could improve ATCO's situational awareness and significantly reduce response time to perform conflict resolution. Resolving critical situations more effectively means that ATCOs can resume normal operations within the rest of the sector sooner minimizing the overall impact to other aircraft and the air traffic system generally. Civil Aviation Authorities, Air Navigation Service Providers and Air Traffic Management System Providers could all benefit from the findings of this research with a view to ensuring that Air Traffic Controllers are provided with the optimal context-specified alerting schemes to increase their situational awareness to handle unforeseen critical events.

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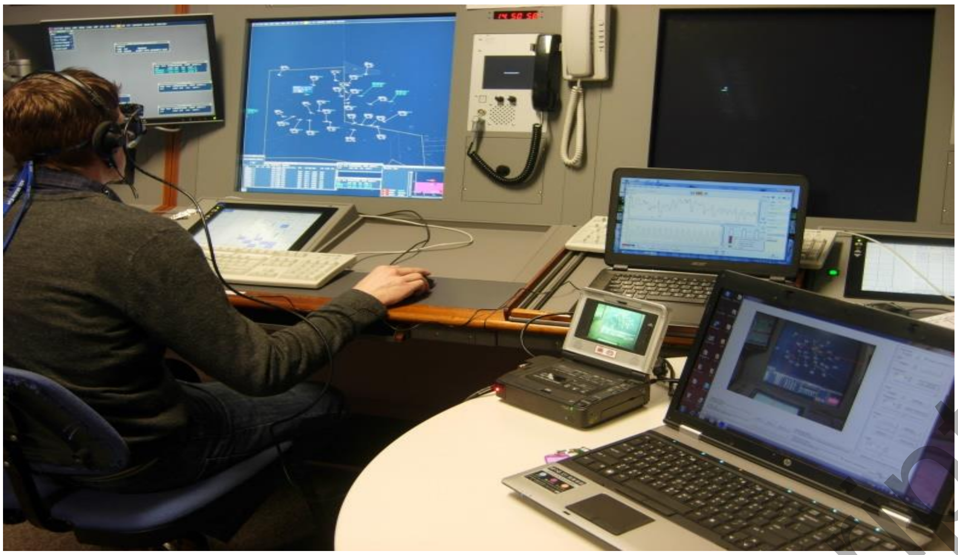
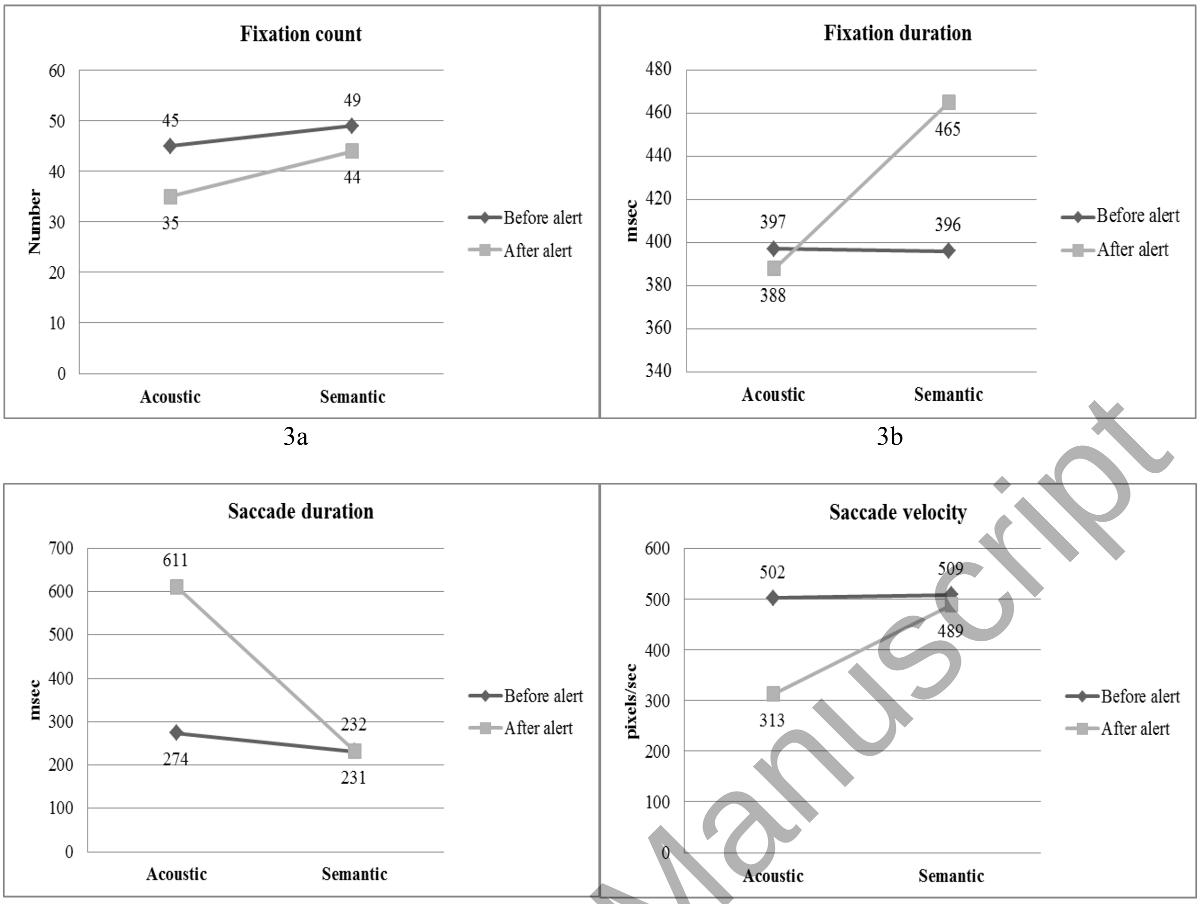


Figure 1. Participants conducted the trial by wearing an eye tracker whilst operating the COOPANS ATM trainer

2a 2b

Figure 2a. STCA alert is triggered (in red circle) by acoustic alert at 90 seconds before the conflict while ATCO's fixation on the red cross position; figure 2b shown the presentation of STCA on the COOPANS ATM System



3a 3b

3c 3d

Figure 3. ATCO’s eye movement patterns show significant interaction between alerting design (acoustic vs semantic) and alerting phases (before vs after) on (3a) fixation count; (3b) fixation duration; (3c) saccade duration and (3d) saccade velocity

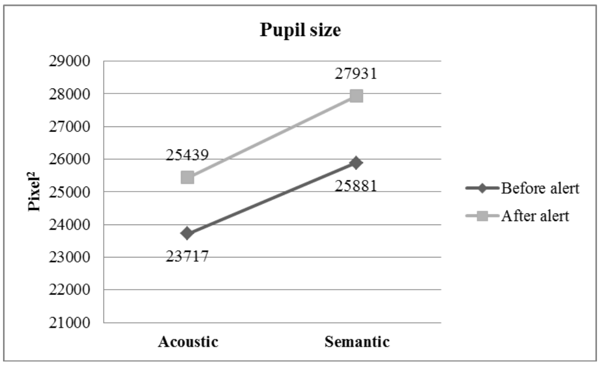


Figure 4. ATCO's pupil dilation shows no significant interaction between alerting design (acoustic vs semantic) and alerting phases (before vs after), however, it has significant difference between before alert and after alert.

Table 1. Participants' demographical variables for alerting designs (N=26)

Variables	Groups	Frequencies
Gender	Male	5 (19.2%)
	Female	21 (80.8%)
Age	25-30	7 (26.9%)
	31-35	5 (19.2%)
	36-40	8 (30.8%)
	41 and above	6 (23.1%)
Working Experience (years)	5 and less	11 (42.3%)
	6-10	7 (26.9%)
	11-15	4 (15.4%)
	16-20	1 (3.8%)
	21 and above	3 (11.5%)

Table 2. Summary of eye movement parameters main effects on alerting designs

Variables	Alerting Designs	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Fixation counts	Designs	561.80	1	561.80	31.35	**<.001**	0.193
	Errors	2353.20	24	98.05			
Fixation duration	Designs	17539.23	1	17539.23	0.883	.357	0.035
	Errors	476977.00	24	19874.04			
Saccade duration	Designs	546750.35	1	546750.35	4.973	**.035**	0.172
	Errors	2638566.42	24	109940.27			
Saccade velocity	Designs	102761.73	1	102761.73	1.676	.208	0.065
	Errors	1471880.75	24	61328.36			
Pupil dilation	Designs	66696483.83	1	66696483.83	0.585	.452	0.024
	Errors	2736000000.00	24	113996049.42			

Table 3. Summary of eye movement parameters main effects on alerting phases

Variables	Alerting Phases	*SS*	*df*	*MS*	*F*	*p*	η_p^2
Fixation counts	Phases	760.85	1	760.85	42.5	**<.001**	0.639
	Errors	430.08	24	17.92			
Fixation duration	Phases	10692.62	1	10692.62	2.6	.120	0.098
	Errors	98561.30	24	4106.72			
Saccade duration	Phases	352586.81	1	352586.81	12.515	**.002**	0.343
	Errors	676140.27	24	28172.51			
Saccade velocity	Phases	134435.23	1	134435.23	9.806	**.005**	0.290
	Errors	329028.33	24	13709.51			
Pupil dilation	Phases	43770578.50	1	43770578.50	14.280	**.001**	0.373
	Errors	73564523.42	24	3065188.48			

Table 4. Summary of interactions between alerting designs and alerting phases of eye movement parameters

Variables	Designs	Phases	*M*	*SD*	*df*	*F*	*p*	$\eta2\rho$
Fixations	Acoustic	Before	45.10	7.94	24	5.147	**.033**	0.177
		After	34.50	11.73				
	Semantic	Before	48.81	6.08				
		After	43.69	5.31				
Fixation duration (msec)	Acoustic	Before	397.27	93.41	24	4.623	**.042**	0.162
		After	387.63	174.99				
	Semantic	Before	395.85	81.46				
		After	464.65	90.13				
Saccade duration (msec)	Acoustic	Before	273.68	195.56	24	12.395	**.002**	0.341
		After	611.26	539.88				
	Semantic	Before	231.34	83.70				
		After	232.03	127.08				
Saccade velocity (pixels/sec)	Acoustic	Before	502.19	237.91	24	6.393	**.018**	0.21
		After	313.35	153.94				
	Semantic	Before	509.23	176.06				
		After	488.94	202.20				
Pupil dilation (pixel$^{2)}$	Acoustic	Before	23716.91	8512.55	24	0.108	.746	0.004
		After	25438.99	8426.45				
	Semantic	Before	25881.01	7444.76				
		After	27930.65	6767.00				