The Development of Eye Tracking in Aviation (ETA) Technique to Investigate Pilot's Cognitive Processes of Attention and Decision-making

*****Wen-Chin Li[1], John J. H. Lin[2], Graham Braithwaite[1] and Matt Greaves[1]

[1]Safety and Accident Investigation Center, Cranfield University, United Kingdom
[2] Institute of Education, National Chiao Tung University, Taiwan

Abstract. Eye tracking device had provided researchers a promising way to investigate what pilot's cognitive processes when they see information present on the flight deck. There are 35 participants consisted by pilots and avionics engineers participated in current research. The research apparatus include an eye tracker and a flight simulator divided by five AOIs for data collection. The research aims are to develop cost-efficiency of eye tracking technique in order to facilitate scientific research of cognition and decision-making in aviation. The results indicated that participants' eye movement patterns did have significant differences on the following variables including fixation count, $F_{(4,\ 136)}$ = 601.01, p < .001; average fixation duration, $F_{(4,\ 136)}$ = 100.87, p < .001; percentage of total fixations, $F_{(4,\ 136)}$ = 779.92, p < .001, and average pupil area, $F_{(4,\ 136)}$=2.51, p < .05. The findings demonstrated that eye tracker is a suitable tool to investigate pilots' cognitive process of attention and decision-making on flight deck. Furthermore, it can be applied to improve pilots' SA and decision-making during flight operations.

Keywords: Attention Distribution, Aviation Safety, Decision-making, Eye Movement Patterns, Flight Deck Design

Introduction

With the development of eye tracking technology, human factors experts could conduct the research of eye movements and attention distributions in aviation for pilot's situation awareness and decision-making processes on the flight deck. Eye-tracking is promising for research focused on internal process of pilots during flight operations. However, the complex nature of eye movement makes it difficult to directly derive conclusion via single statistical analysis. Eye tracking research provides scientific evidence on the underlying relationships between independent variables (such as flight experience or interface designs) and dependent variables (such as attention distributions or SA performance). In other words, eye-trackers offer not only what causes the situations, but also how the situations are triggered (Mayer, 2010). The application of eye-tracking in the study of flight simulation is promising as it provides direct feedback, which could diagnose potential factors that impact upon pilot attention and situation awareness on the flight deck (Robinski & Stein, 2013).

The application of autopilot can reduce pilot fatigue by maintaining a set course and steady, level flight for long periods of time without needing the human pilot to concentrate on this task (Harris, 2011). However, while the original aim of this was to reduce crew workload in terms of manually flying the aircraft, it shifted the pilot's role from hands-on flying to a systems managing role while the autopilot is in operation. Rather than reducing workload, this changed the workload; relieving the pilot of perceptual motor load ('doing') with an increase in cognitive workload ('thinking'). Humans are not ideally suited to monitoring roles.

Combined with inadequate feedback from automation systems, this creates a recipe for mode awareness to be reduced (Endsley, 1996).

Eye tracking methodology is based on eye-mind assumptions and immediacy assumptions. The immediacy assumption proposed the location of a fixation coincides with the cognitive processing of concurrent visual stimuli (e.g., texts or symbols) at that location. The eye-mind assumption indicated eye movement is correlated to concurrent perceptual and cognitive processes which coincides with the position fixated at the point in time, and this processing starts at the point of fixation and continues until all possible analyses were completed (Just & Carpenter, 1980). Furthermore, eye tracking studies focus on two aspects: "When" and "What" (Van Gompel, 2007). The temporal aspect of eye movement control (when) primarily concerns the question as to when a given saccade is executed or, more precisely, the time course of cognitive processing events and control decisions occurring during a fixation. In contrast, "What" concerns what information is extracted concurrently to guide the eyes. With the development of technologies, more research has adopted eye-tracking in various contexts, such as cognitive processes in reading (Rayner, 1998), learning (van Gog & Scheiter, 2010), problem solving (Hegarty & Just, 1993; Hegarty, Mayer, & Monk, 1995; Lin & Lin, 2014), information processing (Lu et al., 2011), and flight deck design (Li, Yu, Braithwaite, & Greaves, 2015). It provides researchers a promising way to study what people think when they see something, such as text or graphics (Renshaw, Finlay, Tyfa, & Ward, 2004). In current research, authors try to propose an approach that is applied to analyse eye movement data which is obtained from a typical flight-simulation based research. Such kind of data usually involves demographics, surveys, and eye movement measures (e.g., fixation counts, or gaze duration). To present this approach in a practical way, a worked example is used to demonstrate the procedure for analysing eye-tracking data in the field of flight simulation. To analysis eye-tracking based data with minimal bias, authors are developing an integrated procedure of ETA (Eye Tracking in Aviation). ETA approach can verify, reconstruct, and analyse eye-tracking data in aviation domain. The example presents an empirical research by using ETA to analyse eye movement data and derive research findings related to interface design, attention distributions, situation awareness, perceived workload and cognitive processes of decision-making in flight operations.

Method

2.1 Participants

There are 35 participants consisting of pilots and avionics engineers. As data were gathered from human participants a research proposal was approved by Cranfield University Research Ethics System (CURES) before conducting the experiment.

2.2 Apparatus

B747-400 Flight Simulator: The experiment was run on Cranfield University's high-fidelity B747-400 Flight Simulator. This simulator comprises a realistic mock-up of a cockpit of Boeing commercial aircraft with functioning flight controls, stick-shaker stall warning, and over-speed alerts (Figure 1a). Eye Tracking Device: Participant's eye movement patterns were recorded by using a mobile head-mounted eye tracker (ASL Series 4000) designed by Applied Science Laboratory. It is a light (76 g) and portable device allowing subjects to move their head without restriction during flight operations.

2.3 Research Design

All participants undertook the following procedures; (1) the participant completed the consent form including gender, working backgrounds, type ratings and total flight hours (3 minutes to complete); (2) a short briefing explained the purposes of the study and briefing the scenario of B-747 instrument landing (5 minutes); (3) the participant was seated at left seat in the simulator and conducting the eye tracker calibration (5-10 minutes); (4) the participant performed the landing task (6 minutes). The eye tracker recorded both the scene video and corresponding eye movement data during the flight operations. The eye movement data in five areas of interest (AOIs) were recorded as follows: AOI-1, Primary Flight Display (PFD); AOI-2, Navigation Display (ND); AOI-3, Engine-Indicating and Crew-Alerting System (EICAS); AOI-4, Mode Control Panel (MCP); and AOI-5, Outside of Cockpit (OC) (Figure 1b).

Figure 1(a) Figure 1(b)

Figure 1(a): Research apparatus including eye tracker and Boeing 747 flight simulator; Figure 1(b): The definition of AOIs: AOI-1(Primary Flight Display); AOI-2 (Navigation Display); AOI-3 (Engine Indication and Crew Alerting System); AOI-4 (Mode Control Panel), and AOI-5 (Outside of Cockpit).

2.4 Approach of Eye Movement Data Analysis

To illustrate the approach of ETA, there are four steps of data analysis involved in the current research. Step-1: select proper eye movement measures, including descriptive statistics, means, standard deviations, extreme values of data, and plots for visual inspecting of distributions. Step-2: reduce number of eye movement measures, including remove items that have significantly high correlation coefficients. Step-3: conduct repeated measure ANOVAs for AOIs to examine whether eye movement are different among five AOIs. Step-4: examine connections between variables of eye movement and cognitive processes for performing the flight simulation.

Results and Discussions

3.1 Select proper eye movement variables

The eye movement information captured by eye trackers can be analyzed to investigate pilots‘ attention shifts, situation awareness and decision-making while performing tasks (Ahlstrom & Friedman-Berg, 2006). Eye scan pattern is one of the methods for assessing a pilot’s cognitive process in the cockpit based on physiological measures (Ayaz et al., 2010). It can provide numerous clues concerning the mental process of encoding information perceived by pilots, such as what instruments they scan, fixate and attend (Salvucci & Anderson, 1998). The manufactory of eye trackers provided a variety of eye movement variables at a set of AOIs by the specific software integrated with hardware. In current research, seventeen eye movement variables were generated by the software (Table 1). To simplify the process of analysis, by using EYE-id in representation 17 variables of eye movement data, for example, EYE-1 refers to the “number of fixations before first arrival” accordingly. Descriptive statistics, including means, standard deviations, extreme values of data, and plots for visual inspecting of distributions. The figure 2(a) is the plot of average fixation duration of AOI 1 for all participants. It is clear that data is normal distribution. By contrast, f**Error! Reference source not found.** demonstrated fixation number significantly skewed on the AOI-1 and AOI-5. Therefore, the eye movement measure should be used with caution to prevent bias. Due to skewed and standard deviation not fit estimating population mean, EYE-7 and EYE-14 will be excluded from subsequent analysis.

Table 1. Description of eye movement measurement used in current research

1.	Number of fixations before first arrival	10.	Total fixation duration
2.	Duration before first fixation arrival (seconds)	11.	Average fixation duration
3.	Total time in zone (seconds)	12.	Std dev fixation duration
4.	Percentage of total fixations before first arrival	13.	Average pupil area in fixations
5.	Percent Total time in zone (seconds)	14.	Pupil area std deviation in fixations
6.	Average pupil area	15.	Gazepoint count
7.	Pupil std deviation	16.	Gazepoint count / Total time in zone
8.	Fixation count	17.	Gazepoint count / Total fixation duration in zone
9.	Percentage of total fixations		

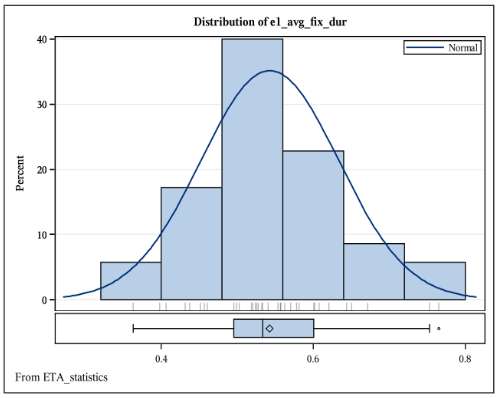

Figure 2(a)

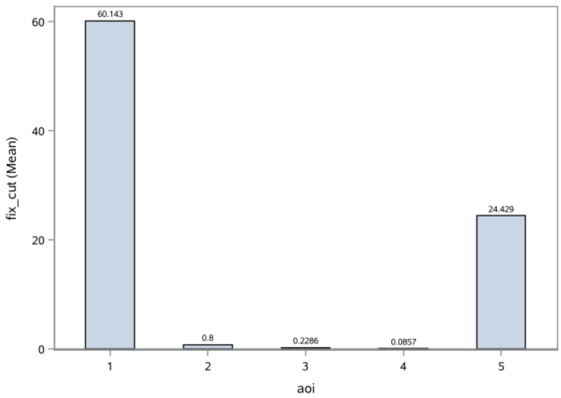

Figure 2(b)

Figure 2(a): demonstrated average fixation duration of AOI-1 on the normal distribution; Figure 2(b): demonstrated fixation number significantly skewed on the AOI-1 and AOI-5.

3.2 Refine eye movement variables

By utilizing the combination of an eye-tracking device and a flight simulator, pilots' eye movement variables information including cognitive processes of attention distribution, SA performance and perceived workload could be collected for further analysis, and the results could serve as a feedback loop for improving interface design in the future. There are lots of eye movement variables, and not all of these eye movement variables have significantly related to cognitive processes. Therefore, it is necessary to refine eye movement variables. The correlation coefficients among eye movement variables for all AOIs present various meanings, however some measurements might be more relevant than others. Moreover, these measurements were generated from fundamental fixation and saccade. In other words, some of these measurements might be highly correlated. It is suggested that eye movement research with high correlation can be excluded from subsequent analysis. To achieve this goal, The ETA approach generates correlation coefficients, as well as significant levels. It is beneficial to remove items that have significantly high correlation coefficients. The threshold is 0.90 in current research. In other word, eye movement measures with correlation higher than 0.90 in all AOIs will be excluded. Researchers could adjust the threshold based on the context of experiments. Table 2 shows correlation coefficients which are higher than 0.90 with respect to each AOI. As mentioned in the previous section, correlation among fixation-based measures are usually high. It is clear that EYE-3 and EYE-5 are highly correlated, and the pattern is consistent across five AOIs in this study. Likewise, EYE5 and EYE12 are highly correlated as well. Therefore, EYE-3 (Total time in zone) and EYE-12 (gaze count) will be excluded from subsequent analysis. In other words, twelve eye movement measures were used for further analyses (i.e., repeated measure ANOVA and linear regression analysis). By eliminating the number of eye movement measures, researchers could focus on analysing distinctive eye movement measures.

Table 2. Correlation coefficients among eye movement measurements

	AOI-1	AOI-2	AOI-3	AOI-4	AOI-5
EYE1 and EYE4	.92	.96	.97		.93
EYE3 and EYE5	.97	.99	.99	.96	.99
EYE3 and EYE9	.95	.94			
EYE3 and EYE12	.99	.99	.98		.93
EYE5 and EYE9	.94	.95			
EYE5 and EYE12	.96	.99	.98	.95	.91
EYE9 and EYE12	.94	.92			
EYE7 and EYE8		.99	.99	.99	.95
EYE7 and EYE12		.91			
EYE8 and EYE12		.91			
EYE7 and EYE9			.96	.99	
EYE7 and EYE10			.94	.97	
EYE8 and EYE9			.95	.99	
EYE8 and EYE10			.91	.98	
EYE9 and EYE10			.94		
EYE4 and EYE10				.91	
EYE4 and EYE14				.99	
EYE6 and EYE11					.95

3.3 Conduct repeated measure for defined AOIs

Eye movement measurement offers deep insights into human-machine interaction and the mental processes of pilots. Measurements based on different aspects of ocular behavior, such as the number of fixations, dwell time, and the dilation of pupil, have been used to reveal the status of mental workload. There is evidence that increases in workload could increase both dwell time and the frequency of long fixations (Van Orden, Limbert, Makeig, & Jung, 2001). The eye movement variables have to be analysed on defined AOIs including PFD, ND, EICAS, MCP and OC in flight simulator. In this regards, a series of repeated measure ANOVA were conducted to examine whether eye movement variables are different among five AOIs. Repeated measure ANOVA could help to evaluate whether pilots uniformly distribute attention on specific AOIs. The results could be used to identify which AOIs draw pilots' attention. Results indicated that for all selected eye movement measures, difference among the five AOIs are significant. Table 3 showed F values, degree of freedom, and significant levels for eye movement variables including fixation numbers, fixation duration, percentage of fixation, pupil dilation. Pilots' did pay different attention on different AOIs for different flight tasks.

Table 3. F values, degree of freedom, and significant levels for each eye movement measure

Id	Eye Movement Variables in an AOI	Statistics
1	Number of fixations before first arrival	$F(4, 136) = 006.76$, $p < .001$
2	Duration before first fixation arrival (seconds)	$F(4, 136) = 112.74$, $p < .001$
~~3~~	~~Total time in zone (seconds)~~	
4	Percentage of total fixations before first arrival	$F(4, 136) = 014.35$, $p < .001$
5	Percent Total time in zone (seconds)	$F(4, 136) = 560.62$, $p < .001$
6	Average pupil area	$F(4, 136) = 002.51$, $p < .05$
7	Fixation count	$F(4, 136) = 601.01$, $p < .001$
8	Percentage of total fixations	$F(4, 136) = 779.92$, $p < .001$
9	Total fixation duration (seconds)	$F(4, 136)= 528.01$, $p < .001$
10	Average fixation duration (seconds)	$F(4, 136) = 100.87$, $p < .001$
11	Average pupil area in fixations	$F(4, 136) = 015.39$, $p < .001$
~~12~~	~~Gazepoint count (Sampling count)~~	
13	Gazepoint count / Total time in zone	$F(4, 136) = 010.13$, $p < .001$
14	Gazepoint count / Total fixation duration in zone	$F(4, 136) = 046.55$, $p < .001$

3.4 Establish relationships between eye movement and internal information processes

The preliminary results of eye movement data indicated that pilots inclined to focus on specific areas of interests such as PFD or outside of cockpit, it is worthy to verify whether pilots' eye movement patterns reflect to internal process (e.g., executing cognitive function or mental workload). There is a raising need to investigate whether pilots' eye movement variables parallel to pilots' attention distribution, situation awareness and decision-making eventually. Therefore, Regression Analysis was conducted to test whether the flight experience, performance, and NASA-TLX score have influence on selected eye indicators of crucial AOIs. Based on descriptive statistics, it is observed that participants focused on AOI-1 and AOI-5. Therefore, we conducted a regression of those four crucial factors on each selected eye indicators of AOI-1 and AOI-5.

Multiple regression is used to evaluate whether a set of factors could influence the response. Typically, the scale of factors and response are interval. In this research, multiple regression were conducted to determine whether mental demand, main flight hours, and instructor score have influence on total time in zone of AOI-1. Mental demand, main flight hours, and instructor score are commonly targets of flight-simulation based research. Research suggested that this combination of factors were unable to significantly predict total time in zone of AOI-1, $F(3, 31) = 1.00$, $p > .05$. Suppose the overall testing is significant, the author could further conduct post-hoc analysis to evaluate the influence of each factor. Example of statistical analysis, including the beta weights were presented in Table 4. The adjusted R squared value was almost zero, indicating percentage of total time in zone of AOI-

1 was unable explained by the dependent variables. Table 5 presents the corresponding coefficient and standardized coefficient for the regression analysis.

Table 4. Regression analysis of total time in zone (percentage)

Source of variance	DF	Sum of Squares	Mean Square	F	*p*	Adjusted R^2
Model	03	3236.01	1078.61	1.00	0.40	0.0002
Error	31	33359.00	1076.59			
Corrected Total	34	36595.00				

Table 5. Coefficient for regression analysis of total time in zone (percentage)

Variable	DF	Parameter	SE	t	*p*	Standardized Parameter
Intercept	1	114.94025	32.12986	3.58	0.0012	0
Main flight hours	1	-0.01540	0.01011	-1.52	0.1376	-0.26949
Mental demand	1	0.42888	0.45633	0.94	0.3546	0.16653
Instructor hours	1	0.00265	0.30855	0.01	0.9932	0.00155

Conclusion

Eye movement information can serve as a direct index of attention allocation (Wickens, Goh, Helleberg, Horrey, & Talleur, 2003), therefore, tracking eye movements are promising for aviation human factors experts to get insight into pilots' internal processes, for instance situation awareness (Foyle & Hooey, 2007), or difference between novice and experienced pilots (Bellenkes, Wickens, & Kramer, 1997). However, there are several issues required to be addressed not only to reduce bias of eye movements, but also methodologically help to acquire robust eye movement data. First, eye trackers employed PCCR or ICCR to obtain coordinates of fixation point, therefore reflection of illumination on the glasses could be recognized as a reflection of cornea, which could lead to considerable missing data or incapable of collecting eye movements. The adjustment of illumination on the flight deck in simulator could potentially reduce this interference. Second, the accuracy of eye trackers need to be taken into account while setting areas of interest (AOI), as imprecise fixation points have impact on calculating eye movement measure (e.g., total fixation duration) of AOI. Especially the distances between pilots and the different displays (instruments on flight deck or head-up display) are varied on difference surfaces which would induce errors on the processes of data collection. Third, sampling rates serve as an index of spatial resolution. High sampling rates facilitate sophisticate observation on saccades, which represent how pilots shift attention in a specific context. Therefore, an eye tracker with adequate sampling rate has to be selected so as to meet the requirement of research. Fourth, although head-mounted/mobile eye trackers have advantages that they are suitable for contexts in which individuals have frequent physical activities (e.g., monitoring interface displays on the flight deck), it could also generate eye movement with dynamic AOIs, which is challenging for quantitative analysis. Researchers might have to familiar using software at handling dynamic

AOIs for data analysis (Papenmeier & Huff, 2010). Fifth, finding eye movement indicators with high reliability and validity is of great importance in eye-movement based research. To achieve these goals, the relations between eye movement indicators and individuals' internal processes should be focused. Defining fundamental parameters, such as the minimal fixation duration (Mumaw et al., 2000), which represents time required to extract information from visual stimuli, is promising for methodical development of pilot's SA and in-flight decision-making. It is to promote aviation human factors research by effectively scientific approach. It will be expected that the developed ETA technique can facilitate aviation human factors researchers obtaining accurate information regarding pilots' attention distribution, SA, processes of decision-making, interface design of flight deck, pilots perceived workload and performance in flight operations.

References

Ahlstrom, U., & Friedman-Berg, F. J. (2006). Using eye movement activity as a correlate of cognitive workload. *International Journal of Industrial Ergonomics, 36*(7), 623-636. doi:10.1016/j.ergon.2006.04.002

Ayaz, H., Willems, B., Bunce, B., Shewokis, P. A., Izzetoglu, K., Hah, S., . . . Onaral, B. (2010). Cognitive workload assessment of air traffic controllers using optical brain imaging sensors. *Advances in understanding human performance: Neuroergonomics, human factors design, and special populations*, 21-31.

Bellenkes, A. H., Wickens, C. D., & Kramer, A. F. (1997). Visual scanning and pilot expertise: The role of attentional flexibility and mental model development. *Aviation Space and Environmental Medicine, 68*(7), 569-579. Retrieved from <Go to ISI>://WOS:A1997XG51100002

Endsley, M. R. (1996). Automation and situation awareness. *Automation and human performance: Theory and applications*, 163-181.

Foyle, D. C., & Hooey, B. L. (2007). *Human performance modeling in aviation*: CRC Press.

Harris, D. (2011). *Human performance on the flight deck*: Ashgate Publishing, Ltd.

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of memory and language, 32*(6), 717-742. doi:10.1006/jmla.1993.1036

Hegarty, M., Mayer, R. E., & Monk, C. A. (1995). Comprehension of arithmetic word problems: A comparison of successful and unsuccessful problem solvers. *Journal of Educational Psychology, 87*(1), 18-32. doi:10.1037/0022-0663.87.1.18

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixation to comprehension. *Psychological review, 87*(4), 329-354. doi:10.1037/0033-295X.87.4.329

Li, W.-C., Yu, C.-S., Braithwaite, G., & Greaves. (2015). The analysis of pilots fixation distribution for performing air-to-air and air-to-surface tasks *Contemporary Ergonomics and Human Factors 2015* (pp. 466-473): Taylor & Francis.

Lin, J. J. H., & Lin, S. S. J. (2014). Tracking eye movements when solving geometry problems with handwriting devices. *Journal of Eye Movement Research, 7*(1), 1-15.

Lu, W., Li, M., Lu, S., Song, Y., Yin, J., & Zhong, N. (2011). Visual Search Strategy and

Information Processing Mode: An Eye-Tracking Study on Web Pages under Information Overload. In L. Qi (Ed.), *Information and Automation* (Vol. 86, pp. 153-159).

Mayer, R. E. (2010). Unique contributions of eye-tracking research to the study of learning with graphics. *Learning and Instruction, 20*(2), 167-171. doi:10.1016/j.learninstruc.2009.02.012

Mumaw, R., Sarter, N., Wickens, C., Kimball, S., Nikolic, M., Marsh, R., . . . Xu, X. (2000). *Analysis of pilots' monitoring and performance on highly automated flight decks*. Retrieved from Seattle, WA:

Papenmeier, F., & Huff, M. (2010). DynAOI: A tool for matching eye-movement data with dynamic areas of interest in animations and movies. *Behavior Research Methods, 42*(1), 179-187. doi:10.3758/brm.42.1.179

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*(3), 372-422. doi:10.1037/0033-2909.124.3.372

Renshaw, J. A., Finlay, J. E., Tyfa, D., & Ward, R. D. (2004). Understanding visual influence in graph design through temporal and spatial eye movement characteristics. *Interacting with computers, 16*(3), 557-578. doi:10.1016/j.intcom.2004.03.001

Robinski, M., & Stein, M. (2013). Tracking visual scanning techniques in training simulation for helicopter landing. *Journal of Eye Movement Research, 6*(2), 1-17.

Salvucci, D. D., & Anderson, J. R. (1998). Tracing eye movement protocols with cognitive process models.

van Gog, T., & Scheiter, K. (2010). Eye tracking as a tool to study and enhance multimedia learning. *Learning and Instruction, 20*(2), 95-99. doi:10.1016/j.learninstruc.2009.02.009

Van Gompel, R. (2007). *Eye movements: A window on mind and brain*: Elsevier Science Ltd.

Van Orden, K. F., Limbert, W., Makeig, S., & Jung, T. P. (2001). Eye activity correlates of workload during a visuospatial memory task. *Human Factors, 43*(1), 111-121. doi:10.1518/001872001775992570

Wickens, C. D., Goh, J., Helleberg, J., Horrey, W. J., & Talleur, D. A. (2003). Attentional models of multitask pilot performance using advanced display technology. *Human Factors, 45*(3), 360-380. doi:10.1518/hfes.45.3.360.27250

Contact Information

Corresponding author:

Wen-Chin Li PhD C.ErgHF

Senior Lecturer, Safety and Accident Investigation Centre
Martell House, Cranfield University, Bedfordshire, MK43 0TR
United Kingdom
E-Mail: wenchin.li@cranfield.ac.uk
Website: www.cranfield.ac.uk
Tel: +44 (0)1234 758527