The Investigation of Pilots' Eye Scan Patterns on the Flight Deck during an Air-to-Surface Task

Wen-Chin Li[1,*], Graham Braithwaite[1], and Chung-San Yu[2]

[1] Safety and Accident Investigation Centre, Cranfield University, Martell House, University Way, Cranfield, Bedfordshire, MK43 0TR, United Kingdom
[2] Department of Industrial Engineering and Engineering Management, National Tsing Hua University, R.O.C.
wenchin.li@cranfield.ac.uk

Abstract. Twenty qualified mission-ready F-16 pilots participated in this research. The ages of participants are between 26 and 46 years old (M=33, SD=6); total flying hours between 400 and 3,250 hours (M=1358, SD=882); F-16 type flying hours between 101 and 2,270 hours (M=934, SD=689). Eye movement data were collected by a head-mounted ASL (Applied Science Laboratory) Mobile Eye which was 76 grams in weight, combined with F-16 flight simulator, a dynamic high fidelity trainer that replicates actual aircraft performance, navigation and weapon systems. The scenario is an air-to-surface task. Participants have to intercept the proper route and turn toward the target at an altitude of 500 feet with speed of 500-KIAS, then performing a steep pop-up manoeuver to increase altitude abruptly for appropriate reconnaissance, following by dive and roll-in toward the target to avoid hostile radar lock-on. When approaching the target, subjects have to roll-out, level the aircraft, aiming at the target, release the weapon, and finally pull-up with a 5～5.5 G-force to breakaway from the range. The results show significant differences in pilots' number of gaze points among five different AOIs, $F(4, 95) = 533.84$, $p<.001$, $\eta 2\rho = .97$. Further comparisons using post-hoc Bonferroni adjusted tests showed HUD has a significantly higher numbers of gaze points than ICP, DED, RMFD and LMFD; and ICP has significantly higher gaze points than DED, RMFD and LMFD. Also, there were significant differences in pilots' number of fixation among five different AOIs, $F(4, 95) = 306.98$, $p<.001$, $\eta 2\rho = .94$. Further comparisons using post-hoc Bonferroni adjusted tests showed HUD has significantly higher number of fixation than ICP, DED, RMFD and LMFD; and ICP has significantly higher number of fixations than DED, RMFD and LMFD. Pilots have to be able to 'see and process' the information to understand the situation, and then, to 'project' the situation in the near future. There is a long-standing argument concerning bottom-up or top-down visual processes in the eye movement literature. It is observed in this research that pilots applied both bottom-up and top-down visual processes, depending on the salience of information or previous experience.

Keywords: Aviation Safety, Eye Movement, Cognitive Processes, Fixation.

[*] Corresponding author.

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1 Introduction

Eye scan pattern is one of the methods for assessing a pilot's cognitive process in the cockpit based on physiological measures (Ayazet al, 2010). It can provide numerous clues concerning the mental process of encoding information perceived by pilots by using in-flight visual behaviors, such as what areas of interest (AOIs) they scan, dwell and attend (Salvucci and Anderson, 1998). Eye movement can be measured continuously and objectively as these are able be recorded without interrupting pilot's activities. The visual information captured by eye tracking tools provides for the possibility of eye movement fluctuations while operating the task in hand occurring over short time intervals (Ahlstrom and Friedman-Berg, 2006). One more advantage is that eye movements are a sensitive and automatic response which may serve as a window into the process of the SA mechanism and reflection the mental state of a pilot (Kuo, Hsu and Day, 2009). For example, gaze trajectories can indicate pilot's attention distribution when he or she encounters certain displays of the cockpit interface or outside, such as terrain and direct fixation on specific AOIs in real time (Henderson, 2003; Pomplun and Sunkara, 2003). However, eye tracking technologies still have their limitations. For instance, the point the pilot fixated upon is not definitely where the attention was accurately located, which is known as "look but didn't see" (Shinar, 2008). SA has been recognized an essential component within a pilot's cognitive process in the domain of aviation (Sohn and Doane, 2004). Endsley (1995) defines three levels of SA which is linked closely with the major components within cognitive processes. The first level is to perceive environmental cues, such as warning lights in the cockpit. The second level is a process of comprehending the cues based on knowledge and experience. The third level is to predict the possible situation in the near future and project the related measurements to resolve the specific status.

There were considerable arguments regarding gaze control theories for decades: bottom-up and top-down visual processes (Henderson, 2003). There is an increasing need for further investigation of the relationship between gaze control and SA performance. The bottom-up visual process is stimulus-based and generated from the saliency of environment. It can be explained by level one of SA: perception of the cues; on the other side, the top-down approach is a knowledge-based theory that directs by internal cognitive process. The gazes are controlled to see a specific AOI to acquire the information to satisfy the task in hand. It complied with the three levels of situational awareness theory proposed by Endsely (1995). Pilot has to perceive the stimulus in the cockpit, understand the encountering situation, and predict the possible consequences. These visual searching within a flight deck are critical for collecting information, and over 75% of pilot errors are caused by perceptual failures (Jones and Endsley, 1996). It highlights the importance of the study concerning gaze control and SA performance. However, the empirical study of gaze control in aviation is relatively scarce compared with other eye movement behaviors such as fixation or saccade, not to mention the research of gaze control and three-level of SA. The visual behaviour directing gaze points to a specific AOI is attracted by the salient stimulus or controlled by a pilot's intention. Previous researches (Bellenkes, Wickens and Kramer, 1997; Ratwani, McCurry and Trafton, 2010) emphasize on how much fixation or how long the duration on an AOI is held approximately stable on the fovea of the retina to identify whether pilot's visual behaviour is meaningful.

Pilots need to allocate attention to the interior and exterior of the cockpit to collect information and make decisions (Janis et al., 1996). However, pilots make more errors under stress such that attention tends to be focused on central information to the neglect of peripheral cues, resulting in tunnel vision (Orasanu, 2005). It was found that peripheral vision is useful for detecting objects, especially essential for detecting moving objects outside the fovea (Yang, 2012). Moreover, pilots with different levels of flying experience show various patterns of the usage of peripheral vision. More experienced pilots are more likely than the less experienced to use peripheral vision to process a wider field of visual cues, allowing experienced pilots to perform the main task while still obtaining the needed information (Kasarskis et al., 2001). Therefore, from an information processing perspective, the capability of peripheral vision is associated closely with cue acquisition and cue interpretation, which can be an index to evaluate pilot's SA performance that enables task-related information to be engaged and the problem to be resolved (Wiggins, 2006). Recognizably, peripheral vision is also linked closely with the bottom-up visual process, but it is impacted by the initial fixation location becoming longer and less gaze moving around the operational environment (Jungkunz and Darken, 2011). Also, pupil size is significantly influenced by the factor of task difficulty, and it is relevant to the operator's cognition loading. However, it is very complicated to interpret due to the influence from multiple factors such as cognitive workload, context complexity, environmental illumination and gaze angle (Pomplun and Sunkara, 2003; Gabay, Pertzov and Henik, 2011).

By utilizing a combination of an eye tracking device and flight simulator, pupil size can be collected for further analysis of pilots' cognitive processes in terms of attention allocation and SA performance at certain phase of flight operations, and this can be correlated with training and evaluation in aviation. This study combines an F-16 flight simulator and portable eye tracking device to investigate pilots' visual scan pattern and SA performance during an air-to-surface mission If the relationship of gaze points, fixation, pupil size and perceived workload related to SA performance could be identified in flight operations, then eye tracking tools could be considered for use in combination with flight simulators to improve training efficiency in the future.

2 Method

2.1 Subjects

There are 20 participants of F-16 pilots. The ages of participants are between 26 and 46 years old, and the total flying hours are between 400 and 3,250 hours.

2.2 Apparatus

Flight Simulator. The F-16 flight simulator is high-fidelity training device. It utilizes an actual cockpit with identical display panels, layout and controls to those in the actual aircraft. This simulator provides a realistic representation of the flight management systems. The instructors can observe the pilot's performance via three screens without any intrusion. The scenario is designed to replicate an air-to-surface task. It is a challenging situation for subjects to perform as it represents a high demand flying task combined with hostile threats. Subjects not only have to execute the task precisely by operating the aircraft, but also have to follow navigation system entering the appropriate codes by using various flight deck interfaces. Simultaneously, subjects have to intercept the proper route and turn toward the target at an altitude of 500 feet with speed of 500-KIAS (Knots Indicated Air Speed), then performing a steep pop-up maneuver to increase altitude abruptly for appropriate reconnaissance, following by dive and roll-in toward the target to avoid hostile radar lock-on. When approaching the target, subjects have to roll-out, level the aircraft, aim at the target, release the weapon, and finally pull-up with a 5～5.5 G-force to break-away from the range.

Eye Tracking Device. Pilot's eye movements were recorded using a mobile head-mounted eye tracker (ASL Series 4000) which is designed and built by Applied Science Laboratory. It is light (76 g) and portable meaning it is easy for subjects to move their head without any limitations during the air-to-surface maneuvers. Video records the pattern of eye movements and the related data were collected and stored using a Digital Video Cassette Recorder (DVCR) and then transferred to a computer for further processing and analysis. The sampling frequency for eye movements was 30 Hz. The definition of an eye fixation point was when three gaze points occurred within an area of 10 by 10 pixels with a dwell time which was the time spent per glance at a location. There were five AOIs set up to collect subjects' eye movement data. Those AOIs were selected for performing the task of air-to-surface. AOI-1: Head-up Display (HUD); AOI-2: Integrated Control Panel (ICP); AOI-3: Data Entry Display (DED); AOI-4: Right Multiple Function Display (RMFD); and AOI-5: Left Multiple Function Display (LMFD).

2.3 Research Design

All subjects undertook the following procedures, (1) completed the demographical data including training experience and total flight hours (5 minutes); (2) a briefing of the study and the air-to-surface scenario (10 minutes); (3) calibration of the eye tracking device by using three points distributed over the cockpit display panels and screen (10-15 minutes); (4) participants performed the air-to-surface task (3-5 minutes).

3 Results

Twenty qualified mission-ready F-16 pilots participated in this research. The ages of participants are between 26 and 46 years old (M=33, SD=6); total flying hours between 400 and 3,250 hours (M=1358, SD=882); F-16 type flying hours between 101 and 2,270 hours (M=934, SD=689). Subjects' eye movement data described by number of fixation and number of gaze points are shown as table 1; subjects' average fixation duration and pupil diameters in five AOIs are shown as table 2.

There were significant differences in the pilots' number of gaze points among five different AOIs, F (4, 95) = 533.84, p<.001, η2ρ = .97. Further comparisons using post-hoc Bonferroni adjusted tests showed HUD has a significantly higher numbers of gaze points than ICP, DED, RMFD and LMFD; and ICP has significantly higher gaze points than DED, RMFD and LMFD. Also, there were significant differences in pilots' number of fixation among five different AOIs, F (4, 95) = 306.98, p<.001, η2ρ =.94. Further comparisons using post-hoc Bonferroni adjusted tests showed HUD has significantly higher number of fixation than ICP, DED, RMFD and LMFD; and ICP has significantly higher number of fixations than DED, RMFD and LMFD (table 1).

Table 1. Subjects' Eye Movement data for Number of Fixation and Gaze Points

Subject	Age	Total hours	Number of Gaze Points					Number of Fixations				
			HUD	ICP	DED	RMFD	LMFD	HUD	ICP	DED	RMFD	LMFD
1	27	550	2778	52	0	5	3	386	4	0	0	0
2	30	630	2307	420	20	28	5	297	27	2	3	0
3	41	2186	2187	67	4	4	5	321	6	0	0	0
4	26	400	2350	109	9	0	0	256	11	0	0	0
5	30	550	3044	191	71	2	0	457	24	11	0	0
6	28	620	2775	156	10	1	17	393	13	0	0	2
7	28	630	3432	76	69	3	1	456	10	12	0	0
8	35	1300	2833	117	1	51	0	447	7	0	4	0
9	35	1500	2339	99	1	0	4	312	12	0	0	0
10	42	3250	2925	60	16	37	1	421	5	1	6	0
11	28	582	2879	47	16	10	1	427	3	2	2	0
12	31	1000	1726	158	32	2	0	196	21	2	0	0
13	31	1032	2390	105	1	6	0	339	11	0	0	0
14	37	1650	1948	262	0	24	12	227	28	0	3	2
15	41	1900	3560	104	7	0	20	531	13	0	0	3
16	27	600	2563	55	4	16	0	297	3	0	2	0
17	37	1500	2925	16	13	57	0	427	1	2	8	0
18	34	1458	2086	24	1	0	0	296	1	0	0	0
19	46	2800	2155	119	102	6	7	269	8	9	0	0
20	41	3030	2365	70	0	3	0	330	3	0	0	0
M	33.75	1358.4	2578.35	115.35	18.85	12.75	3.80	354.25	10.55	2.05	1.40	0.35
SD	6.04	882.94	478.28	92.80	28.53	17.51	5.94	88.89	8.42	3.83	2.33	0.88

HUD: Head-up Display; ICP: Integrated Control Panel; DED: Data Entering Display; RMFD: Right Multiple Function Display; LMFD: Left Multiple Function Display

There were significant differences in pilots' average fixation among five different AOIs, F (4, 95) = 21.04, p<.001, η2ρ = .53. Further comparisons using post-hoc Bonferroni adjusted tests showed HUD has a significantly higher numbers of gaze points than DED, RMFD and LMFD; and ICP has significantly higher gaze points than DED, RMFD and LMFD. Also, there were significant differences in pilots' pupil diameter among five different AOIs, F (4, 95) =10.42, p<.001, η2ρ = .35. Further comparisons using post-hoc Bonferroni adjusted tests showed HUD has a significantly larger pupil diameter than DED and LMFD; and ICP has significantly larger pupil diameter than DED and LMFD (table 2).

Table 2. Performance, Workload and Average of Fixation Duration and Pupil Diameter

Subjects	Average Fixation Duration (ms)					Average Pupil Diameter in Region(pixel)				
	HUD	ICP	DED	RMFD	LMFD	HUD	ICP	DED	RMFD	LMFD
1	140	150	0	0	0	88.34	86.75	0	84.76	87.41
2	140	120	130	130	0	79.02	71.76	70.28	73	0
3	140	130	0	0	0	89.35	91.61	87.06	80.79	87.99
4	130	130	0	0	0	91.86	89.81	65.49	0	0
5	160	140	150	0	0	81.47	82.65	74.83	85.53	0
6	150	140	0	0	180	95.5	99.05	66.72	0	98.02
7	140	150	150	0	0	81.58	84.3	84.65	0	0
8	140	140	0	180	0	65.26	64.91	67.54	70.77	0
9	130	140	0	0	0	71.71	73.21	0	0	74.75
10	140	150	130	140	0	111.47	111.62	104.82	106.12	0
11	150	130	170	100	0	82.46	83.4	76.04	75.1	0
12	140	140	150	0	0	104.98	104.13	100.37	101.81	0
13	150	130	0	0	0	86.8	87.96	0	82.14	0
14	130	140	0	140	130	105.34	102.7	0	104.02	110.09
15	150	150	0	0	180	74.95	76.09	78.12	0	74.98
16	130	110	0	130	0	100.52	102.63	104.03	96.02	0
17	140	170	130	140	0	76.72	78.45	73.8	77.95	0
18	140	170	0	0	0	73.59	74.04	0	0	0
19	130	130	120	0	0	71.49	76.77	69.31	72.85	74.95
20	140	130	0	0	0	88.28	87.48	0	87.02	0
M	140.50	139.50	56.50	48.00	24.50	86.03	86.47	56.15	59.89	30.41
SD	8.26	14.68	71.69	68.41	60.57	12.67	12.51	39.43	41.44	43.19

4 Discussion

There are an average 2,578 number of gaze points on the HUD, however, there are only 354 fixations recorded by the eye tracking device (table 1). The setting of fixation in this study is that three gaze points occurred within an area of 10 by 10 pixels with the time spent per glance at allocation. The gaze control is the process of directing fixation through area of interests in the service of on-going perceptual, cognitive and behavior activities which are important for pilots to seek task relevant information. Fixation point is meaningful and is closely linked to attention allocation, however, gaze point is the foundation of fixation and it triggers pilots shifting attention to different AOIs in order to perform multiple tasks simultaneously, such as searching for target, keying data, analyzing information, and operating the aircraft to complete the mission. There is a close relationship between peripheral vision and gaze points to be observed. While pilots rapidly shift gazes from buttons within the ICP interface, their fingers can precisely key-in a series of codes without forming a fixation, and simultaneously search for the outside target. It demonstrates that gaze might be the precursor of fixation and enable the peripheral vision processing information promptly.

Previous research on gaze control has focused on two potential approaches; bottom-up of stimulus-based information generated from the image, and top-down of memory based knowledge generated from internal visual and cognitive systems (Henderson, 2003).There was an argument concerning bottom-up or top-down visual processes on the eye movement researches for a long time, it is observed by this research that pilots applied both bottom-up and top-down visual processes depending on the prominence of information or previous experience. The top-down visual process indicates that the pilot recognized the subsequent engagement and planned the tactical strategies of air-to-surface by inputting navigation data into the ICP interface. Pilots have to move their fixations shifting to the buttons of ICP in order to guide his fingers to the specific number. When the directing attention allocation is completed, pilots relocate their fixations to the DED to determine if the information is precisely displayed. The bottom-up eye movement explains that the salient cues attract pilots' gazes to the objects by conducting a visual scan to perceive the unusual signal, such as the pilot moving gazes from surface target to the activated warning light on the HUD, reset on the master caution, then continued to aim at the surface target to complete the task. The analysis of frame-by-frame DVCR data of the eye tracking device found pilots also applied top-down visual process in the air-to-surface task. The integration of bottom-up and top-down visual processes might explain the three-levels of SA model as described by Endsely (1995); pilots perceived the warning light (level-1) and realized which system was malfunctioning (level-2), then predicted the malfunction's impact to the task (level-3). In this study, the level-1 of SA is a bottom-up approach for perceiving the stimulus of an activated warning light, level-2 and level-3 are top-down visual processes for understanding the stimulus by cross-checking the information from the HUD and relevant AOIs, then projecting the future situation by entering the codes to ICP for conducting the tactical manoeuver.

There are 94% of pilots' gaze points and 96% of fixations on the HUD, whilst performing the air-to-surface task. Although pilots have to key different codes into the ICP for aiming and releasing the weapon to target, it represents only 3% of fixation on the ICP. This phenomenon can be observed by analyzing eye tracking DVCR data which shows that while pilots are keying the codes into the ICP, they are also simultaneously searching for the surface target. To complete the task, pilots have to prioritize and switch attention between different AOIs depending on the specific stage of operating requirements for keying the navigation data. The LMFD mainly provides a moving map with terrain, while the pilots' priority information is altitude, speed and vertical speed whilst the target on the surface is in sight. It explains the low number of gaze points and fixation on the LMFD recorded in the air-to-surface task. Furthermore, blinking might reduce the number of gaze points and number of fixations counted, as it is an involuntary act of shutting and opening the eyelids which blocks the pupil and cornea from the illuminator resulting in raw data points missing. Searching for information in the cockpit and aiming at targets involve pilots' attention allocation. Pilots have to be able to 'see and process' the information to understand the situation, and then, to 'project' it in the near future (Endsely, 1995). It is a series of cognitive processes that constitute pilot aeronautical decision-making (ADM).

A close relationship between peripheral vision and gaze points can be observed as pilots rapidly shift gazes from buttons within ICP, while their fingers precisely key-in a series of codes without forming a fixation. Pilots not only have gaze points on the buttons of the ICP for entering a series of codes, but also simultaneously search for the outside target. In this study, pilots have the average of 2,578 gaze points, however, the average of pilots' fixation number were only 354 recorded by the eye tracker. This finding supports previous research by Henderson (2003) that the gaze control is an important topic in scene perception for seeking out task-relevant visual information and allocating attention. It provides evidence that gaze might be the precursor of fixation and enable peripheral vision in processing information promptly. According to the definition of fixation in this research, three gaze points occurred within an area of 10 by 10 pixels with a glance. Fixation point is definitely meaningful and is closely linked to attention allocation (Ratwani, McCurry and Trafton, 2010). However, gaze point is the foundation of fixation and it triggers pilots shifting attention to different AOIs whilst performing multi-tasks simultaneously, such as searching information, keying information, analyzing information, and operating the aircraft.

Research has shown that the retina needs about 80 ms of seeing a new image before that image is registered in normal light conditions. This doesn't mean that pilots consciously have noticed any change; it is only that the eye has registered a change. Furthermore, it has been observed that seeing a word in order to perceive it needs between 50-60 ms, while looking at a picture might need more than 150 ms to be able to interpret the content. The average fixation duration on the HUD and ICP are significant higher than DED, RMFD and LMFD. The information can be identified rapidly within the duration of single fixation, but this rapid apprehension may require attention allocation. The average of fixation duration on the HUD and ICP are 140 ms in this research (table 2), which differs from previous research where the overall average fixation duration was approximately 400 ms on the Primary Flight Display (PFD) and Navigational Display (ND) (Diez et al., 2008). The difference might be that the contexts of the research are different; one in a civil aviation setting, the other in military tactical operations. Generally, military pilots have higher standard of response time (shorter) compared with civil pilots, as the tactical operation has to be precisely accomplished under time pressure. Therefore, military pilots have shorter average fixation duration than civil pilots.

Pupil size is affected by human emotional and cognitive processes, and the increase in pupil size is an indicator of cognitive load (Bee et al., 2006). Under conditions of controlled illumination in the training simulator, pupil size is an effective and reliable measure of mental workload, as pupil size can reveal the condition of cognitive load, and the increases in pupil size correlate with increases in mental workload. Table 2 shows that pilots' pupil size at the ICP is the largest, followed by HUD and RMPD, LMFD is the smallest for the pupil size. When approaching the target, pilots have to roll-out, level off the aircraft, and with only very limited time to aim at the target, release the weapon and pull-up with a 5︱5.5 G to break-away from the range, otherwise the aircraft will be exposed to high risk. Pilots conduct lots of tactical manoeuvers to level-off the aircraft under hostile conditions and with limited time to aim at the target. If they cannot successfully aim and lock on the target, the mission has failed. All the critical information related to mission completion were provide by HUD and ICP; HUD shows all the important navigation and weapons information such as pitch, bank, airspeed/Mach, heading, altitude, horizon line, load factor, navigation information, airsurface target information, and the ICP is used for weapons release, landing, NAV/COM frequencies and to show air or surface target information. It is the reason why the pupil size on the ICP and HUD were significant larger than DED and LMFD (table 2).

The number of fixations multiplied by average fixation duration is the total fixation duration. Pilots have large amounts of total fixation duration time on the HUD. This demonstrates a phenomenon of focusing on particular parameters on the HUD which might potentially result in tunnel vision or overlooking critical parameters and missing the target. A limitation of simulator training is that the instructor cannot identify which AOIs a trainee is looking at to get information during training. If a trainee's real-time visual scan pattern can be recorded and displayed on the control panel simultaneously for an instructor to be aware of their attention allocation, it might improve training effectiveness and therefore also pilots' performance and aviation safety.

5 Conclusion

It is very important to improve military pilots training for the air-to-surface task, as it is the training element with highest risk of control flight into terrain (CFIT). Understanding a pilot's visual scan pattern and attention distribution during the air-to-surface task will allow aviation professionals to develop effective training. This research observed that over 90% of pilots' gaze points and fixations are on the HUD. It implies that the HUD might provide all the necessary information for pilots to perform the air-to-surface task; or it might be the evidence of pilots' over-reliance on the HUD. Therefore, the intervention of training could focus on the HUD to address how to improve the function of HUD, or how to conduct proper attention allocation between AOIs. The limitation of traditional simulator training is that there is no specific feedback of a trainee's visual scan pattern provided to the instructor to address the critical timing of attention distribution on the flight deck. This is because a pilot's visual scan patterns and attention allocation could not be observed simultaneously by an instructor. Eye tracking devices can aid in capturing a pilot's attention allocation where traditional flight simulators training were lacking. Therefore, a simulator integrated with eye tracking devices will be a creative method to promote safety and effectiveness in flight operations.

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