Pilots' Visual Scan Patterns and Attention Distribution During the Pursuit of a Dynamic Target

Chung-San Yu; Eric Min-yang Wang; Wen-Chin Li; Graham Braithwaite; Matthew Greaves

INTRODUCTION: The current research was to investigate pilots' visual scan patterns in order to assess attention distribution during air-to-air maneuvers.

METHODS: A total of 30 qualified mission-ready fighter pilots participated in this research. Eye movement data were collected by a portable head-mounted eye-tracking device, combined with a jet fighter simulator. To complete the task, pilots had to search for, pursue, and lock on a moving target while performing air-to-air tasks.

RESULTS: There were significant differences in pilots' saccade duration (ms) in three operating phases, including searching (M = 241, SD = 332), pursuing (M = 311, SD = 392), and lock-on (M = 191, SD = 226). Also, there were significant differences in pilots' pupil sizes (pixel^2), of which the lock-on phase was the largest (M = 27,237, SD = 6457), followed by pursuit (M = 26,232, SD = 6070), then searching (M = 25,858, SD = 6137). Furthermore, there were significant differences between expert and novice pilots in the percentage of fixation on the head-up display (HUD), time spent looking outside the cockpit, and the performance of situational awareness (SA).

DISCUSSION: Experienced pilots have better SA performance and paid more attention to the HUD, but focused less outside the cockpit when compared with novice pilots. Furthermore, pilots with better SA performance exhibited a smaller pupil size during the operational phase of lock on while pursuing a dynamic target. Understanding pilots' visual scan patterns and attention distribution are beneficial to the design of interface displays in the cockpit and in developing human factors training syllabi to improve the safety of flight operations.

KEYWORDS: aviation safety, pupil size, saccade duration, situational awareness, training evaluation.

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The advanced technologies of head-up displays (HUD) provide large amounts of information rapidly and precisely to improve pilots' situational awareness (SA) and facilitate a successful sortie. Pilots process information relying on the perceived stimulus from the visual environment, which might potentially lead to confusion and perceptual illusions in certain situations.[18] Information processed by pilots is mostly acquired by visual scans of the interior and exterior of the cockpit, and a majority of pilot errors in flight operations result from poor situational awareness.[11] The visual scan pattern is a precursor to initiating the cognitive process and information from eye movements within the cockpit are directly connected with a pilot's attention allocation.[16]

Pattern of eye movement is one of the methods for assessing pilots' cognitive processes based on real-time physiological measurements.[7] Eye-tracking devices have been applied to human-computer interaction domains for a long time, such as cockpit display design,[10] display design for air traffic controllers,[1] interface displays for uninhabited aerial vehicles,[24] and the design of control rooms of nuclear power plants.[6] In general, an individual spends more time looking at important or interesting objects in the environment. The length of fixation duration can reflect difficulty in extracting information and the number of fixations indicates the importance of the areas of

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interest (AOIs).[13] Also, the phenomenon of tunnel attention could be observed by the concurrence of an excessively long fixation duration on a specific area, reduced saccades,[10] and decreased scanning frequency on the display interfaces.[15] Research on the differences in visual time distribution has suggested that experts spend more time looking at thematically relevant elements of a task, while novices spend more time on the salient stimuli.[2]

Pilots' attention distributions play a central role in cognitive processing and eye movements may serve as a window into visual scan patterns used for SA, which is a precursor to pilots' aeronautical decision-making. Lack of visual attention is an indicator of missing SA, which is a known contributing factor in aviation accidents.[17] Although there is a debate concerning a 'bottom-up' or 'top-down' approach to visual attention in eye-tracking research, it was observed that pilots integrated both bottom-up and top-down visual processes based on their experience and salience of information during tactical operations.[25] The bottom-up eye movement is a stimulus-based visual process. The salient cues (such as an activated warning light) attract the pilot's gaze, causing the pilot to pay attention using visual scan to perceive the stimulus. Level 1 of SA is a bottom-up approach for perceiving the stimulus of an activated warning light while level 2 and level 3 are top-down visual processes for understanding the stimulus by cross-checking the information, then projecting the probable course of action in the near future.[3] The analysis of frame-by-frame eye tracking data can proceed using both a top-down approach based on design hypotheses and a bottom-up approach based on observation of the data without predefined theories relating eye movements to cognitive activity.[5]

Expert pilots have been shown to have a longer duration of focus on relevant cues when a warning light was present.[22] Furthermore, expert pilots are able to attend quickly to relevant indicators for required information when making decisions, with a pattern of more fixations and shorter fixation duration during landing operations.[12] Therefore, it was suggested that fixation numbers and fixation duration focused on certain AOIs might indicate where attention is allocated. The distribution of fixations and fixation duration on relevant AOIs can be not only an effective indicator of pilot's expertise level, but can also be closely related to a pilot's situational awareness.[25] Military pilots operating aircraft during tactical maneuvers have to identify rapidly and precisely where, or how, to move to the most appropriate position based on the relative dynamic information of a moving target, as pilots have to assess potential risks of intended tactical maneuvers to gain the most advantageous dynamic positions by projecting the trajectory movement in the near future. Experienced pilots frequently switch their attention more efficiently to search and acquire relevant information compared with novices, as extensive visual surveys are critical for ensuring that saccades land on the selected object in a timely manner.[14] Therefore, effective saccades play an important role in pursuing a moving target during air-to-air maneuvers. It appears that saccades might be associated with pilot's attention shifting for pursuing a dynamic target, as saccade duration is the total time to make a saccade and the saccade velocity is how fast the eyes move between fixations.[19]

The definition of SA is 'the perception of the elements in the environment within a volume of time and space (level 1), the comprehension of their meaning (level 2), and the projection of their status in the future (level 3).[3] In this definition the higher level of SA, which is a projection of future status using cognitive processing, depends on the lower level of SA, which is the perceived information. As most information in the cockpit is presented visually and over 75% of pilots errors are related to perceptual failures,[11] it is very important to understand pilots' visual information processing and eye movement patterns since they underpin SA performance in flight operations. Military pilots have to detect, recognize, and identify a foe via visual scan and radar displays for conducting target acquisition, target tracking, weapon release, and in order to fly out safely. Pilots' eye movements in response to tracking a dynamic target usually represent a fast linear readout of the direction and speed of cognitive processing. Selective attention results in the enhancement of relevant information and suppression of irrelevant information. For example, the time interval from the ending time of the last fixation on the Safe Check Switch (SCS: a three-way toggle switch for ordnance safety) to the starting time of the first fixation on the moving target is a critical saccadic interval. It might be linked with attention distribution, which could be the factor impacting a pilot's SA performance in tracking a moving target.[20] Although pilots can look in one direction and attend to another, covert and overt attention are often aligned in space, making eye movements a useful means to assess visual attention during searching.[26]

Pupil dilation is a quick response not only to changes in the brightness of the visual environment, but also of a person's cognitive workload while performing a visual task such as tracking a moving target. Pupil size is an important indicator to understand an operator's visual attention and workload, and has been used to assess training effectiveness[23] and to explore a pilot's mental process, cognitive workload, and visual attention objectively while performing a flight task.[15] In addition, pupil diameter changes were significantly higher when subjects were performing well on an auditory task compared with subjects performing poorly.[1] Pilots have to estimate the trajectory movements and relative approaching speed of a target, and use this information to decide where and how to move to the best intercept position. There have been several accidents involving air-to-air maneuvers that resulted in Controlled Flight into Terrain as pilots focused on maneuvering and overlooked the relative position of the aircraft and terrain. Causes included pursuing a foe into cloud, inducing spatial disorientation, or ineffective visual scan, resulting in the loss of situational awareness and flying below the safe altitude limit.[17]

Eye-tracking techniques are efficient in identifying attentional distribution and assessing cognitive countermeasures. There is an increasing need to study pilots' attention distribution, selective attention, and attention shift during the pursuit of a dynamic target in order to improve aviation safety. Therefore, the objectives of this study were: 1) to investigate pilots' scan patterns among different AOIs during the pursuit of a dynamic target; 2) to evaluate pilots' saccades and attention shifts during the tasks; and 3) to measure the relationship between pupil size and SA performance during pursuing a dynamic target.

METHODS

Subjects

A total of thirty mission-ready fighter pilots participated in this research. The ages of subjects ranged between 26 and 51 yr old (M = 29, SD = 6). Their total flying experiences varied between 310 and 2920 h (M = 844, SD = 720). The subjects were categorized into a novice group ($N = 15$), with total flight hours below 550 (M = 370, SD = 68), and an expert group ($N = 15$), with equal to and over 550 flight hours (M = 1319, SD = 766). The threshold between expert and novice pilots is 550 flight hours, as it is the milestone for fighter pilots to be the leader of a two-ship tactical formation. All of the subjects were volunteers and were informed that there was no incentive to secure participation; subjects had the right to cease the experiment and withdraw without any reason, and the storage of obtained data was in accordance with the Data Protection Act. The treatment of subjects was approved by the Research Ethics Regulations of National Tsing Hua University.

Equipment

Flight simulator. The simulator is equipped with a 2-D and 1:1 image projected on the 5-m wide and 3-m high screen. It uses an actual cockpit with identical display panels, layout, and controls to those in the actual fighter, and is capable of supporting pilots' tactical operational training by providing a realistic representation of the combat mission. An instructor can install scenarios and observe a trainee pilot's performance via a three-screen console. The information display on the HUD indicates the target's relative position through icons, letters, numbers, lines, and even figures. The Integrated Control Panel (ICP) is an interface like a keyboard for keying navigation and communication data, which is composed of 18 rectangular buttons, 9 circular knobs, and some toggle switches. The right multiple function display (RMFD) provides the information that the pilot keys in over the ICP, which is illustrated with letters and numbers. The left multiple function display (LMFD) shows radar information regarding the target and terrain using a digital map, lines, and numbers. The foe's location, altitude, attitude, speed, and heading, which appeared at the start point of scenario, are fixed until the target is pursued by the interceptor. Basically, the behavior of the foe was programmed by the central computer to maneuver with appropriate G force to make its escape in order to avoid lock on by the interceptor.

Simulator scenario. The scenario of this experiment was an air-to-air maneuver to analyze pilots' visual scanning shifts to search, pursue, and lock on to a dynamic target. The altitude of the interceptor during patrol was 20,000 ft (6096 m) with a cruise speed of 300 knots indicated airspeed (KIAS) and a heading of 50° with weather conditions of 7-mile visibility and scattered clouds. A foe unexpectedly appeared at the same altitude on a heading of 90° with 300 KIAS of airspeed (**Fig. 1**). The subjects have to search the airspace for the target and intercept the target immediately using tactical

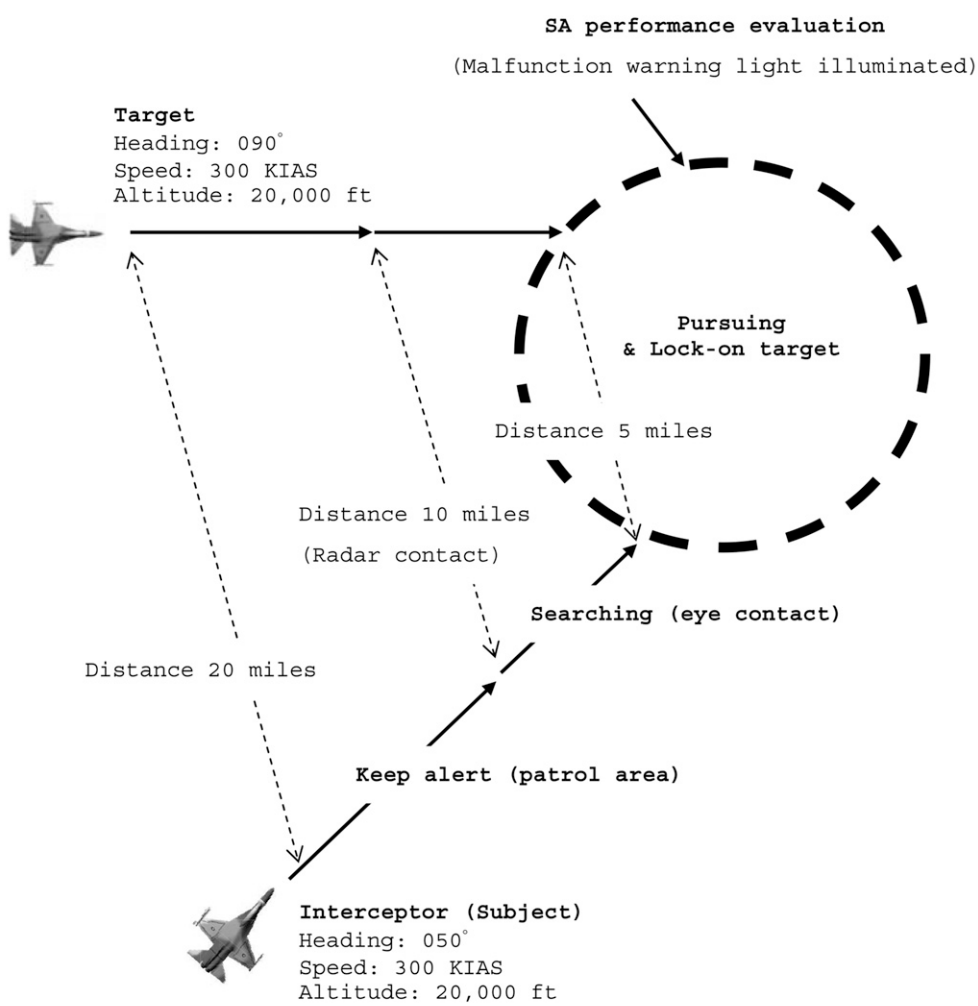

Fig. 1. The air-to-air maneuvering scenario.

maneuvers. However, the target would change its heading, altitude, and speed to escape from the interceptor's pursuit until the interceptor pressed the trigger and completed the task. At the same time, a senior instructor pilot (IP) would mark if the pilot terminated the target or not. In this study, three phases of visual behaviors were analyzed: searching for the target with eye contact (searching), pursuing in order to aim (pursuing), and lock on to the dynamic target (lock-on). In addition, the generator malfunction light on the warning light panel would illuminate unexpectedly during the lock-on phase. This was in order to evaluate pilots' SA performance.

Eye-tracking device. A mobile head-mounted eye tracker designed by Applied Science Laboratory (ASL Series 4000; Bedford, MA) was used to collect pilots' eye movement data. The eye tracker is a light (76-g) and portable device, and it was easy for subjects to move their head without any limitations during the air-to-air combat scenario. The pattern of eye movements and the related data were collected by a digital video cassette recorder and transferred to computer for further analysis. The sampling frequency of this device is 30 Hz, which means a 1-s eye movement is captured in 30 frames. The definition of a fixation in the present research was three gaze points occurring within an area of 10×10 pixels with a dwell time (the time spent per glance at an area or instrument) over 200 ms. There were five AOIs set up to observe subjects' eye movement data during the air-to-air task. These AOIs were selected in consultation with the chief training instructor as the most important elements in performing air combat maneuvers and that could provide the most vital information to complete the mission. The AOIs are detailed as follows, AOI-1: HUD; AOI-2: ICP; AOI-3: RMFD; AOI-4: LMFD; and AOI-5: outside the cockpit.

Research Design

All subjects undertook the following procedures: 1) completed the demographical data on the performance evaluation form, including rank, age, qualifications, type ratings, and total flight hours, followed by reading the description of research ethics (5-7 min); 2) a short briefing to explain the purpose of the study and introduce the air-to-air scenario (5-10 min); 3) calibrating the eye tracking device by using three points distributed around the cockpit display panels and screen (10-20 min); 4) subjects performed the air-to-air task (2-3 min); and 5) a debrief collected subjects' feedback and comments (5-10 min). In total, approximately 50 min was required for each subject to complete the experiment.

Based on the context of the air-to-air maneuvers, the main operational phases were defined as Searching, Pursuing, and Lock on. To standardize the processes of data analysis, eye movement data was only counted for the 15 s which comprised the above three phases of tactical maneuvers, as the instructor pilot observed all subjects' performance and suggested that the lock-on phase is the most critical phase for terminating the foe. Therefore, starting from the point at which the foe was terminated, the analysis tracked back through the three phases of lock on (5 s), pursuing the target (5 s), and the searching phase (5 s). Those 15 s are the most important in terms of cognitive processes for military pilots performing an air-to-air mission. The total time of measurement for performing the task and the fixation duration should be considered concurrently. It is obvious that the longer the total time of measurement, the higher the number of fixations that will be counted. Due to the varied time frames for each pilot in performing the air-to-air mission (between 28 and 140 s) in the present study, standardizing the processes of data analysis was necessary. Pilots' eye movement data were analyzed using the following: percentage of fixation, average fixation duration, pupil size, and saccades occurring within the AOIs. The unexpected event of a generator malfunction warning was activated by the IP during pilots pursuing the target. If the pilot called 'generator out' and pressed the master caution light, the IP would mark the pilot's SA performance as 'good SA'; if the pilot did not press the master caution, he would be marked as 'poor SA'. The current study adopted the embedded task measures to evaluate each pilot's SA performance to avoid interrupting ongoing tasks.

RESULTS

Subjects' eye movement data described by percentage of fixation and average fixation duration among five AOIs are shown as **Table I**. The 'percentage of fixation' is proportional data; therefore, it is necessary to perform an arcsine transformation before conducting analysis of variance.[8] Significant effects among the five AOIs were observed in terms of percentage of fixation during air-to-air combat [$F(4, 145) = 164.35$, $P < 0.001$, $\eta 2\rho = 0.85$]. Further comparisons by post hoc Bonferroni adjusted tests showed that AOI-5: outside of cockpit (53.1%) had a significantly higher percentage of fixation than AOI-2: ICP (2.5%), AOI-3: RMFD (0.7%), and AOI-4: LMFD (1.3%); and AOI-1: HUD (35.8%) had significantly higher percentage of fixation than ICP, RMFD, and LMFD. Furthermore, there were significant differences in pilots' average fixation duration among the five different AOIs [$F(4, 145) = 85.74$, $P < 0.001$, $\eta 2\rho$

Table I. Means and Standard Deviations for the Percentage of Fixations and Average Fixation Duration Among Five AOIs During Air-to-Air Combat.

		AOIs				
MEASURES		HUD	ICP	RMFD	LMFD	OC
Percentage of fixation (arcsine values)	Mean	35.8	2.5	0.7	1.3	53.1
	SD	14.55	4.73	2.1	3.01	13.8
Average fixation duration (ms)	Mean	457	98	34	59	460
	SD	152	163	107	140	102

AOI-1: head-up display (HUD); AOI-2: integrated control panel (ICP); AOI-3: right multiple function display (RMFD); AOI-4: left multiple function display (LMFD); and AOI-5: outside of cockpit (OC).

= 0.75]. Further comparisons by post hoc Bonferroni adjusted tests showed that outside of cockpit (460 ms) had significantly longer average fixation duration than HUD (457 ms), ICP (98 ms), RMFD (34 ms), and LMFD (59 ms); and HUD had significantly longer fixation durations than ICP, RMFD, and LMFD.

It is important to investigate pupil size, saccade duration, and saccade velocity, as saccades represent the mechanisms of fixation and rapid eye movement. The parameters of pupil size, average saccade duration, and saccade velocity were analyzed during the three operational phases of the air-to-air task: searching, pursuing, and lock on. There were significant differences between pilots' pupil size in the three operating phases [$F(2, 87) = 15.30$, $P < 0.001$, $\eta 2\rho = 0.35$]. Further comparisons by post hoc Bonferroni adjusted tests showed that pilots' pupil size in the phase of lock on (27,237 pixel^2) was significantly larger than during the pursuit (26,232 pixel^2) and searching phases (25,858 pixel^2). Furthermore, there were significant differences in pilots' average saccade duration during the three operational phases [$F(2, 87) = 6.43$, $P < 0.005$, $\eta 2\rho = 0.18$]. Further comparisons by post hoc Bonferroni adjusted tests showed that pilots' average saccade duration during the pursuit phase (311 ms) was significantly longer than during the searching (241 ms) and lock-on (191 ms) phases. However, there were no significant differences in pilots' average saccade velocity during the three operating phases [$F(2, 87) = 0.36$, $P > 0.05$, $\eta 2\rho = 0.01$].

The differences in SA performance between experienced pilots and novice pilots by Chi-squared test are shown in **Table II**. Significance was observed in pilots' SA performance ($\chi^2 = 6.65$, $P < 0.05$) between experts and novice pilots. It showed that 76.9% of experienced pilots and 23.1% of novice pilots could identify the activated warning light in highly demanding tactical combat maneuvers. Furthermore, **Table III** shows significant differences in percentage of fixation between the experienced and novice pilots in the HUD ($t = 3.78$, $P < 0.005$, $d = 1.38$) and outside of cockpit ($t = -4.12$, $P < 0.001$, $d = 1.50$). Experienced pilots have more fixations on the HUD (44.1%) and fewer fixations outside of the cockpit (44.8%) compared with novice pilots (HUD: 27.5%; outside of cockpit: 61.5%). To assess pilots' attention distribution and attention shift during the lock-on phase, the two indicators 'length of duration on SCS' and 'interval from SCS to refixating the target' were evaluated. There were significant differences in the length of duration on the SCS ($t = 4.42$, $P < 0.001$, $d = 1.62$) and in the time interval from the SCS to refixating on the target ($t = -2.60$, $P < 0.05$, $d = 0.95$). Experienced pilots spent more time (605.1 ms) on the SCS than novice pilots (388.3 ms). However, experienced pilots spent significantly less time (398.1 ms) from the SCS to refixating on the target compared with novice pilots (1185.5 ms).

Table II. Chi-Square of SA Performance Between Experienced and Novice Pilots.

		SA PERFORMANCE		PEARSON CHI-SQUARE		
GROUPS	NUMBER	POOR	GOOD	χ^2	DF	*P*-VALUE
Experienced	15	5(29.4%)	10(76.9%)	6.652	1	0.01
Novice	15	12(70.6%)	3(23.1%)			

DISCUSSION

To search for a moving target during air-to-air maneuvers, pilots have to divide attention, use selective attention, scan airspace and cockpit instruments in order to achieve situational awareness, and conduct aeronautical decision-making in a timely fashion.[17] On the other hand, pilots may lose SA as they focus on pursuing the dynamic target and enter fatal zones if their fixations and attention are not directed to appropriate AOIs. In addition, pilots may be distracted and suffer mode confusion due to an unexpected system malfunction, which may limit a timely response in an emergency.

Table I indicates that the information captured by pilots' visual scans from the HUD and outside of the cockpit are critical to conducting time-limited tactical maneuvers for precisely tracking and aiming at a moving target. In addition, Table III shows that there are significant differences in percentage of fixation on the HUD and outside of cockpit AOIs between expert and novice pilots during air-to-air maneuvers. Military pilots have to shift their attention between the information provided by the HUD and the movements of a dynamic target precisely to perform tactical maneuvers effectively. The findings of pilots' percentage of fixation and average fixation duration in the present study confirmed that pilots pursuing a moving target have to filter and evaluate the perceived cues from the HUD and the trajectory of a foe outside the cockpit. The cognitive processes of attention distribution and selective attention are based on pilots' expectations, knowledge, and experience.[15] Therefore, pilots not only pay attention to the most salient stimulus (symbols on the HUD), but also shift their attention simultaneously to the main priority, which is maneuvering to track the target's unpredicted tactical movements.

The eye movement patterns shown by Table I indicate that the highest percentage of fixation was outside of the cockpit. The results of the present study are different from the previous study,[25] which showed the highest percentage of fixation allocated on the HUD (59.92%), followed by outside of cockpit (39.18%). This difference is due to the context of the task between pursuing a dynamic target (air-to-air task) and a stationary target (air-to-surface task). It is consistent with the findings of pilots who did not employ a standardized scanning pattern, but monitored their in-flight situation based on expectations associated with specific flight contexts.[21] Although the average fixation duration on the HUD and outside of cockpit are not much different—a difference of 3 ms (457 and 460 ms, respectively)—the phenomenon of longer fixation duration focused on certain locations might indicate that the information coming from those AOIs is critical to the operation and in need of more attention.[13]

Table III. Means and Standard Deviations for the Visual Scan Patterns of Experienced and Novice Pilots.

				t-TEST				
VARIABLES	GROUPS	MEAN	SD	*t*	DF	*P*	SE	COHEN'S D
Percentage of fixation on the HUD (AOI-1)	Expert	44.1	10.1	3.784	28	0.001	6.25	1.384
	Novice	27.5	13.7					
Percentage of fixation on OC (AOI-5)	Expert	44.8	9.6	-4.118	28	0.000	6.02	1.504
	Novice	61.5	12.3					
Length of duration on SCS (ms)	Expert	605.1	134.3	4.424	28	0.000	48.99	1.619
	Novice	388.3	134.0					
Interval from SCS to refixate on the target (ms)	Expert	398.1	301.9	-2.598	28	0.019	303.09	0.949
	Novice	1185.5	1134.4					

HUD: head-up display; OC: outside the cockpit; SCS: safe check switch.

According to **Fig. 2A**, there were significant differences in pilots' saccade duration between the three operational phases. The shortest saccade duration was during the lock-on phase, followed by searching then pursuing. **Fig. 3** indicates different trends in saccade duration between experienced and novice pilots in the three operational phases. Except for the searching phase, expert pilots show longer saccade duration than novice pilots in the pursuit and lock-on phases. Saccade duration is the total time to make a saccade between fixations, which may reflect the path of attention shifts.[15] During the searching phase expert pilots made saccades which took a significantly shorter time (211 ms) to shift their attention than novice pilots (271 ms). It revealed that expert pilots can accurately identify the cues of a moving target on the HUD and viewing the image of the foe by shifting their attention. It was found that while pursuing the moving target, saccades were related to the trajectory of the target's movements. When the target was captured by eye contact during the pursuit phase, expert pilots had significantly longer durations (347 ms) than novices (275 ms), thus distributing wider attention shifts in order to monitor the whole situation. On the other hand, novice pilots might narrow down their attention by only conducting tactical maneuvers for pursuing and aiming at the moving target since they were only focused on the task of pursuing the foe rather than shifting their attention to the whole operating environment. It is possible that this is the reason only 23.1% of novice pilots perceived the warning light for the generator malfunction and projected trouble-shooting processes for assessing SA performance (Table II).

Although there were no significant differences in saccade velocity between expert and novice pilots across the three operational phases, the results reflect that the closer pilots were to the target, the faster their saccade velocity was to shift attention during the dog-fight. The fastest saccade velocity occurred during the lock-on phase, followed by searching, then pursuing. The attention shift to critical stimulus both on the HUD and from the visual scan should simultaneously direct pilots' attention to the most important signals; this is crucial to successful execution of the task. However, the total time of measurement for performing the task and the fixations should be considered concurrently, since longer periods of measurement time are usually accompanied with more fixation points.

Pilots' visual scan patterns for attention distribution among the AOIs and selective attention are a critical component in pursuing a dynamic target. However, the cognitive processes of selective attention related to prioritizing the information perceived is reinforced by pilot's knowledge and experience. Selective attention of pilots is important, as human beings' perceptual systems have limited processing capacity, as it enables pilots to constrain the selection of appropriate incoming information and become aware of the presence of environmental changes.[10] However, novice pilots' fixation distribution on the outside of cockpit is significantly higher than experienced pilots. The visual scan patterns showed experienced pilots distributed their attention on seeking target-related information from the HUD and outside of cockpit almost equally. In comparison, novice pilots paid significantly more attention to the outside of cockpit during air-to-air maneuvers, which might suggest that their use of the HUD is less proficient than experienced pilots. In addition, quick distribution of attention between the interior and exterior of the cockpit might be the reason that a higher percentage of experienced pilots showed good SA performance at the unexpected activation of the generator malfunction warning light. Pilots' mental status in such a critical phase was not only revealed with shorter saccade duration, but was also reflected in pilots' pupil size. Pupil size is influenced by illumination and also by the difficulty and complexity of tasks in hand and the pilots' cognitive workload.[4] **Fig. 2B** indicates that the pilots' pupil

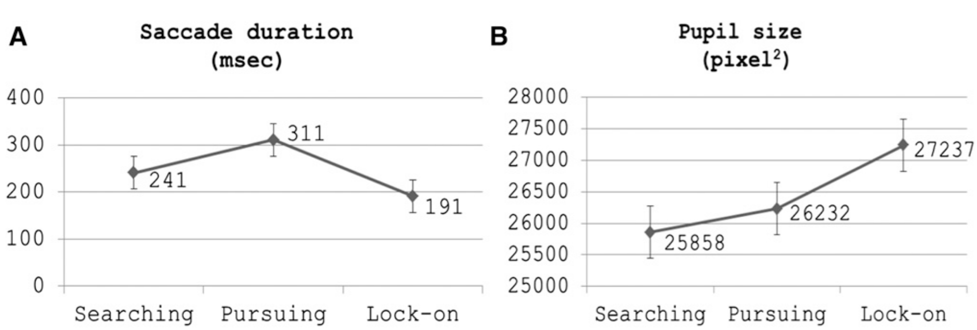

Fig. 2. Pilots' A) saccade duration (ms) and B) pupil size (pixel^2) during the three operational phases.

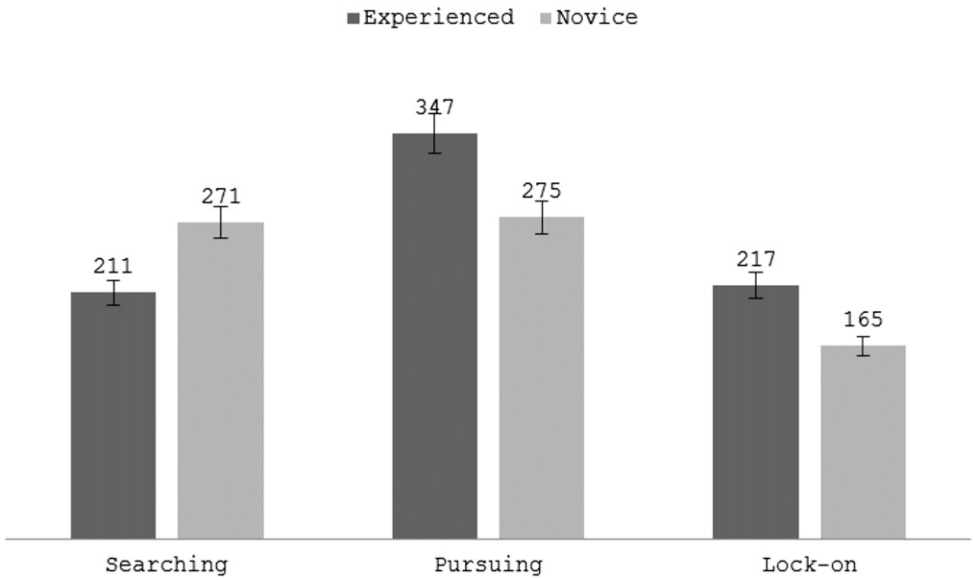

Fig. 3. Comparison of experienced and novice pilots' average saccade durations during three operational phases (ms).

size in the lock-on phase (27,237 pixel^2) was significantly higher than when pursuing (26,232 pixel^2) or searching (25,858 pixel^2). It revealed that pilots reach the most complicated situation for making decisions (to fire or not to fire) at the lock-on phase. Therefore, this finding could justify the research design of the present study in which the warning light for evaluating pilots' SA performance was designed to be activated at the lock-on phase.

The current research found that experienced pilots have shorter durations on weapon safe check during lock-on and a shorter interval time from visually checking the weapon safe switch is ready for tactical operations to refixating on the target than the novice (Table III). The application of an eye-tracker is appropriate to measure where pilot's visual attention is allocated.[26] However, the main challenge of the eye-tracker is related to the retrospective analysis based on the eye movement data recorded by a near real-time approach. The problem of retrospective analysis is to find appropriate ways to interpret the data concerning human beings' cognitive processing and behavior.[9] The findings related to the differences of attention distribution in visual scan patterns for seeking information between experts and novices might be applied to the assessment of pilots' competence in pursuing moving targets during tactical maneuvers.

The findings of the current research into the pursuit of a moving target compared with the previous study of tracking a stationary target[25] indicate that pilots do not apply standardized visual scanning patterns, but rather they are based on situational requirements associated with specific operational contexts. Pilots' attention distribution seems to be closely related to level 1 (perception) of the three-level SA model,[3] especially in searching for a moving target in open airspace. Thus, selective attention was mostly conducted after the target was pursued and during lock on, which corresponds to level 2 (comprehension) and level 3 (projection) of the SA framework. Therefore, future applications might have two directions: either to explore the interface design for maintaining an operator's attention to improve situational awareness, such as primary flight displays of airliners and the displays of air traffic control panels; or develop training syllabi to increase an operator's cognitive processes for visual scans for attention distribution. An eye-tracker is an appropriate device offering a non-intrusive approach for investigating in-flight visual attention and for analyzing pilots' cognitive processing, which can offset the weakness of traditional flight training. Specifically, the application of an eye-tracking device combined with a fighter simulator allows for the study of pilots' pupil size, saccades, fixations on AOIs, and SA performance while performing air-to-air maneuvers. Understanding pilots' visual scan patterns and attention distribution can have potential applications to improve the design of interfaces and develop training to improve aviation safety.

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