Pilots' Attention Distributions Between Chasing a Moving Target and a Stationary Target

Wen-Chin Li; Chung-San Yu; Graham Braithwaite; Matthew Greaves

INTRODUCTION: Attention plays a central role in cognitive processing; ineffective attention may induce accidents in flight operations. The objective of the current research was to examine military pilots' attention distributions between chasing a moving target and a stationary target.

METHOD: In the current research, 37 mission-ready F-16 pilots participated. Subjects' eye movements were collected by a portable head-mounted eye-tracker during tactical training in a flight simulator. The scenarios of chasing a moving target (air-to-air) and a stationary target (air-to-surface) consist of three operational phases: searching, aiming, and lock-on to the targets.

RESULTS: The findings demonstrated significant differences in pilots' percentage of fixation during the searching phase between air-to-air ($M = 37.57$, $SD = 5.72$) and air-to-surface ($M = 33.54$, $SD = 4.68$). Fixation duration can indicate pilots' sustained attention to the trajectory of a dynamic target during air combat maneuvers. Aiming at the stationary target resulted in larger pupil size ($M = 27{,}105$, $SD = 6565$), reflecting higher cognitive loading than aiming at the dynamic target ($M = 23{,}864$, $SD = 8762$).

DISCUSSION: Pilots' visual behavior is not only closely related to attention distribution, but also significantly associated with task characteristics. Military pilots demonstrated various visual scan patterns for searching and aiming at different types of targets based on the research settings of a flight simulator. The findings will facilitate system designers' understanding of military pilots' cognitive processes during tactical operations. They will assist human-centered interface design to improve pilots' situational awareness. The application of an eye-tracking device integrated with a flight simulator is a feasible and cost-effective intervention to improve the efficiency and safety of tactical training.

KEYWORDS: attentional processes, eye movements, mental workload, simulation and training, situation awareness.

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Pilots have to process information based on interior cockpit indicators and the exterior environmental stimuli by visual search during flight operations. Compared with commercial flight, exterior stimuli for military pilots also include either the moving target of a foe or a stationary surface target. Lavine et al.[12] suggest that visual attention is a precursor to initiating the cognitive process and that information acquired from a pilot's visual scan is closely associated with the pilot's attention allocation. Ineffective attention distribution may induce accidents, e.g., Asiana Airlines Flight 214, which crashed on final approach, as pilots' lack of situation awareness of the airspeed indicator was a critical human factors issue in the accident.[16] Attention plays a central role in cognitive processing. How and where pilots distribute attention is critical to the quality of situational awareness (SA) and links to the features of an individual's expectations.[7] Therefore, eye movements may serve as a window to illustrate pilots' attention distribution and mental state during flight operations.[13] The pattern of pilots' eye movement is one of the methods for assessing pilots' cognitive processes based on real-time physiological measures.[1] Therefore, pilots' visual behaviors are indicators to reveal attentional distributions during flight operations.[9,20]

Fixation is defined typically as the eye movement pausing over informative regions of interest. Human beings usually retain fixations on objects to acquire the most essential

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information to support the task at hand.[20] The patterns of fixations on the indicators or the areas of interest (AOIs) can reveal a pilot's visual trajectory of attention.[23] Moreover, the percentage of fixations on the relevant AOI is deemed as a predictor of the overall SA performance.[22] In addition, the length of fixation duration is the total time fixating on an AOI, which can reflect the level of importance or difficulty in extracting information.[2] Fixation duration might reveal how long pilots sustain attention while scanning the visual fields in order to complete the mission. On the other side, fixation duration might be an index of cognitive capture or over-concentration on a specific indicator, which will slow down attention shifts to the tactical situation.[7]

Pupil dilation is known to quickly respond to changes in the illumination in the visual field and to a human being's perceived workload while performing a visual task. Under controlled illumination, pupil size is an effective and reliable indicator of mental workload. An increase in pupil size is correlated with an increase in mental workload.[6] Attention is critical to pilots filtering the stimuli to the perceptual system. However, workload usually has negative impacts on the effectiveness of visual attention.[14] The increasing pupil size is a physical feature of cognitive load,[18] as it can be an important indicator of a pilot's cognitive process and visual attention.[23]

Saccadic eye movements are controlled by top-down visual processes, which are coordinated closely with perceptual attention.[24] It indicates that saccadic paths are intentional and meaningful, based on the requirements of the task at hand and the trajectory prediction in the near future.[11] Therefore, the path of saccades is associated with selective attention and accurate judgments for perceptual targets.[4,15] Saccade duration is the total time taken to make a saccade, which is recognized as one of the indexes to assess operator's workload, e.g., increase in workload has been found to decrease saccade duration.[19] Saccade velocity is how fast the eyes move between fixations, which are associated with rapid deployment of attention. Thus saccades might be an effective indicator of attention distribution.

The information provided in the cockpit is mostly acquired by pilots' visual scans among cockpit interfaces, and previous research has shown that 75% of pilot errors result from poor perceptual encoding.[3,8] It highlights the importance of the interactions between pilots' visual scan and the characteristics of cockpit interface design. It is obvious that attention is a critical precursor to in-flight SA performance and decision-making.[17] Eye tracking has been gaining in popularity over the past decade as a window into subjects' visual and cognitive processes. Therefore, the analysis metrics of the current research include five parameters of visual behavior: the percentage of fixations, fixation duration, pupil size, saccade duration, and saccade velocity. These metrics were measured among three operational phases, composed of: searching for visual contact with a target; aiming at a target; and lock-on for weapon release (press the trigger to launch weapon) between air-to-air for a moving target and air-to-surface for a stationary target.

Based on the above literature review, there are four fundamental hypotheses that will be investigated as follows: 1) there is no significant difference in pilots' fixation duration between chasing a moving target and a stationary target; 2) there is no significant difference in pilots' fixation duration among three operational stages; 3) there is no significant difference in pilots' pupil dilation between chasing a moving target and a stationary target; and 4) there is no significant difference in pilots' saccade velocity among three operational stages.

METHODS

Subjects

A total of 37 qualified, mission-ready F-16 pilots participated in this research. The subjects' flying experience varied between 372 and 3200 h (M = 1280, SD = 769). The ages ranged between 26 and 45 yr of age (M = 33, SD = 5). All of the subjects were male volunteers and informed that they had the right to cease the experiments and withdraw information they provided without any reason. Subjects signed an informed consent form and reported normal levels of visual function. The treatment of all subjects complied with the ethical standards required by the research ethics regulations of Cranfield University.

Equipment

Flight simulator. The flight simulator used in the experiment is a formal F-16 trainer manufactured by Lockheed Martin. It is a high-fidelity and fixed-base type flight simulator. It consists of identical cockpit displays to those in the actual aircraft to supports pilots' routine flight training and combat planning. It is integrated with high-definition databases, image generation systems, and physics-based processing technology which enable pilots to detect, judge the orientation of, recognize, and identify targets as they would in the real world of tactical operations. The instructor can install scenarios and observe the trainee pilot's performance via a console with three monitors.

Eye-tracking device. Pilots' eye movement data were collected by a mobile head-mounted eye-tracker which is designed by Applied Science Laboratory (ASL Series 4000). It is portable and light (76 g) so subjects can move their head without any limitations. The sampling frequency of this type of eye-tracker is 30 Hz. Video recordings of eye movements and the related data were collected and stored using a digital video cassette recorder and then transferred to a computer for further analysis. The definition of an eye fixation in the present study was when three gaze points occurred within an area of 10 by 10 pixels with a dwell time more than 200 ms.[20]

Simulator scenarios. Scenario 1 is an air-to-air maneuver to pursue a dynamic target. The altitude of the interceptor (subject) at the patrol area was 20,000 ft (6096 m) with a cruise speed of 300 knots indicated airspeed (KIAS). The heading was 050° under the weather conditions of 7-mile visibility and scattered clouds. A foe unexpectedly appears at the same altitude as the target, moving from left to right, with a heading of 090° and air speed of 300 KIAS. The subjects have to search the airspace for the target and intercept the target immediately using tactical maneuvers. At the same time, the target would change its heading, altitude, and speed in order to escape from the interceptor's pursuit (**Fig. 1A**).

Scenario 2 is an air-to-surface maneuver to pursue a stationary target. Subjects were dispatched unexpectedly to attack one stationary target, where they not only needed to execute tasks precisely by operating the aircraft, but also to follow the navigation system, entering appropriate codes by using various cockpit interfaces. Subjects had to intercept the proper route and turn toward the target at an altitude of 500 ft (152 m) with a speed of 500 KIAS simultaneously, then perform a steep pop-up maneuver to increase altitude abruptly for appropriate target reconnaissance, followed by a dive and roll in toward the surface target to avoid hostile radar lock-on. When approaching the target, subjects had to roll out, level the aircraft, aim at the target, and lock-on for weapon release to the target (**Fig. 1B**).

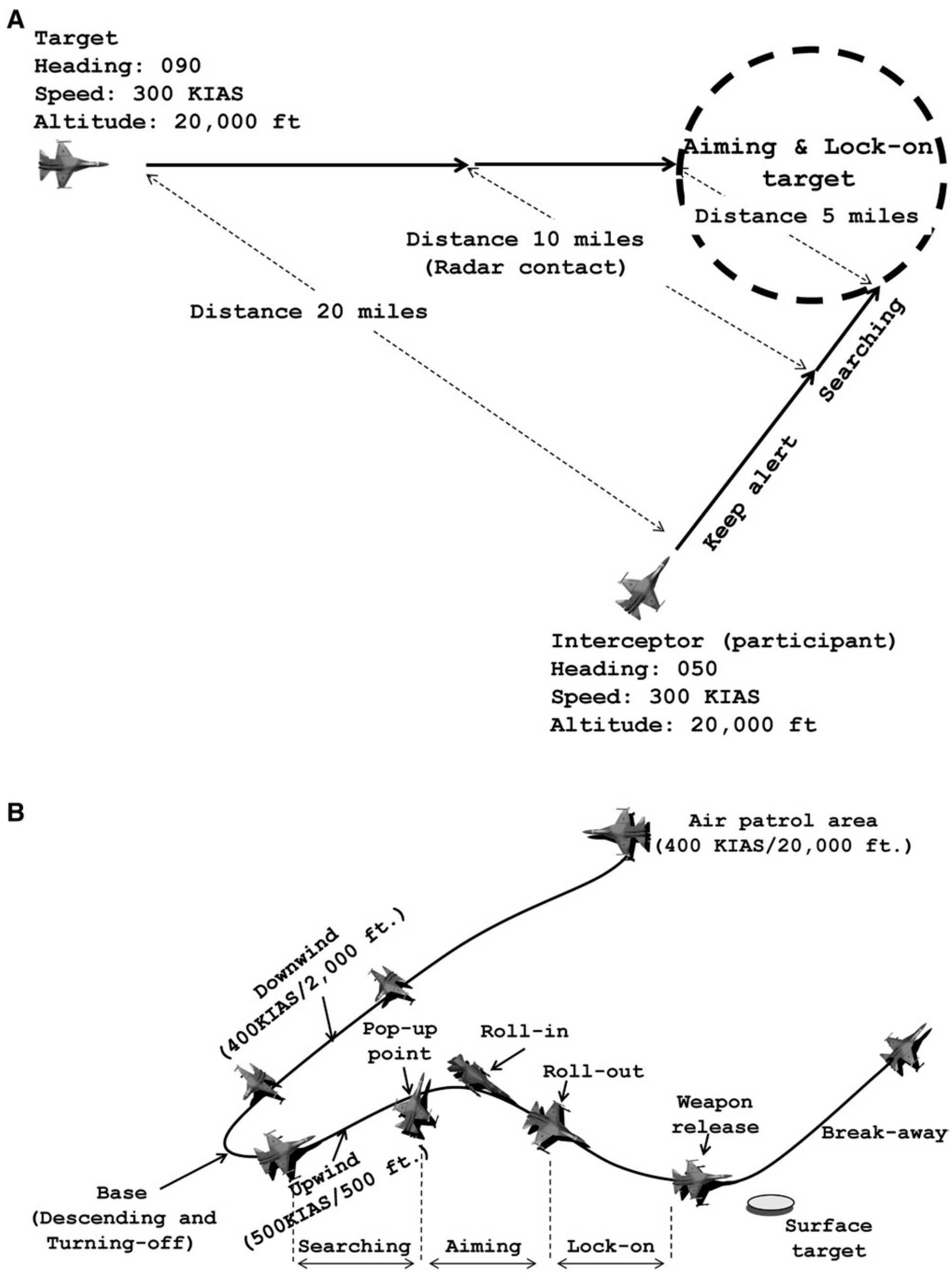

Fig. 1. Illustrations of A) air-to-air and B) air-to-surface tasks.

Procedure

All subjects undertook the following procedures: 1) provide demographic data, including rank, job title, age, education level, qualifications, type hours, and total flight hours (5 min); 2) a short briefing explaining the purpose of the study and the introduction of the air-to-air and air-to-surface scenarios without mentioning any potential aircraft equipment failure (20 min); 3) subjects were seated in the F-16 simulator and then the eye-tracker was put on for calibration using three points distributed over the cockpit display panels and outer screen (15–25 min); 4) perform the air-to-air task for aiming at a dynamic target (5 min); and 5) perform air-to-surface task for aiming at a stationary target on the ground (5 min). Simultaneously, the instructor pilot in the simulator console evaluated subjects' performance. It took around 60 min for each subject to complete the experiments.

Statistical Analysis

The eye movement data of both the air-to-air and air-to-surface tasks in this study were analyzed by three phases of visual behavior during tactical operations: searching for the target with eye contact (Searching), pursuing the target for aiming (Aiming), and lock-on to the target for weapon release (Lock-on). Therefore, a paired *t*-test and ANOVA were applied to analyze the differences in eye movement data. The length of time used to analyze each operational phase was 6 s (18 s in total for three phases). It was grounded by the consensus of experienced instructor pilots based on the most critical decisive time to process tactical information while performing both air-to-air and air-to-surface tasks. The eye movement data were analyzed as: percentage of fixation, fixation duration, pupil size, saccade duration, and saccade velocity.

RESULTS

The demographic information of subjects' age, rank, qualification and total flight hours are shown as **Table I**. As percentage of fixation is proportional data, it is necessary to perform an arcsine transformation in advance to enable further statistical analysis.[5] Based on the research design of the current study, a paired *t*-test and ANOVA were applied to analyze the differences in eye movement data between air-to-air and air-to-surface during three operational phases of searching, aiming, and lock-on (dependent variables). The analysis for this study is a within subjects test, as all subjects were performing both tactical tasks of aiming at a dynamic target (air-to-air) and a stationary target (air-to-surface).

There were five dependent variables related to pilots' eye movement characteristics between air-to-air and air-to-surface tasks among three operational phases, which are fixations/percentage of fixation, fixation duration, pupil size, saccade duration, and saccade velocity. The results demonstrated that there were significant differences in pilots' fixations [$t(36)=-2.52$, $P < 0.05$, $d=-0.624$] and fixation duration [$t(36)=3.26$, $P < 0.005$, $d=0.748$] between air-to-air and air-to-surface tasks. Therefore, the null hypothesis 'there is no significant difference in pilots' fixation duration between chasing a moving target and a stationary target' was rejected. Also, there were significant differences in pilots' saccade duration between the two tasks. However, there were no significant differences in pilots' pupil size and saccade velocity between the two tasks (**Table II**).

Significant differences among the three operational phases were observed in terms of percentage of fixation during air-to-air and air-to-surface tasks. Further comparisons by post hoc Bonferroni adjusted tests showed that during the air-to-air task, searching (37.57) had a higher percentage of fixations than aiming (35.11) and lock-on (32.94); the highest percentage of fixations occurred in the aiming phase during the air-to-surface task. There were significant differences in pilots' fixation duration among the three operational phases during the air-to-air and also the air-to-surface tasks. Further comparisons by post hoc Bonferroni adjusted tests showed that lock-on (938 ms) had significantly longer fixation duration than aiming (702 ms) and searching (612 ms) during the air-to-air task; the patterns showed that air-to-surface was the same as air-to-air, with lock-on the longest fixation duration (580 ms), then aiming (462 ms), and searching (332 ms) (**Table III**). Therefore, the null hypothesis 'there is no significant difference in pilots' fixation duration among the three operational stages' was rejected.

There were significant differences in pilots' pupil dilation among the three phases of the air-to-air and air-to-surface tasks. Further comparisons by post hoc Bonferroni adjusted tests showed that pilots' largest pupil size during air-to-air was in the lock-on phase (26,147 pixel^2); the largest one during air-to-surface occurred during aiming (27,105 pixel^2). Therefore, the null hypothesis 'there is no significant difference in pilots' pupil dilation between chasing a moving target and a stationary target' was rejected.

There were significant differences in pilots' saccade velocity among the three phases during the air-to-surface tasks. Further comparisons by post hoc Bonferroni adjusted tests showed that pilots' saccade velocity during the air-to-surface task in the lock-on phase (1148 pixels/s) was significantly longer than during aiming (1045 pixels/s) and searching (829 pixels/s). However, there were no significant differences in pilots' saccade velocity among the three phases of the air-to-air task (Table III). Therefore, the null hypothesis 'there is no significant difference in pilots' saccade velocity among the three operational stages' was partially rejected.

Table I. Subjects' Demographic Variables.

VARIABLES	FREQUENCIES
Age	
25–30	13 (35.1%)
31–35	11 (29.7%)
36–40	7 (18.9%)
41–45	6 (16.2%)
Rank	
Lieutenant	1 (2.7%)
Captain	16 (43.2%)
Major	9 (24.3%)
Lieutenant Colonel	10 (27%)
Colonel and Above	1 (2.7%)
Qualification	
Combat ready	13 (35.1%)
Two fighter team leader	4 (10.8%)
Four fighter team leader	9 (24.3%)
Daytime back seat instructor	2 (5.4%)
Training instructor	9 (24.3%)
Total Flight Hours	
500 and less	3 (8.1%)
501–1000	13 (35.1%)
1001–1500	11 (29.7%)
1501–2000	4 (10.8%)
2001 and above	6 (16.2%)

DISCUSSION

The characteristics of the air-to-air task in the current study involved engaging a dynamic target by visual searching to aim and lock-on to the moving target. In the air-to-surface task, pilots have to perform a steep pop-up maneuver to search for the target, followed by a rapid dive and roll in to aim and lock-on the stationary target. The results showed significant differences in pilots' fixations and fixation duration between the pursuit of a moving and a stationary target (Table II). Pilots demonstrated different patterns of fixations and fixation duration between chasing a moving target and stationary target. Furthermore, pilots' in-flight cognitive processes are extremely dynamic, which needs to be explored within the contexts of the operational environment.

Two different tactical tasks in the current study are composed of three operational phases; each phase has specific tactical requirements and threats. Table III shows pilots displayed the highest percentage of fixations on aiming at the surface target (37.62 arcsine values). It reflects the tactical standard operating procedures where pilots have to precisely aim at the surface target

Table II. *t*-Test of Eye Movement Variables Between the Air-to-Air (AA) and Air-to-Surface (AS) Tasks.

					t-TEST				
VARIABLES	TASKS	M	SD	*N*	*t*	DF	*P*	SE	COHEN'S D
Fixations	AA AS	8.0 9.2	2.2 1.6	37	−2.521	36	0.016	0.44	−0.624
Fixation duration (ms)	AA AS	751 458	543 111	37	3.263	36	0.002	89.67	0.748
Pupil size (pixel^2)	AA AS	23,990 25,746	7703 6173	37	−1.922	36	0.063	913.33	−0.252
Saccade duration (ms)	AA AS	196 267	215 163	37	−2.297	36	0.028	30.82	−0.372
Saccade velocity (pixels/s)	AA AS	948 1007	319 224	37	−1.308	36	0.199	45.60	−0.214

searching to aiming (90 ms). It revealed that pilots have to keep tracking and precisely project the target's probable trajectory movement in the vast airspace while aiming and locking on a dynamic target.

Fig. 2 indicates that pilots' pupil size in the phase of lock-on (26,147 pixel^2) is the greatest during the pursuit of a moving target. Also, the tendency of increasing pupil dilation during task performance might reveal pilots' increasing cognitive load from searching to lock-on. However, pupil size during the pursuit of a stationary target was, on average, greater than during pursuit of the moving target. Fig. 2 also shows the greatest pupil size occurred during the aiming phase. The results did reveal there are significant differences in pilots' pupil dilation among the three operational stages. Also, the increase in pupil dilation from searching to aiming during the air-to-surface task (3108 pixel^2) was significantly greater than during the air-to-air task (1904 pixel^2). It showed that pilots might have a tremendous cognitive workload during the air-to-surface task compared with air-to-air. These findings are useful to better comprehend pilots' cognitive processes regarding workload while chasing a stationary target, where there is potential risk of controlled flight into terrain (CFIT).[10]

within the time frame (between 3–5 s), otherwise the mission would be aborted. On the other hand, searching for a moving target during an air-to-air task represents the highest percentage of fixations (37.57 arcsine values), which demonstrates that the uncertain trajectory of a moving target might increase pilots' cognitive load in searching for the unknown airborne target.

Pilots' fixation duration during the air-to-air task was significantly longer than the air-to-surface task across all phases (Table III). It might indicate that pilots have to sustain substantial attention to avoid missing the trajectory of a dynamic target during the high kinetic maneuvers. For example, in the interval (236 ms) from aiming to lock-on, pilots' fixation duration increased 2.6 times compared to the interval from

Table III. ANOVA of Eye Movements in the Three Operational Phases: Searching (S), Aiming (A), and Lock-On (L) During the Air-to-Air (AA) and Air-to-Surface (AS) Tasks.

VARIABLES	TASKS	PHASES	M	SD	DF	*F*	*P*	$\eta^2\rho$
Percentage of fixations (arcsine values)	AA	S	37.57	5.72	36	5.75	0.005	0.138
		A	35.11	2.96				
		L	32.94	5.37				
	AS	S	33.54	4.68	36	6.29	0.003	0.149
		A	37.62	3.93				
		L	34.23	4.35				
Fixation duration (ms)	AA	S	612	487	36	5.39	0.007	0.130
		A	702	515				
		L	938	881				
	AS	S	332	71	36	18.48	<0.001	0.339
		A	462	145				
		L	580	270				
Pupil size (pixel^2)	AA	S	21,960	10,132	36	7.57	0.001	0.174
		A	23,864	8762				
		L	26,147	6449				
	AS	S	23,997	6180	36	38.82	<0.001	0.519
		A	27,105	6565				
		L	26,136	6152				
Saccade duration (ms)	AA	S	239	332	36	1.34	0.269	0.036
		A	167	188				
		L	183	270				
	AS	S	457	288	36	29.06	<0.001	0.447
		A	204	198				
		L	141	170				
Saccade velocity (pixels/s)	AA	S	970	438	36	0.68	0.510	0.019
		A	983	438				
		L	891	437				
	AS	S	829	368	36	7.87	0.001	0.179
		A	1045	328				
		L	1148	394				

The significant difference in pilots' saccade duration was observed between the air-to-air and air-to-surface tasks (Table II). **Fig. 3** reveals that pilots significantly decreased the time to make a saccade while searching for a dynamic target (239 ms) than searching for a stationary target (457 ms). It illustrated that pilots shifted attention with shorter time to search for an almost unknown and moving target than for a stationary target with awareness of approximate location. As a result, the level of knowledge of the target influences pilot's saccade duration. In addition, the saccadic duration is accompanied by a shift of attention to the selected target.[11] Searching for the stationary surface target seems to reflect higher cognitive load than searching for the dynamic target.[19] Pilots operating fighter aircraft toward a surface target

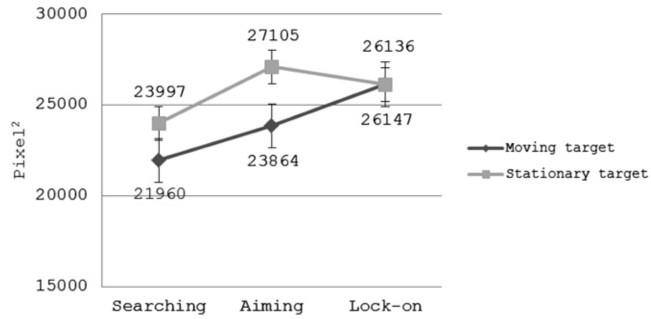

Fig. 2. Pilots' pupil dilation among the three operational phases while pursuing a moving target and a stationary target. The error bars represent standard deviation of the mean.

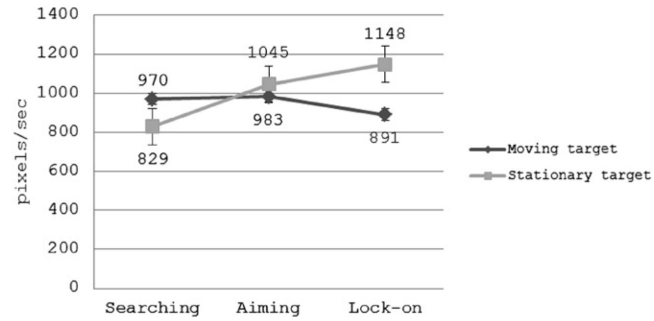

Fig. 4. Pilots' saccade velocity during the three operational phases while pursuing the moving target and the stationary target. The error bars represent standard deviation of the mean.

must fly precisely in order to avoid a CFIT accident. Simultaneously, they also have to be aware of hostile threats while assessing appropriate timing for lock-on and weapon release. It was found that the decreasing rate in saccade duration from searching to aiming during the air-to-surface task is 55.36% (Fig. 3).

There was no significant difference between the two tasks, although Table II reveals average saccade velocity during the pursuit of a stationary target (1007 pixels/s) was faster than during the pursuit of a moving target (948 pixels/s). However, there were significant differences among the three phases during the air-to-surface task (Table III). **Fig. 4** reveals the fastest saccade velocity occurred in the lock-on phase (1148 pixels/s). In contrast, the slowest saccade velocity was in the searching phase (829 pixels/s), which is the stage of collecting relevant navigation and target information for further operations. Processing massive amounts of information, thus inducing high cognitive load, might be the reason that the searching phase demonstrated the slowest saccade velocity and the longest saccade duration. In addition, the fastest saccade velocity reveals that the lock-on phase requires quick attention shifts to enhance situational awareness as the aircraft is flying at extreme low altitude for the air-to-surface task. The findings of saccade duration and saccade velocity reveal that pilots' top-down visual scan patterns in tactical operations are based on pilots' expectations (projection of the course of action) associated with specific objectives, which matches previous research.[4,21]

The current research found that pilots apply different approaches of visual scan patterns for searching and lock-on to

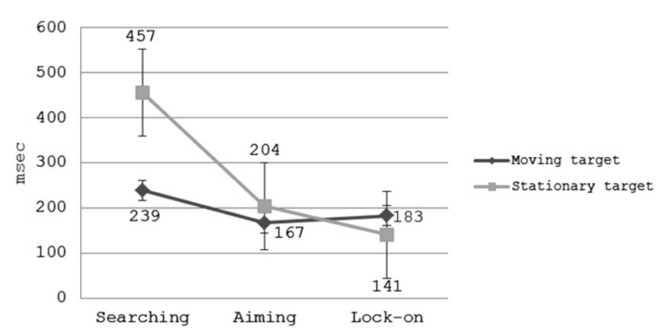

Fig. 3. Pilots' saccade duration during the three operational phases while pursuing the moving target and the stationary target. The error bars represent standard deviation of the mean.

different types of targets. Eye tracking devices can aid in capturing a pilot's attention allocation where traditional flight simulator training was lacking. Additionally, the analysis of eye movement parameters in real-time tactical maneuvers could provide system designers with a better understanding of pilots' cognitive processes and, therefore, optimize interface design and alleviate pilots' workload. The findings of the current research could also facilitate the development of tactical training syllabi for air-to-air and air-to-surface tasks to improve pilots' attention distribution and situational awareness. However, the present findings were based on experiments conducted in a ground-based flight simulator. In order to reflect military pilots' in-flight cognitive process, the next step is to develop a cockpit eye tracker to further study pilots' eye movement patterns and attention distributions in real tactical operations.

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