Attention and Entropy in Simulated Flight with Varying Cognitive Loads

Tianjiao Lu; Zhenshan Lou; Feng Shao; Yuan Li; Xuqun You

INTRODUCTION: This study is conducted to observe the effects of cognitive load on the visual search and attention allocation strategies of pilots. Research on pilots' visual search strategies can provide valuable information regarding attention distribution and transformation, as well as useful situation awareness (SA) predictions.

METHODS: A total of 18 pilots performed flight tasks in a two-condition (high and low cognitive load) within-subject experiment to compare their flight performance and eye movement indicators. Eye movements were tracked during the flight mission by a portable eye-tracking device.

RESULTS: Compared to the low cognitive load task, in the high cognitive load task, the subjects exhibited shorter average fixation times (M = 420.38, SD = 60.56), higher fixation frequencies (M = 2.27, SD = 0.30), and lower saccade frequencies (M = 2.7, SD = 0.31). Their flight performance was better during the low cognitive load task, as evidenced by the lower entropy (M = 0.11, SD = 0.03) of their eye movements. Analysis of fixation time percentages and fixation counts showed that the distribution of attention to each area of interest was adjusted dynamically over the course of the given task.

DISCUSSION: Significant differences were observed in both fixation order and fixation frequency across the instrument array. When the cognitive load is high, the subjects used more efficient eye movement patterns and search strategies accompanying a higher level of SA.

KEYWORDS: cognitive load, eye movements, visual search, pilots.

Lu T, Lou Z, Shao F, Li Y, You X. *Attention and entropy in simulated flight with varying cognitive loads*. Aerosp Med Hum Perform. 2020; 91(6):489–495.

Flying modern, high-performance aircraft requires a set of superior sensory-motor skills. One of the more important of these skills is acquiring and tracking moving visual targets.[8] Pilots conduct visual searching based on their experience, the requirements of the task at hand, the features of the environment, and through other normal processes of acquiring and understanding information. Cognitive strategies and attention attribution are influenced by different cognitive load conditions. Knowledge regarding the influence of various eye movements on visual searching in pilots can be used to establish effective training techniques.

As a complex cognitive process, the visual search is an important approach to accessing information. Visual searching helps pilots to obtain external stimulus information through a series of saccades and fixations as they process information.[29] Individuals identify a specific stimulus in a certain background when they have a strong purpose for doing so.[17] Visual searching during flight requires the pilot to collect the information he or she needs to complete the action related to the given task per the task's requirements in the surrounding visual range. Different visual search strategies must be deployed at different moments to monitor the flight status. During flight, pilots make decisions based on the information obtained from visual searching. In short: the visual search plays a key role in the pilot's mission.

The visual search is influenced by a combination of the environment, the mission (and its difficulty), and the searcher's characteristics. In other words, under different cognitive load conditions, the pilot may need to use different visual search

---

From the Shaanxi Key Laboratory of Behavior and Cognitive Neuroscience, Institute of Psychology, Shaanxi Normal University, Shaanxi, China; the Hangzhou Center of Aeromedical Evaluation and Training for Air Force; Zhejiang Province, China; and the Department of Psychology, Dujiangyan Center of Aeromedical Evaluation and Training for Air Force; Sichuan Province, China.

This manuscript was received for review in September 2019. It was accepted for publication in March 2020.

Address correspondence to: Xuqun You, Professor, Ph.D., Shaanxi Key Laboratory of Behavior and Cognitive Neuroscience, Institute of Psychology, Shaanxi Normal University, 199, Chang'an South Road, Xi'an, Shaanxi Province 710000, China; youxuqun@snnu.edu.cn.

DOI: https://doi.org/10.3357/AMHP.5504.2020

modes to complete the task at hand. Wang et al.[29] found that the search time necessary for a difficult task is shorter than that for an easier task. According to cognitive load theory,[26] the human capacity of information processing is limited—only a certain amount of information can be processed at any one time. This limit may be pushed when the operator engages in a variety of activities in performing difficult tasks. Cognitive resources must be allocated to different tasks, which can tax the resources and drive down the efficiency of the task in a phenomenon called "cognitive overload."[18]

Previous researchers have found that cognitive workloads affect productivity by influencing information processing.[3] For pilots, mission implementation requires a certain amount of resources while other secondary operations during the flight also require some amount of attention. Resources can grow scarce as they are allocated continually to different tasks during a mission, ultimately reducing the pilot's situational awareness and affecting his or her flight performance. The natural limitation of cognitive processes and the vast number of (often parallel) tasks in flight increase the critical stress exerted on the pilot.

The pilot faces extreme difficulties and high workload during multi-missions, dynamic aircraft maneuvers, and within the adverse environmental conditions of tactical missions.[29] Pilots must make and share decisions not only regarding management of the airspace, but also about the operating state (mode of control) of that airspace. The workload may be increased dramatically during abnormal situations or system failures.

Cognitive workload can negatively affect the pilot's performance and increase operation errors. The pilot employs different strategies in the target search process. He or she decides which search strategy to use at any given time according to his or her own knowledge and experience while processing all given information. For example, information regarding the effects of different visual scanning strategies on traffic detection accuracy and aircraft control can be used to recommend traffic scanning procedures to pilots. Search strategies tailored to traffic detection and free flight scanning domains have been shown to be effective.[19]

Here we propose that different task difficulties introduce different cognitive loads to the pilot; different visual search modes are deployed under higher cognitive load during an efficient visual search. Beginning in the 1970s, American psychologists such as John Gould[9] began to use the eye movement method to study the visual search mechanism. The extant research has grown more sophisticated and now includes more detailed problems such as internal visual searching mechanisms and visual search efficiency training.

The concept of situation awareness (SA) relates to human perception, knowledge, and understanding in the context of dynamic tasks. As defined by Endsley[5] it is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p. 36).

Many researchers have extrapolated SA theory into a three-level model.[27,28] SA is characterized by three levels: information acquisition (Level 1), understanding information (Level 2), and accurate decision making (Level 3). Level 1 of SA is a bottom-up approach for perceiving the stimulus of an activated warning light while Levels 2 and 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.[5] Many researchers have investigated concepts related to SA and the influencing factors corresponding to different levels. In addition to studies on influencing factors, researchers have sought SA measurement methods specifically corresponding to the three levels.

Studies have also shown that the level of SA can be predicted by eye movement.[6] An eye tracker, as mentioned above, reveals where the tested pilot focuses his or her SA. Basic eye movement indicators are a helpful value to measure Level 1 SA.[27] The visual search mode represents Levels 2 and 3 of SA. The rescanning of information, number of fixations, fixation rate, and structure of visual scanning are also known predictors of performance and SA.[15,20,27] Researchers have found that different measurement methods apply to the cognitive characteristics of different stages. Eye movement trackers can be used to measure the level of SA, especially for Level 2 and Level 3 measurements. Scanning patterns are an eye movement indicator reflecting Level 2 which reveal the searching strategy that is used by the pilot. Entropy is an indicator of eye movement regularity representing Level 3.

The pilot's SA is a key factor affecting his or her decision-making quality and performance. Losing SA and failing to complete complex cognitive tasks can lead to catastrophic consequences.[30] An eye movement is an indicator of a dynamic and direct response to the state of the pilot's SA. Moore and Gugerty,[15] among other researchers, have used percent fixations, average fixation time, total fixation counts, and the nearest neighbor index to investigate air traffic control tasks.

The "nearest neighbor index" refers to random scanning behavior, i.e., entropy. The randomness of the pilot's scanning pattern might reveal the search strategies of the pilot (coherent or flexible). Researchers have investigated whether eye movement measurements respond well to SA levels. The percentage of fixation time in the relevant area of interest served as an effective predictor of SA score. This index, in a certain region of interest, is also a strong predictor of current and future SA scores. Research on pilots' visual search strategies can provide valuable information regarding attention distribution and transformation as well as useful SA predictions. Knowledge of the role of cognitive effort in flight operations may be useful in improving aviation training practices to enhance situational awareness and safety.

Recording and analyzing pilot eye movement rules under different flight conditions can help establish techniques for predicting SA. Few previous researchers have attempted to measure SA and eye movements at the same time. Hauland[13] collected eye movement data from air traffic controller students in a two-person simulator training and recorded the SA process accordingly. The results showed that radar controllers have high SA levels and effective air traffic control performance. These researchers tested a distributed attention strategy under normal circumstances. Eye tracking data proved to be an effective method for directly measuring dynamic SA[12] as well as pilot attention allocation and cognition in using visual information during flight.

Previous researchers[14] have tended to focus on pilots' eye movement modes in the general flight process or in comparisons between the eye scanning modes of expert and novice pilots. There have been few previous studies on the rules of visual searching under the different cognitive load conditions. Such information may help to improve the pilot's attention distribution model and to design effective eye movement training techniques per different cognitive loads.

In the present study, we used eye movement measurements to analyze the search strategy rules employed by pilots under different cognitive loads. The pilot's SA can be predicted through his or her eye movements. We tested two specific predictions. First, we predicted that when the cognitive load is large, the pilot uses more efficient eye movement patterns and search strategies accompanying a higher level of SA. By analyzing the eye movement indicators in flight under different cognitive loads, we established rules regarding the visual search features of pilots which reflect their attention distribution. This information may benefit new eye movement-based training techniques. Second, we validated the eye movement measurements' correlation to pilot SA and predicted that visual search strategies produce different SA levels. These differences can be exploited to predict the pilot's SA and to optimize the visual search strategy to improve SA. The results presented here may also provide a workable theoretical basis for further research on eye movements and SA.

METHODS

Subjects

Eighteen military pilots were recruited on a voluntary basis and provided written informed consent before participating. This research complies with the China Psychological Association Code of Ethics and was approved by the Institutional Review Board at Shaanxi Normal University. All 18 participants were men, were between 22 and 32 yr of age at the time of their participation (M = 29.22, SD = 2.647), and had logged between 650 and 1650 h of flight in total (M = 1200, SD = 314.83). All the pilot subjects had normal visual acuity with binocular acuity of 1.0 or better.

Equipment and Materials

Cockpit-based simulator. The simulator is a military fighter cockpit manufactured by the Air Force Research Laboratory that replicates actual aircraft performance. The interior cockpit consists of an instrument panel, joystick, throttle lever, and rudder pedals. The display screen (LED) simulates the fighter's operating interface, including the inner cockpit instrumentation and a certain range of outside visuals. There are 10 training courses provided by the equipment including the simulation of a simple flight task, instrument orientation, instrument reading, and illusion training.

We used the simple flight mission for the purposes of this experiment. The main interface of the simulator firstly presents the cabin display of the selected models during the instrument flight rules (IFR) task, namely, the main instrument area (electronic and mechanical) in the cabin. Mechanical instruments serve as backups under normal navigation conditions while pilots acquire basic information from electronic instruments.

SMI eye tracking system. Eye movements were recorded at 120 Hz with SMI's BeGaze software (Berlin-Teltow, Germany) as fixations and saccades with a dispersion-based event detection algorithm. Fixations and saccades were determined using a displacement threshold of 0.1°. The dispersion is 100 px with a minimum fixation duration of $80° \cdot s^{-1}$. Fixations slower than $100 \text{ m} \cdot s^{-1}$ are commonly used to explore visual search patterns. We used a five-point calibration to ensure that recordings had a mean spatial error of less than 0.8°. During the flight task, the subjects sat in the simulation modules and keep 30 cm away from the screen. We allowed subjects to perform head movements in a small area as long as they were continually fixated on the screen.

Flight task. Subjects were asked to complete two tasks related to two levels of cognitive load on the simulator in IFR conditions. The subjects were shown only the instrument area during the flight in order to effectually reproduce real instrument flight conditions.

The first task had low cognitive load (LCL); this task simulates the manual horizontal flight after takeoff. They were asked to fly in a fixed state [heading 180, altitude 9843 ft (3000 m)] for 90 s as far as possible to reduce the difference from the initial value. The second was a high cognitive load (HCL) task wherein the simulation was run again with random numbers in quick succession at different places on the screen to increase the cognitive load. The pilots were asked to add three numbers and then press a key: if the results were even, they pressed the button on the joystick (and made no response if the results were odd).

Throughout the process, a rolling "+" appeared on the screen as a stimulus. No score was recorded if there was no response within 1 s after the numbers appeared. The correct rate of the computing task was recorded as the performance on additional tasks. The difference between the heading indicator and altimeter readings was recorded as the flight performance once the task was complete.

Procedure

Before the pilots accomplished the flight simulations, they were given background information on the experiment and fitted with a head-mounted eye tracking system for a calibration. After the calibration, the participant was allowed a 5-min period for familiarization with the flight and simulator. The order of the two types of flight task was randomized. Subjects were instructed to complete the two tasks described above two times each and their results were averaged.

Statistical Analysis

As discussed above, pilots use different eye scanning modes and attention allocation strategies on different areas of interest (AOIs) during flight. Pilots tend to perform operations in accordance with instrument information during IFR flight. Based on the task requirements, we statistically analyzed the attention to each instrument area. We divided vision information sources into five categories according to the task: the AOI of four instrumentation panels of the cockpit, and the remainder of the instrument area. This allowed us to analyze the fixation transition path of the whole visual area comprehensively.

The percentage fixation count is the ratio of the fixation point number in each AOI to the total fixation point in each trial. This index is related to the fixation frequency of the outview or the instrument. The percentage fixation time of the algorithm is the same as that described above. We generalized the sequence of fixation for all the AOIs according to link analysis, which provided information regarding the number and duration of glances to the AOIs as well as the sequential transition from one AOI to the next.[23]

The "normalized stratified entropy" observed in the experiment is defined as a dependent variable that varies between 0 (scan patterns completely predictable) and 1 (scan patterns completely random). Entropy is an indicator of the randomness of visual scanning behavior.[10] Entropy indicates the level of strategic visual search activity (or lack thereof) in the pilot and is also linked to visual workload: a high entropy level indicates low visual workload and vice versa.

The experiment consisted of a single factor, LCL vs. HCL within the subject's factorial design. The dependent variables measured were the eye movement indicators. In order to compare the differences between the two tasks, we used paired *t*-tests and an independent sample *t*-test for performance and eye movement data analysis.

RESULTS

The participants' flight performance indicators under different cognitive loads are shown in **Fig. 1**. The difference in altimeter and heading indicators was significant [$t_1(17) = -5.34$, $P_1 < 0.001$, $d_1 = -1.48$; $t_2(17) = -2.68$, $P_2 < 0.05$, $d_2 = -0.85$] and the additional task score was 78.11 points.

We also assessed eye movement indexes under different cognitive loads. The fixation frequency and saccade frequency in the LCL task were lower than in the HCL task [$t_1\,(18) = -5.455$, $P_1 < 0.01$, $d = -3.46$; $t_2(18) = -5.295$, $P_2 < 0.01$, $d = -3.29$;] and average fixation time was larger in the LCL than the HCL task [$t(18) = 3.758$, $P < 0.01$, $d = 2.43$]. The differences between other indices were not significant ($P > 0.05$), as shown in **Table I**.

The differences in pilot attention allocation between the two tasks are shown in **Table II**. In the HCL task, the area outside of these four AOIs was divided into a blank area. Apart from the altimeter, there was a significant difference between each AOI in terms of fixation time distribution (Table II). Significant differences were also observed in fixation count between the scanning modes used in the horizon sensor, heading indicator, and altimeter (Table II).

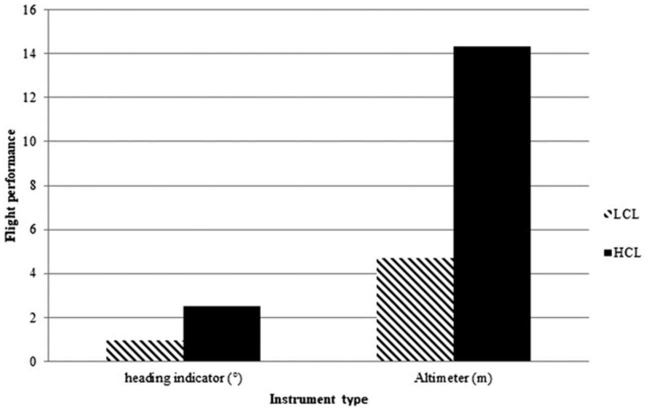

Fig. 1. The participants' flight performance indicators under different cognitive loads.

We determined the main fixation transition path in both tasks based on the percent of transition count matrix among all AOIs.[11] In the LCL task, the scan path was: Horizon sensor → Airspeed indicator → Altimeter → Heading indicator. In the HCL task, the scan path was: Horizon sensor → Blank → Airspeed indicator → Altimeter → Heading indicator. The fixation order frequency was used to determine the scan paths in two tasks as listed in **Table III**. Our Chi-squared analysis indicated significant differences in the order of fixation on other instruments (except the horizon sensor) in both tasks.

The participants showed significantly higher visual scanning entropy rate in the HCL task ($M = 0.29$, $SD = 0.22$) than the LCL task [$M = 0.11$, $SD = 0.034$; $t(18) = -2.550$, $P < 0.05$, $d = 1.20$]. The eye movements of the pilots became less systematic in the HCL task.

DISCUSSION

In this study, participant pilots selected different visual search strategies under two levels of cognitive load. Our observations can be explained according to the cognitive resource model.[1] The elasticity of cognitive resources and the adaptability of the pilots, however, suggest that the pilots were fully capable of adjusting their own attention distribution over time to complete the two tasks effectively, as the newly added task did not have time pressure.

We analyzed the eye movement indicators between the two tasks to find that, compared to a single-task flight, the average duration of the pilots' attention was significantly shortened after increasing the cognitive load. Fixation frequency, saccade frequency, and saccade velocity significantly accelerated, at which point the pilot's visual search strategies allowed for rapid information searching and for diverting attention to different AOIs as necessary. The increased cognitive load required greater search speed, so the pilot used a more efficient visual search strategy to compensate. Additional tasks occupying a

Table I. Mean and Standard Deviation of Eye Movement Indicators.

TASK	FIXATION FREQUENCY (COUNT/s)	AVERAGE FIXATION TIME (ms)	SACCADE FREQUENCY (COUNT/s)	AVERAGE SACCADE TIME (ms)	AVERAGE SACCADE AMPLITUDE (°)	SACCADE VELOCITY (°/ms)
LCL	1.26 ± 0.49	899.62 ± 398.71	1.24 ± 0.53	30.60 ± 43.42	12.96 ± 17.68	233.92 ± 131.07
HCL	2.27 ± 0.30**	420.38 ± 60.56**	2.70 ± 0.31**	22.50 ± 19.55	7.39 ± 7.67	211.88 ± 60.12
DF	18	18	18	18	18	18
t	−5.455	3.758	−5.295	0.538	0.914	0.483
P	0.000	0.004	0.000	0.597	0.373	0.635

** $P < 0.01$.

portion of the pilot's cognitive resources can reduce flight performance, partly because in short task duration, flight performance can be recovered as cognitive resources are recovered and as the pilot fully adjusts to the task. The use of entropy as an indicator of new information acquisition activities also reflects the randomness of scanning behavior.[27] By comparing attention and eye entropy, we found that the pilot's eye movement pattern is more regular when the cognitive load is small. To this effect, the process we observed relies on the mental model of the pilot's flight experience and is indicative of a fixed strategy. We speculate that a higher cognitive load requires a greater level of awareness in the pilot.

In the case of a single-task flight, we find that pilots tend to focus more on a fixed AOI, which is recorded for a longer period of time. In this study, this was the horizon area related to attention distribution. For other AOIs, the pilot only solved the corresponding problem by quickly scanning a specific area to complete the information search. We assumed there is a reserved and saved visual search mode for remaining attention to prepare for contingencies that may occur at any time during the flight. Good SA benefits appropriate and timely responses to the unexpected.[7,30] A professional pilot performs with rapid cognitive efficiency and conserves cognitive resources by top-down processing. This information related to the cognitive process is demonstrative of novice pilots' visual scanning skills.

After increasing their cognitive load, our participating pilots gave almost equal attention to horizon sensor and blank areas. They did so to maintain the implementation of the mission while avoiding the interference stimulus and quickly searched out targets to complete the task. The remainder of their attention was evenly distributed in the remaining AOIs to stabilize the performance of the mission. This visual search mode is more efficient and more targeted than the mode employed for a single task. This also suggests that the pilot adjusts his or her visual scanning strategy at a given time to suit the requirements of the task at hand.

Previous studies have shown that expert pilots' information processing and cognitive abilities are more likely to be programmed and automated to process information in a modular manner, which allows them to quickly extract and encode information as they complete any given task.[4] This temporal advantage assists the pilot in effective multitasking. From the perspective of human-automation interactions, and for the sake of multitask management (with the exception of the optimization of system design), this relates to the system optimization of information representations on the flight deck.[23] This further relates to human-computer interactions such as training for scanning and attention allocation based on eye movement behavior. Similar training for efficient attention distribution and eye movement patterns under high cognitive load can optimize the trainee pilot's multitask management and information priorities.

Military pilots benefit from learning efficient visual search modes[1,21,22] and top-down information processing to meet the needs of multi-information perception and processing.[2,25] The scanning path is the order in which pilots give attention to relevant AOIs. The path also formed under certain rules. In the HCL task, an additional search target appeared which required the pilot to distribute his attention to the search target and perform a simple cognitive process. Thus, the

Table II. Fixation Time and Fixation Count of Different Tasks in Each Area of Interest.

		AREA OF INTEREST			
INDEX	**TASK**	**ALTIMETER**	**HEADING INDICATOR**	**AIRSPEED INDICATOR**	**HORIZON SENSOR**
Fixation time	LCL	0.11 ± 0.07	0.03 ± 0.03	0.09 ± 0.08	0.77 ± 0.14
	HCL	0.08 ± 0.07	0.08 ± 0.07*	0.04 ± 0.03*	0.46 ± 0.21**
DF		17	17	17	17
t		0.626	-2.122	2.417	7.512
P		0.269	0.024	0.013	0.000
d		0.428	-0.928	0.827	1.737
Fixation count	LCL	0.19 ± 0.10	0.04 ± 0.04	0.15 ± 0.09	0.62 ± 0.16
	HCL	0.07 ± 0.07**	0.07 ± 0.07*	0.11 ± 0.13	0.31 ± 0.10**
DF		17	17	17	17
t		3.554	-2.311	1.539	6.904
P		0.001	0.017	0.071	0.000
d		1.390	-0.526	0.357	2.323

* $P < 0.05$, **$P < 0.01$.

Table III. Different Tasks in Each Area of Interest with Order Frequency.

TASK	ORDER	ALTIMETER	HEADING INDICATOR	AIRSPEED INDICATOR	HORIZON SENSOR	BLANK AREA
LCL	0	1	6	3	0	0
	1	5	2	5	25	0
	2	6	3	19	8	0
	3	23	4	5	1	0
	4	1	21	4	2	0
	5	0	0	0	0	0
HCL	0	2	3	3	1	0
	1	1	2	2	19	12
	2	3	2	4	11	16
	3	9	9	11	3	5
	4	15	9	7	1	3
	5	6	11	10	1	0
DF		16	16	16	16	
Chi-squared		29.493**	20.392**	25.504**	4.500	
Cramer's V		0.858	0.714	0.798	0.335	

** $P < 0.01$.

attention order changed. The base sequence in the HCL task was similar to that in the LCL task apart from the added fixation on the blank area. The fixation order reflects the importance of each instrument and indirectly shows that the importance of each instrument in the task is fixed. We designed the task to mimic the manual operation of instruments in horizontal flight, so the rule is also limited to similar tasks in real-world situations.

In different flight phases with varying level of difficulty (e.g., takeoff or landing), the pilot will assign his or her attention differently. We plan to explore this phenomenon in our follow-up research.

Pilots constantly adjust their search strategies to meet the two-task requirements at a certain SA level. The eye movement characteristics of different pilots reveal differences in attention distribution under different conditions and allow for SA level predictions. Kasarskis et al.[14] found that eye movement experiments in aviation tasks are mostly controlled by the top-down mechanism, so the fixation locus and attention are tightly linked with each other. The close relationship between fixations and task performance in landing tasks also shows that fixations reflect the primary distribution of attention.

The findings of this study may indeed have practical implications. Namely, eye training tasks may be tailored to the benefit of novice pilots. Our findings suggest that scanning pattern efficiency is higher under higher cognitive loads; related eye movement training under high-load tasks can improve the trainee pilot's ability to process and manage multiple sources of information, facilitating better flight performance in high load tasks and reducing mistakes otherwise caused by cognitive overload. The specific eye movement patterns of high-performing pilots performing daily missions comprise very useful information. Establishing a set of standardized scanning models and adding them into training for novice pilots can help pilots to optimize their attention distribution in the cockpit and develop correct and flexible scanning patterns.

We believe the results presented here may be used to improve the ability of novice pilots to manage the abundance of dynamic visual information presented to them during flight. During flight, massive quantities of information from flight instruments and instructions on the flight deck greatly increase the pilot's cognitive load. Eye movement training can promote information processing, thereby enhancing the pilot's performance on high information load tasks. Training for scanning modes and attention distribution encompass the management of multiple information sources and task prioritization. Novice pilots may also benefit from mastering the eye movement modes already presented by expert pilots.[19,22,24]

In this study, we conducted a simulated flight experiment with different cognitive loads and measured how pilot subjects adjusted their corresponding search modes and eye movement strategies to complete different tasks. The difficulties of the tasks were set differently to simulate IFR conditions. The pilots adjusted their eye movement strategies to complete the tasks based on the difficulty. Our findings may contribute to further development and exploration of eye movement analyses as an objective indicator of SA.

We found that increasing the cognitive load influences visual scanning strategy within a brief duration of time, but the results presented here are inconclusive. This study was limited to the simulation of a level flight phase wherein the aircraft attitude was simply maintained. Further research is needed to investigate flight missions during different phases and difficulties. The tasks we designed were likewise not sufficiently difficult to produce significant differences in the flight performance statistics between LCL and HCL. Many studies support the idea that shifts in attention made by the observer are reflected in eye fixations.[16] In IFR conditions, there appears to be a close link between the attention distribution in each flight instrument and the importance of the instruments to a certain task. In this study, the increased cognitive load associated with the HCL task resulted in different eye movement patterns compared to the single task model. The results presented here may establish a foundation for the standardized eye movement-based training of novice pilots in the future.

ACKNOWLEDGMENTS

Financial Disclosure Statement: The authors have no competing interests to declare. Funding was from the Fundamental Research Funds for the Central University [GK201704022] to Tianjiao Lu.

Authors and affiliations: Tianjiao Lu, Ph.D. candidate, Yuan Li, Ph.D., Lecturer, and Xuqun You, Ph.D., Professor, Shaanxi Key Laboratory of Behavior and Cognitive Neuroscience, Institute of Psychology, Shaanxi Normal University, Shaanxi Province, Xi'an, China; Zhenshan Lou, Master, Archiater, Hangzhou Center of Aeromedical Evaluation and Training for Air Force, Zhejiang Province, Hangzhou, China; and Feng Shao, Ph.D., Director, Department of Psychology, Du Jiangyan Center of Aeromedical Evalution and Training for Air Force, Sichuan Province, Du Jiangyan, China.

REFERENCES

1. Bellenkes A, Bason R, Yacavone DW. Spatial disorientation in naval aviation mishaps: a review of class a incidents from 1980 through 1989. Aviat Space Environ Med. 1992; 63(2):128–131.
2. Chan AHS, Tang NYW. Visual lobe shape and search performance for targets of different difficulty. Ergonom Brozekics. 2007; 50(2):289–318.
3. Cooper G, Sweller J. Effects of schema acquisition and rule automation on mathematical problem-solving transfer. J Educ Psychol. 1987; 79(4):347–362.
4. Dzeng RJ, Lin CT, Fang YC. Using eye-tracker to compare search patterns between experienced and novice workers for site hazard identification. Saf Sci. 2016; 82:56–67.
5. Endsley MR. Measurement of situation awareness in dynamic systems. Hum Factors. 1995; 37(1):65–84.
6. Endsley MR, Garland DJ, editors. Situation awareness analysis and measurement. Boca Raton (FL, USA): CRC Press; 2000.
7. Engelken EJ, Stevens KW, Bell AF, Enderle JD. Analysis of pursuit tracking eye movements in pilots and nonfliers. Biomed Sci Instrum. 1994; 30: 93–97.
8. Fitts PM, Jones RE, Milton JL. Eye fixations of aircraft pilots. III. Frequency, duration, and sequence fixations when flying air force Ground-Controlled Approach System (GCA). Wright-Patterson AFB (OH, USA): Air Materiel Command; 1949.
9. Gould JD. Eye movements during visual search and memory search. J Exp Psychol. 1973; 98(1):184–195.
10. Harris RL Sr, Glover BJ, Spady AA Jr. Analytical techniques of pilot scanning behavior and their application. Hampton (VA, USA): NASA Langley Research Center; 1986. NASA Technical Paper 2525.
11. Hasanzadeh S, Esmaeili B, Dodd MD. Measuring construction workers' real-time situation awareness using mobile eye-tracking. In: Perdomo-Rivera JL, Gonzales-Quevedo A, del Puerto CL, Maldonado-Fortunet F, Molina-Bas OI, editors. Proceedings of the 2016 Construction Research Congress; May 31–June 2, 2016; San Juan, Puerto Rico. Reston (VA, USA): American Society of Civil Engineers; 2016:2894–2904.
12. Hauland G. Measuring individual and team situation awareness during planning tasks in training of en route air traffic control. Int J Aviat Psychol. 2008; 18(3):290–304.
13. Itoh Y, Hayashi Y, Tsukui I, Saito S. The ergonomic evaluation of eye movement and mental workload in aircraft pilots. Ergonomics. 1990; 33(6):719–733.
14. Kasarskis P, Stehwien J, Hickox J, Aretz A, Wickens C. Comparison of expert and novice scan behaviors during VFR flight [abstract]. In: Proceedings of the 11th International Symposium on Aviation Psychology; March 5–8, 2001; Columbus, OH, USA. Columbus (OH, USA): Ohio State University; 2001.
15. Moore K, Gugerty L. Development of a novel measure of situation awareness: the case for eye movement analysis. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. Los Angeles (CA, USA): SAGE Publications; 2010; 54(19):1650–1654.
16. Muehlethaler CM, Knecht CP. Situation awareness training for general aviation pilots using eye tracking. IFAC-PapersOnLine. 2016; 49(19):66–71.
17. Naglieri JA, Das JP. Construct and criterion-related validity of planning, simultaneous, and successive cognitive processing tasks. J Psychoed Assess. 1987; 5(4):353–363.
18. Nicholson B, O'Hare D. The effects of individual differences, prior experience and cognitive load on the transfer of dynamic decision-making performance. Ergonomics. 2014; 57(9):1353–1365.
19. O'Brien KS, O'Hare D. Situational awareness ability and cognitive skills training in a complex real-world task. Ergonomics. 2007; 50(7):1064–1091.
20. Pollatsek A, Narayanaan V, Pradhan A, Fisher DL. Using eye movements to evaluate a PC-based risk awareness and perception training program on a driving simulator. Hum Factors. 2006; 48(3):447–464.
21. Ren Y, Han Y, Sui X. The saccades and its mechanism in the process of visual search. Xinli Kexue Jinzhan [Advances in Psychological Science]. 2006; 14(03):340–345 [in Chinese].
22. Sadasivan S, Greenstein JS, Gramopadhye AK, Duchowski AT. Use of eye movements as feedforward training for a synthetic aircraft inspection task. In: Proceedings of the SIGCHI conference on Human Factors in Computing Systems; April 2005; Portland, OR, USA. New York (NY, USA): Association for Computing Machinery; 2005:141–149.
23. Schnell T, Merchant S. Assessing pilot performance in flight decks equipped with synthetic vision information systems. Final Report. Cedar Rapids (IA, USA): Rockwell Collins; 2001.
24. Shapiro KL, Raymond JE. Training of efficient oculomotor strategies enhances skill acquisition. Acta Psychol (Amst). 1989; 71(1–3):217–242.
25. Soliman AM, Mathna EK. Metacognitive strategy training improves driving situation awareness. Soc Behav Personal. 2009; 37(9):1161–1170.
26. Theeuwes J, Kooi FL. Parallel search for a conjunction of contrast polarity and shape. Vision Res. 1994; 34(22):3013–3016.
27. van Dijk H, van de Merwe K, Zon R. A coherent impression of the pilots' situation awareness: studying relevant human factors tools. Int J Aviat Psychol. 2011; 21(4):343–356.
28. van Meeuwen LW, Jarodzka H, Brand Gruwel S, Kirschner PA, de Bock JJ, et al. Identification of effective visual problem solving strategies in a complex visual domain. Learn Instr. 2014; 32:10–21.
29. Wickens CD. Aerospace psychology. In: Hancock PA, editor. Handbook of perception and cognition series, 2nd ed. Human performance and ergonomics. San Diego (CA, USA): Academic Press; 1999:195–242.
30. Wickens CD. Situation awareness and workload in aviation. Curr Dir Psychol Sci. 2002; 11(4):128–133.