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EFFECT OF DAYTIME AND NIGHTTIME ON HELICOPTER PILOT'S GAZE BEHAVIOR: A PRELIMINARY STUDY IN REAL FLIGHT CONDITIONS

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Abstract. Nighttime affects pilot visual scan patterns and increase the risks of helicopter operations, contributing to many helicopter accidents and incidents. Several past studies have attempted to examine the effect of nighttime on helicopter pilot gaze behavior, but researchers had limited success due to the difficulty of collecting representative data under real flight conditions. The present study attempted to address this challenge by conducting a real flight study involving daytime and nighttime traffic pattern tasks and using a Tobii Glasses 3 eye-tracking device to collect helicopter pilot eye-tracking data. This study preliminarily explored the feasibility of data collection in real flight conditions in the context of eye-tracking research on civil helicopter pilots in China. Due to safety considerations, only one pilot was recruited to collect data in multiple tasks. Differences and correlations were examined for all gaze behavior metrics. The results suggested that pilot gaze behavior metrics and their correlations differed between daytime and nighttime flights in aspects critical to aviation safety. Pilot gaze behavior also varied with the flight phase. The findings from this study serve as a reference for optimizing helicopter pilot training systems, improving pilot performance during nighttime flights, and ensuring flight safety on helicopters.

Keywords: aviation safety, helicopter pilot, gaze behavior, daytime and nighttime, real flights, preliminary study.

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1. Introduction

Nighttime conditions constrain helicopter operations due to increased danger for pilots. In the United States between 2008 and 2018 according to the National Transportation Safety Board aviation database, weather was a factor in 28% of fatal helicopter accidents, and bad visibility conditions due to low illumination were responsible for most fatal weather-related helicopter accidents (Ramee et al., 2021). Within these helicopter events, 56% of visibility events occurred at night. This is to be expected, as spatial disorientation is more likely to occur at night when there are few visual points of reference for the pilot, leading to a high risk of fatal accidents (Sánchez-Tena et al., 2018). Additionally, Kiliç and Gümüş (2020) have proven that nighttime flights require greater pilot attention. To reduce the risks associated with nighttime flights, the European Commission (2012) set a minimum visibility of 5 kilometers for nighttime flights with Visual Flight Rules (VFR). Meanwhile, the Federal Aviation Administration (FAA) (2019) required pilots to complete three nighttime takeoffs and landings within the last 90 days for the nighttime flying endorsement.

To improve the safety of helicopter flights at night, it is necessary to study the effect of nighttime flying on pilots (Luzik & Akmaldinova, 2006). Previous studies have found that nighttime helicopter flights elicited a different psychophysiological response in pilots (Bustamante-Sánchez & Clemente-Suárez, 2020). At night, most of the normal orientation information is lost. The remaining is evenly distributed between the vestibular system and the proprioceptive system, both of which are prone to illusions and misunderstandings, which places a high demand on the ability of pilots to process information (Newman, 2007). As such, it is crucial to understand a pilot's information processing abilities during nighttime flights. Eye tracking is a noninvasive method that reveals discrete cognitive processes and strategies used to direct behavior (Ayala et al., 2022). Eye movement measures are an important index for human-machine interaction and usability assessment, hazard perception in driving, and pilot behavior assessment in aviation (Vlačić et al., 2019). Hence, the current investigation sought to examine the utility of gaze behavior metrics for objectively characterizing information processing in helicopter pilots during daytime and nighttime flights.

A comprehensive understanding of how pilots manage cognitive tasks and information processing under these challenging conditions is crucial for mitigating the risks associated with nighttime flights.

The pattern of fixations and eye movements used to sample visual information is collectively referred to as gaze behavior (Ayala et al., 2023). Specifically, two related eye movements are fixations (i.e., the duration of one's gaze pointing to a specific position) and saccades (i.e., the rapid movement of the eyes from one fixation point to another) (Ziv, 2016). Gazing behavior is closely related to the cognitive, potential perception, and motor processes associated with the selection and processing of relevant sensory information (De Brouwer et al., 2021). Under varying illumination levels, human visual performance changes significantly, affecting gaze behavior (Loe, 2016). In the low illumination condition, rod cells in the retina become more active, enhancing night vision but reducing color clarity. In the high illumination condition, cone cells increase their activity, improving color discrimination and visual sharpness. These changes in illumination prompt the visual system to adapt to different gaze requirements, reflecting the eye's sensitivity and fine-tuned adjustment to varying illumination conditions (Sharma & Chakraborty, 2024). Thus, gaze behavior is directly influenced by the external environment. Tamura et al. (2016) evaluated eye movements during daytime and nighttime takeoffs and analyzed their correlation with subjective climbing perception. Rainieri et al. (2021) assessed visual scanning techniques in helicopter pilots during an open sea flight simulation under daytime and nighttime conditions and found that pilots' performance and perceived mental workload varied with changes in expertise and flight conditions.

Although some previous studies have analyzed the gaze behavior of pilots during daytime and nighttime flights, due to the difficulty of researching actual flight conditions, these studies collected little information on the gaze behavior of helicopter pilots during real daytime and nighttime flights. Most researchers have attempted well-designed simulation flight experiments to collect data on the gaze behavior of helicopter pilots, but these experiments have substantial limitations. Veltman (2002) found that the blink frequency of pilots decreased in simulation flights, whereas a large increase was found in real flights. This can be partly explained by eye movements, which were made more frequently during real flights. With advances in sensor technology, eye-tracking data acquisition via wearable devices has become increasingly convenient in real working conditions. These eye-tracking data provide the opportunity to analyze the gaze behavior of helicopter pilots during real daytime and nighttime flights.

This study aims to investigate the pilot's gaze behavior in real daytime and nighttime flight conditions, further explaining the differences in information processing between these two conditions. Three traffic pattern tasks were executed in both daytime and nighttime flight conditions. Based on a wearable eye-tracking device, eight gaze behavior metrics were extracted, and nine areas of interest (AOIs) were defined. The statistical analysis was used to determine whether gaze behavior metrics were able to differentiate daytime flights and nighttime flights. Moreover, the differences in gaze behavior metrics under different flight phases during daytime and nighttime flights were analyzed. The findings of this paper could have important implications for developing effective pilot training programs and improving the safety of nighttime helicopter flights.

2. Methods

2.1. Subject

Due to the lack of research on using eye-tracking devices for data collection in real helicopter flights in China, the potential risks involved in the experiment led to the recruitment of only one subject for this study. The subject was a 27-year-old female Chinese pilot cadet with approximately 70 flight hours from the Civil Aviation Flight University of China. The subject (pilot flying, PF) sat in the right seat of the cockpit and piloted the helicopter. To ensure safety, there was a 36-year-old male Chinese flight instructor (pilot monitoring, PM) with approximately 5500 flight hours sitting in the left seat of the cockpit to take over in case of any emergency. Both of them had normal or corrected-to-normal vision and hearing, and they signed an informed consent form before participating. This research complied with the tenets of the Declaration of Helsinki and was approved by the Ethical Review Board of Southwest Jiaotong University with No. SWJTU-2109-001-QT.

2.2. Helicopter

The helicopter used in the experiment was a Robinson R44 helicopter (Registration number: B-70Y9) that belonged to the Civil Aviation Flight University of China, as shown in Figure 1. The Robinson R44 is a lightweight helicopter with a single engine, a semirigid two-bladed main rotor, and a two-bladed tail rotor and has been widely used in pilot training.

Figure 1. The helicopter used in the experiment

2.3. Eye tracker

The authors used an eye tracker manufactured by Tobii AB (Tobii Glasses 3, the third-generation instrument), as shown in Figure 2. This device incorporated a scene camera that captured 95° horizontally by 63° vertically with a sampling frequency of 140 Hz, along with a microphone, gyroscope, accelerometer, and magnetometer. Data were streamed from the glasses via a cable to a recording unit worn by the subject. Data were also stored on a secure digital (SD) card in a variety of file formats: csv, JSON, and mp4. To ensure the accuracy of data capture and reduce the impact of sunlight, the subject wore a clear and tinted protective lense together with the eye tracker.

The cockpit was split into nine AOIs, corresponding to the external view and different flight instruments and displays that pilots could examine during a flight, as shown in Table 1 and Figure 3. Furthermore, the eye-tracking heatmaps were examined to determine the distribution of pilot fixation points under different flight phases during daytime and nighttime flights. The aggregation of fixations over time is known as the heatmap, which indicates the total time spent processing the information within a chosen period (Huo et al., 2020).

Figure 2. The eye tracker used in the experiment

2.4. Experimental procedure

The subject wore the eye tracker and flew the helicopter under visual flight rules. It should be noted that this study only collected the eye movement data of PF in the whole experiment. The subject was required to complete three daytime VFR traffic pattern tasks and three nighttime VFR traffic pattern tasks, and the details of each task are shown in Figure 4. Xinjin Airport was selected to carry out the experiment; it has a runway for fixed-wing aircrafts and a heliport for helicopters. The environmental conditions of each task complied with the requirements of the Operation Safety Bulletin (OSB-2022-05) issued by the Civil Aviation Administration of China (CAAC). Before each task started, a digital lux meter (TES 1330A) was used to test the illuminance on the ground, with specific values shown in Figure 4.

On March 20th and April 24th, before the subject executed the tasks for the day, the staff needed to equip her with the eye tracker and calibrate the eye-tracking signals to ensure that the data were recorded properly. Afterward, the subject entered the cockpit while wearing the eye tracker, adjusted seating positions, and tried to make herself comfortable before beginning the tasks. For each task, the subject took off and climbed with an airspeed of 60 kt. After the helicopter flew above 1800 ft, the subject completed the After Takeoff Checklist and continued to climb. Once the helicopter reached turning point 1 (Hangar) on the ground, the subject turned it right to the crosswind leg. Then, after the helicopter reached over

Table 1. Description of AOIs

AOI	Description	AOI	Description	AOI	Description
1	The vertical speed indicator	4	The dual tachometer	7	The navigation display
2	The airspeed indicator	5	The turn coordinator	8	The manifold pressure gage
3	The attitude indicator	6	The altimeter	9	The view out of the window

Figure 3. Illustration of the nine different AOIs

After Takeoff Checklist

Landing light..Off
Power setting..Check

Before Landing Checklist

Landing light..As required
Power setting..Check

Traffic pattern task		Date	Illuminance (On the ground)
Daytime	No.1	March 20th, 2023	17050~17720 lx
	No.2		
	No.3	April 24th, 2023	16880~17340 lx
Nighttime	No.1	April 24th, 2023	2.82~3.41 lx
	No.2		
	No.3		

Figure 4. Schematic view of the experimental procedure

2100 ft, the subject leveled off the helicopter, accelerated to an airspeed of 75 kt, and maintained a straight flight path. After reaching turning point 2 (River bay) on the ground, the helicopter turned right to the downwind leg and maintained a straight flight path. Before the helicopter reached the next turning point, the subject completed the Before Landing Checklist. Once the helicopter reached turning point 3 (Park) on the ground, the subject turned it right to the base leg, descended to 1800 ft, decelerated to an airspeed of 60 kt, and maintained a straight flight path. After that, when the helicopter reached turning point 4 (Fishpond) on the ground, the subject turned it right to the final leg and landed the helicopter on the heliport. Meanwhile, the subject was required to perform radio calls announcing the position in each task. After completing each task, the subject rested for 10 minutes on the heliport before starting the next task, ensuring that the physiological data collected in the next task would not be affected by the previous task. The duration of each task was approximately 10 minutes. After completing all tasks for the day, the subject was required to exit the helicopter while wearing the eye tracker, then the staff removed the eye tracker from the subject to prevent any data loss due to improper handling.

In addition, based on the changes in flight altitude, each task was divided into three flight phases (FP), namely, takeoff and climb (FP I), cruise (FP II), and descent and landing (FP III). FP I was from takeoff to the end of climb, which was before reaching turning point 2 (River bay) on the ground. FP II was from the end of the climb to the start of descent, which was at turning point 3 (Park) on the ground. FP III was from the start of descent to the landing.

2.5. Gaze behavior metrics

The algorithms built into the eye tracker were used to calculate the position of the eye and gaze points. Seven gaze behavior metrics, as shown in Table 2, were extracted by Tobii Pro Lab (1.217) and used in the analysis. The presented metrics were chosen because they demonstrated a clear relationship with individuals' physical and psychological states (Bitkina et al., 2021). Since pupil diameter was greatly affected by changes in external light conditions, this study standardized FAPD by subtracting the mean value (Ahlstrom et al., 2021).

Gaze entropy-based metrics provide a good indication of the dispersion of the gaze over the visual field. Compared to the metrics above, gaze entropy (GE) relies on less sensitive detection methods and less sophisticated eye-tracking systems. Hence, a 10-second average sliding window was used to generate a time trace that reflected how GE evolved over time (Ayala et al., 2023). GE was calculated using Shannon's equation, as shown in the Equation (1) (Diaz-Piedra et al., 2019).

$$H_g(X) = -\sum p(x,y)\cdot\log_2 p(x,y), \tag{1}$$

where $p(x, y)$ is the probability of the pilot's gaze falling in the (x, y) position of the visual field for a given sample, estimated from the full recording. This provides a measure of the average uncertainty of the instantaneous gaze position during flight, or equivalently, the information provided by a single observation, measured in bits.

Table 2. Description of gaze behavior metrics

Metric	Description	Metric	Description
FD	Fixation duration	SD	Saccade duration
FPX	Fixation point X	SAV	Saccade average velocity
FPY	Fixation point Y	SPV	Saccade peak velocity
FAPD	Fixation average pupil diameter	–	–

2.6. Statistical analysis

To determine whether there were significant correlations between and differences in pilot gaze behavior metrics under real daytime and nighttime flight conditions, statistical analysis was used, as shown in Figure 5. For determining the normality of data distribution, the normality test was first carried out. Among the commonly used normality test methods, the Shapiro-Wilk test is usually suitable for use with small sample sizes ($n \le 50$), while the Kolmogorov-Smirnov test is generally suitable for use with large sample sizes ($n > 50$) (Yap & Sim, 2011). If the variable was normally distributed, it was examined using repeated-measures analyses of variance (ANOVAs), T tests, and Pearson correlation analysis; or else it was examined using Friedman tests, Wilcoxon tests, and Spearman correlation analysis. Specifically, T tests and Wilcoxon tests were used to compare the differences between two groups, and repeated-measures ANOVAs and Friedman tests were used to compare the differences among multiple groups (more than two). The statistical analysis was performed using IBM SPSS 26, and the significance level was set at $p < 0.05$.

3. Results

Heatmaps were generated for each of the three flight phases during daytime and nighttime flights using Tobii Pro Lab, as shown in Figure 6. The red arrow points to the instrument that the pilot focused on at each phase. It can be seen that the distribution of the pilot's fixation points under different flight phases during daytime and nighttime flights differed. In daytime flights, the top 4 AOIs with the largest number of fixation points out of the 9 AOIs were AOI 9, AOI 6, AOI 2, and AOI 3. Similarly, in nighttime flights, the top four AOIs with the largest number of fixation points out of the nine AOIs were AOI 9, AOI 2, AOI 3, and AOI 4. To further explore the changes in gaze behavior metrics within the scope of AOI, gaze behavior metrics in AOI 9, AOI 2, and AOI 3 were separately extracted for analysis, for a total of twenty gaze behavior metrics to be analyzed in this study, namely, FD-All, FPX-All, FPY-All, FAPD-All, GE, FD-AOI2, FPX-AOI2, FPY-AOI2, FAPD-AOI2, FD-AOI3, FPX-AOI3, FPY-AOI3, FAPD-AOI3, FD-AOI9, FPX-AOI9, FPY-AOI9, FAPD-AOI9, SD, SAV, and SPV.

Table 3 shows the results of the normality test for each gaze behavior metric under different flight phases

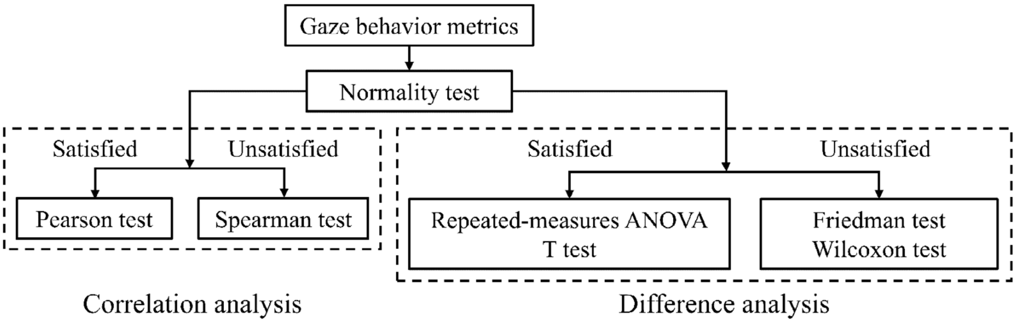

Figure 5. Flowchart of the statistical analysis

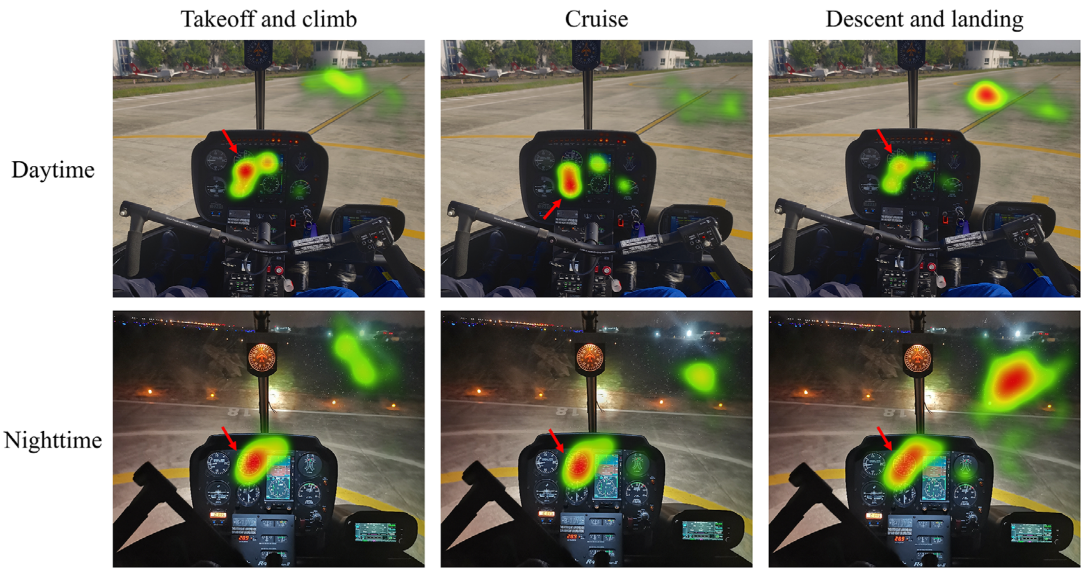

Figure 6. Heatmaps of pilot gaze during different flight phases in daytime and nighttime flights

during daytime and nighttime flights, and $p > 0.05$ is the significance criterion. If the p value meets the criteria, it shows a checkmark ("√"); otherwise, it shows "/". As such, to compare the differences among the three flight phases, a repeated-measures ANOVA was used on FD-All, FPX-AOI3, FPY-AOI9, and FAPD-AOI9 in daytime flights and on FD-All, FPX-AOI2, FPY-AOI2, FAPD-AOI2, FPX-AOI3, FAPD-AOI3, FAPD-AOI9, and SD in nighttime flights. In addition, to compare the differences between daytime and nighttime flights, a T test was used on FD-All, FPX-AOI3, FPY-AOI3, FAPD-AOI3, FPY-AOI9, FAPD-AOI9, and SD in FP I; on FD-All, FPX-AOI2, FPY-AOI2, FAPD-AOI2, FPX-AOI3, FAPD-AOI3, FAPD-AOI9, SD, and SAV in FP II; and on FD-All, FPX-All, FD-AOI2, FPY-AOI2, FAPD-AOI2, FPX-AOI3, FD-AOI9, FPX-AOI9, FPY-AOI9, and FAPD-AOI9 in FP III.

Table 3. Results of normality tests

Gaze behavior metrics	Daytime flight			Nighttime flight		
	FP I	FP II	FP III	FP I	FP II	FP III
FD-All	/	√	√	√	/	/
FPX-All	/	√	√	/	/	√
FPY-All	√	/	/	/	/	/
FAPD-All	√	√	√	√	√	√
GE	/	/	/	/	/	/
FD-AOI2	/	/	√	/	/	√
FPX-AOI2	/	√	/	√	√	√
FPY-AOI2	/	√	√	√	√	√
FAPD-AOI2	/	√	√	√	√	√
FD-AOI3	/	/	/	/	/	/
FPX-AOI3	√	√	√	√	√	√
FPY-AOI3	√	√	/	√	/	/
FAPD-AOI3	√	√	/	√	√	√
FD-AOI9	/	/	√	√	/	√
FPX-AOI9	/	/	√	/	/	√
FPY-AOI9	√	√	√	√	/	√
FAPD-AOI9	√	√	√	√	√	√
SD	√	√	/	√	√	√
SAV	√	√	/	/	√	/
SPV	√	√	/	/	/	/

Table 4 shows the results of comparisons among different flight phases under daytime and nighttime conditions, with $p < 0.05$ as the significance criterion. If the p value did not meet this criterion, the comparison was labeled "not significant". In daytime flights, FD-All, FPX-All, FPY-All, FPX-AOI2, FPY-AOI2, FPX-AOI3, FD-AOI9, FPX-AOI9, FPY-AOI9, SD, SAV, and SPV all significantly differentiated among different flight phases. In nighttime flights, FD-All, FPX-All, FPY-All, FD-AOI2, FPX-AOI2, FPX-AOI9, FPY-AOI9, FAPD-AOI9, SAV, and SPV significantly differentiated among different flight phases.

Based on the results of Table 4, 8 gaze behavior metrics that significantly differentiated among different flight phases in both daytime and nighttime flights were extracted to analyze their variation, as shown in Figure 7. The average values of FD-All, FPX-All, FPX-AOI2, FPX-AOI9, SAV, and SPV during daytime flights were higher than those during nighttime flights, while the average values of FPY-All and FPY-AOI9 during nighttime flights were higher than those during daytime flights.

Likewise, Table 5 shows the results of comparisons between daytime and nighttime flights under different flight phases, with $p < 0.05$ as the significance criterion. If the p value did not meet the criterion, the comparison was labeled "not significant". In FP I, most gaze behavior metrics significantly ditfferentiated between daytime and nighttime flights, except for FAPD-All, FD-AOI2, FAPD-AOI2, and FD-AOI3. In FP II, only FAPD-All, FD-AOI2, and SD did not significantly differentiate between daytime and nighttime flights. In FP III, only FAPD-All, FD-AOI2, FD-AOI3, and SD did not significantly differentiate between daytime and nighttime flights.

On the basis of the results of Table 5, 15 gaze behavior metrics that significantly differentiated between daytime and nighttime flights in all flight phases were extracted to analyze their variation, as shown in Figure 8. The average values of FD-All, FAPD-AOI3, FD-AOI9, FPX-All, FPX-AOI2, FPX-AOI3, FPX-AOI9, SAV, and SPV during daytime flights were higher than those during nighttime flights,

Table 4. Comparisons of gaze behavior metrics among different flight phases in daytime and nighttime flights

Gaze behavior metrics	*p* values		Gaze behavior metrics	*p* values	
	Daytime flight	Nighttime flight		Daytime flight	Nighttime flight
FD-All	0.003	0.002	FPX-AOI3	0.026	Not significant
FPX-All	≤0.001	0.001	FPY-AOI3	Not significant	Not significant
FPY-All	≤0.001	≤0.001	FAPD-AOI3	Not significant	Not significant
FAPD-All	Not significant	Not significant	FD-AOI9	0.005	Not significant
GE	Not significant	Not significant	FPX-AOI9	≤0.001	≤0.001
FD-AOI2	Not significant	0.02	FPY-AOI9	≤0.001	≤0.001
FPX-AOI2	≤0.001	0.005	FAPD-AOI9	Not significant	≤0.001
FPY-AOI2	0.022	Not significant	SD	≤0.001	Not significant
FAPD-AOI2	Not significant	Not significant	SAV	0.001	0.001
FD-AOI3	Not significant	Not significant	SPV	0.001	0.004

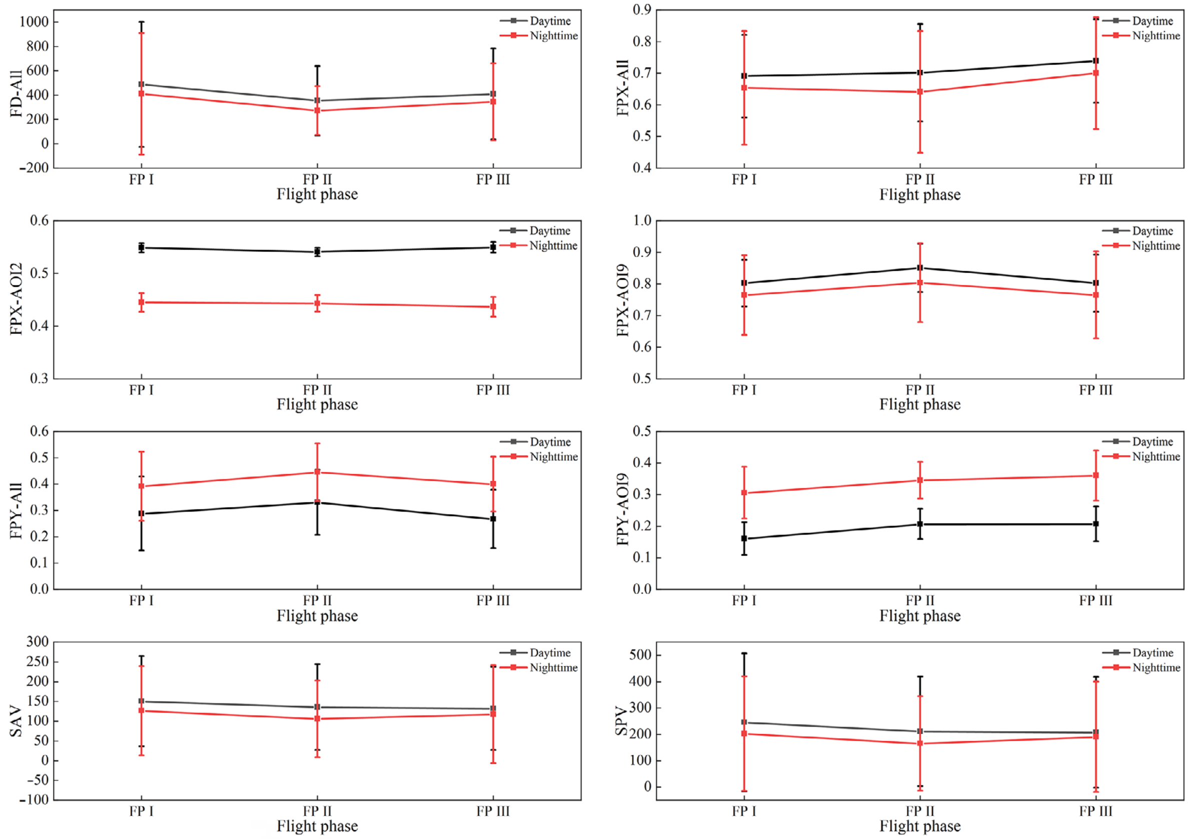

Figure 7. Variation of gaze behavior metrics among different flight phases in daytime and nighttime flights

Table 5. Comparisons of gaze behavior metrics between daytime and nighttime flights in different flight phases

Gaze behavior metrics	p values		
	FP I	FP II	FP III
FD-All	≤0.001	≤0.001	≤0.001
FPX-All	0.003	≤0.001	≤0.001
FPY-All	≤0.001	≤0.001	≤0.001
FAPD-All	Not significant	Not significant	Not significant
GE	≤0.001	0.004	≤0.001
FD-AOI2	Not significant	Not significant	Not significant
FPX-AOI2	≤0.001	≤0.001	≤0.001
FPY-AOI2	≤0.001	≤0.001	≤0.001
FAPD-AOI2	Not significant	≤0.001	0.005
FD-AOI3	Not significant	0.015	Not significant
FPX-AOI3	≤0.001	≤0.001	≤0.001
FPY-AOI3	≤0.001	≤0.001	≤0.001
FAPD-AOI3	0.005	0.018	0.048
FD-AOI9	≤0.001	≤0.001	≤0.001
FPX-AOI9	0.033	0.005	≤0.001
FPY-AOI9	≤0.001	≤0.001	≤0.001
FAPD-AOI9	≤0.001	≤0.001	0.042
SD	0.001	Not significant	Not significant
SAV	≤0.001	≤0.001	≤0.001
SPV	≤0.001	≤0.001	≤0.001

while the average values of FAPD-AOI9, FPY-All, FPY-AOI2, FPY-AOI3, FPY-AOI9, and GE during nighttime flights were higher than those during daytime flights.

Figure 9 shows the results of the correlation analyses of gaze behavior metrics under different flight phases between daytime and nighttime flights. In this figure, boxes containing an asterisk ("*") represent *p* values less than 0.05, while boxes containing two asterisks ("**") represents *p* values less than 0.01. On the color gradient, blue represents *r* values closer to 1 (stronger positive correlations). Red represents *r* values closer to –0.73 (stronger negative correlations). It is clearly seen that the distribution of correlation between gaze behavior metrics varies according to different flight phases of daytime and nighttime flights.

4. Discussion

This study aimed to determine the effect of daytime and nighttime conditions on helicopter pilot gaze behavior using eye-tracking data in real flight conditions. To our knowledge, there is currently a lack of gaze behavior metrics for civil helicopter pilots in real flight conditions in China, and this study helps to fill that gap. Since it is difficult to conduct experiments with helicopter pilots in real flight conditions, few studies have focused on helicopter pilot gaze behavior in real flight conditions-an important contrast to the extensive efforts devoted to automobile

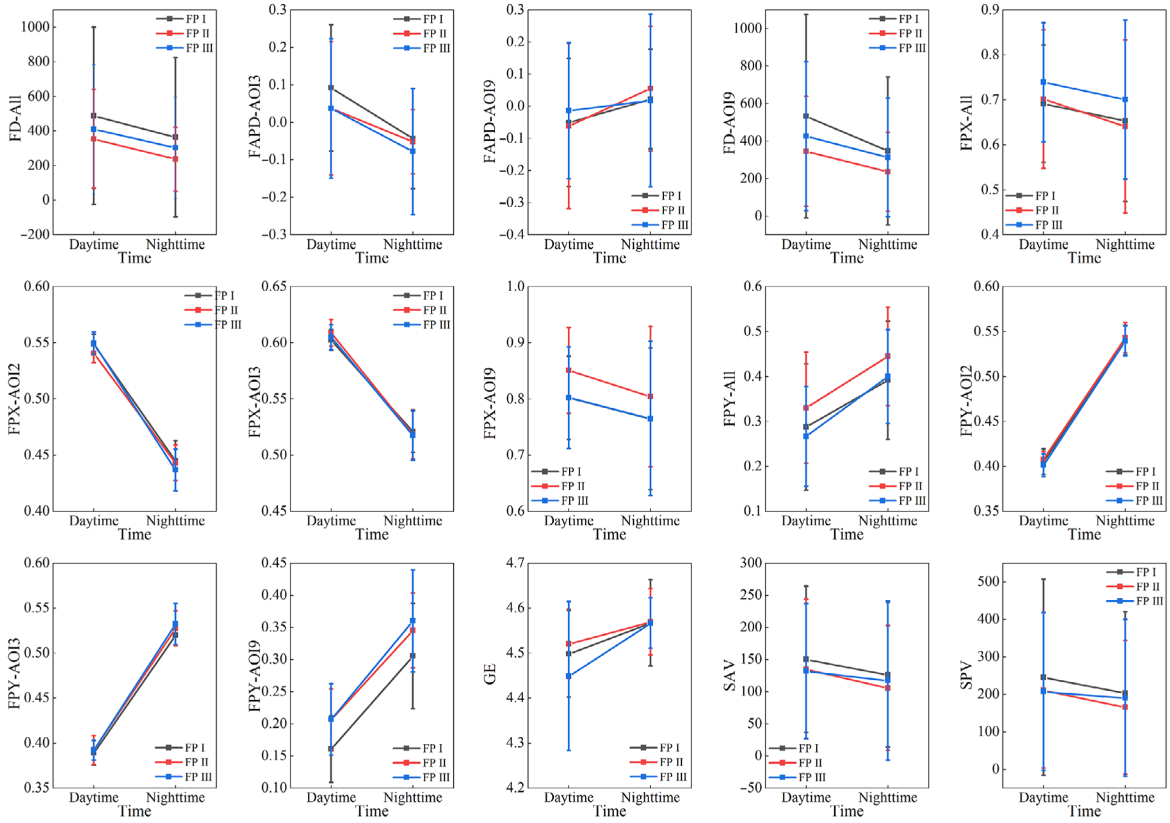

Figure 8. Variation of gaze behavior metrics between daytime and nighttime flights in different flight phases

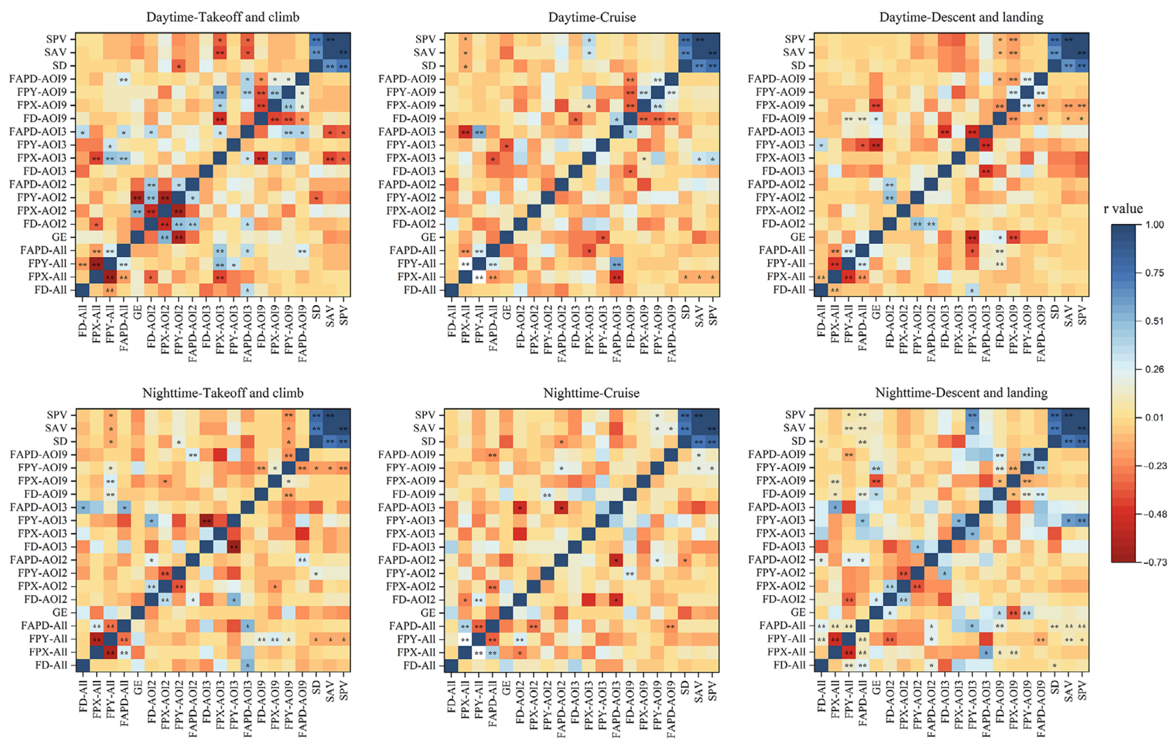

Figure 9. The results of correlation analysis of gaze behavior metrics under different flight phases in daytime and nighttime flights

driver gaze behavior. Therefore, it is worth measuring helicopter pilot eye-tracking data in real flight conditions.

According to heatmaps, regardless of flight time (daytime or nighttime), the pilot focused on the external view (AOI 9), the airspeed indicator (AOI 2), and the attitude indicator (AOI 3). Due to visual flight rules, the pilot had to look at the view out of the window, which might explain why the number of fixation points was highest in AOI 9. Since there were four right turns in each task, the fixation occurred more on the right windshield rather than the left windshield. Moreover, in the descent and landing phase, the allocation of pilot attention appeared biased toward the heliport to monitor and extract the necessary information needed to land. During daytime flights, the pilot's fixations to the heliport were relatively concentrated, while during nighttime flights, the pilot's fixations to the airport were relatively dispersed, which might be because it was more difficult to read heliport information in the nighttime than in the daytime. Because the traffic pattern task set the airspeed and the time of climb and descent, the pilot needed to attend to the airspeed indicator (AOI 2) and the attitude indicator (AOI 3) during the whole task. The airspeed indicator provides the helicopter's flight speed, enabling the pilot to maintain a safe velocity and prevent situations where excessively low speeds may cause the rotor to lose lift. The attitude indicator displays the helicopter's pitch and roll angles, supporting the pilot in preserving spatial orientation, particularly in challenging environments or low-visibility conditions, thereby avoiding loss of control or excessive bank angles. This result was validated by Greiwe and Friedrich (2024), who found that the airspeed and altimeter indicators were the instruments pilots focused on the most during both real and simulated takeoff and landing maneuvers. Other than these three AOIs, the pilot also looked at the altimeter (AOI 6) when flying during the daytime. The altimeter measures the helicopter's altitude relative to sea level, allowing the pilot to change the altitude and assess whether sufficient altitude is available to manage emergencies safely. However, the pilot paid more attention to the dual tachometer (AOI 4) than the altimeter (AOI 6) when flying during the night, which was an interesting finding. The dual tachometer tracks the rotational speeds of both the engine and the rotor, allowing the pilot to ensure that they are functioning within the normal range – critical during emergencies such as engine power failure, vortex ring state, or rotor system malfunctions. This finding might indicate that the pilot paid more attention to the endurance of the engine to different flight maneuvers at different altitudes during nighttime flights because the lift force of a helicopter was greatly affected by temperature and the density of weather (Senol et al., 2010). Also, Cheng et al. (2024) found that pilots paid significantly more attention to the tachometer during the autorotation glide phase compared to level flight, further supporting the findings of this study that the pilot demonstrated heightened safety awareness during nighttime flights. Additionally, in nighttime flights, the pilot's fixation points were concentrated at the edge of the altimeter (AOI 6), rather than the center of the altimeter (AOI 6), resulting in a smaller number of fixation points in the altimeter (AOI 6) than in the dual tachometer (AOI 4). In dim light, people's central vision does not work well, so they rely more on peripheral vision for observation in the dark (Stanko et al., 2017). Thus, it is reasonable to believe that the pilot obtained sufficient information provided by the altimeter during nighttime flights.

From the results of Table 4, regardless of whether flying during daytime or nighttime, FD-All, FPX-All, FPY-All, FPX-AOI2, FPX-AOI9, FPY-AOI9, SAV, and SPV distinguished among flight phases, which demonstrates the feasibility of using eye-tracking data to identify the flight phase in real flight conditions. Flight phases are directly correlated with civil aviation safety (Zhang et al., 2023). Identifying the flight phase with eye-tracking data in real flight conditions helps to evaluate the physiological and psychological state of pilots and further improve flight safety. This result is consistent with previous research on simulated helicopter flights that found a significant difference in the fixation duration among different flight phases, highlighting the sensitivity of fixation metrics to flight phases (Rainieri et al., 2021). Additionally, Scannella et al. (2018) conducted an experiment involving two standard traffic patterns in a real light aircraft and found that the saccade rate was the most efficient indicator for distinguishing among the three flight phases (takeoff, downwind, and landing), which validated the effectiveness of saccade metrics in this study. Specifically, based on the results of Figure 7, the average value of FD-All was lowest in FP II and highest in FP I, regardless of whether it was daytime or nighttime. This might be because, in FP I, the pilot needed to focus on changing parameters such as altitude, speed, and rate of climb, leading to longer fixation times on specific instruments. In contrast, in FP II, the pilot primarily monitored data and only glanced at relevant instruments as needed, given the reduced information processing demands (Liu et al., 2023). Moreover, in all flight phases, the average value of FD-All during nighttime flights was smaller than that during daytime flights, which was contrary to the results obtained by Bai et al. (2018) using the flight simulator. They found that the average fixation duration in low visibility was 0.06 s longer than that in high visibility. However, in real flight conditions, due to low visibility at night, the pilot needed to allocate attention to more areas to gain more information within a certain period, which might reduce the duration of a single fixation. As for saccade metrics, in all flight phases, the average values of SAV and SPV during nighttime flights were smaller than those during daytime flights, which was the same as the results obtained by Pan et al. (2017) who found that the stronger the illumination, the faster the saccade velocity. The saccade velocity reflects the visual processing efficiency (Yan et al., 2013). The faster the saccade velocity, the better the visual processing efficiency. Compared to the nighttime, the ability to process visual signals during the daytime was stronger (Evans et al., 2020). On the other hand, FPY-AOI2, FPX-AOI3, FD-AOI9, and SD distinguished among flight phases during daytime flights but not during nighttime flights; FD-AOI2 and FAPD-AOI9 distinguished among flight phases during nighttime flights but not during daytime flights. More gaze behavior metrics distinguished flight phases during daytime flights than during nighttime flights, which explains the differences in the pilot's visual processing between daytime and nighttime flights. The fact that FD-AOI9 and SD did not distinguish among flight phases during nighttime flights might be due to the pilot focusing more on instruments and spending less time observing the external environment, resulting in lower FD-AOI9 values. Besides, as multiple instruments were concentrated in the same area, SD also decreased. However, FAPD-AOI9 could distinguish among flight phases during nighttime flights, likely due to lights near the landing zone. During daytime flights, illumination differences between flight phases were relatively small, but during nighttime flights, FP I and FP III experienced higher illumination levels than FP II. Since pupil diameter was highly responsive to perceived light changes, FAPD-AOI9 significantly distinguished among flight phases (Jang et al., 2024).

Based on the results of Table 5, most gaze behavior metrics significantly differentiated between daytime and nighttime flights regardless of flight phase, except for FAPD-All, FD-AOI2, FAPD-AOI2, FD-AOI3, and SD, which indicates that daytime and nighttime conditions had a substantial impact on pilot gaze behavior. This finding confirmed that pilot attention allocation during real daytime and nighttime flights differed, which might account for the difference in helicopter accident rates during daytime and nighttime flights. Among the five metrics (FAPD-All, FD-AOI2, FAPD-AOI2, FD-AOI3, and SD), FAPD-All and FD-AOI2 were the least sensitive to flight time (daytime or nighttime) because they could not significantly distinguish between daytime flights and nighttime flights in any flight phase, contrary to the results obtained by Hebbar et al. (2021) which might be due to differences between real and simulated experiments; they were followed by FD-AOI3 and SD. FD-AOI3 only significantly distinguished between daytime flights and nighttime flights in the cruise phase, while SD only significantly distinguished between daytime flights and nighttime flights in the takeoff and climb phases. Finally, FAPD-AOI2 did not significantly distinguish between daytime flights and nighttime flights in only the takeoff and climb phases. With respect to other metrics, in all flight phases, the average value of FAPD-AOI3 during nighttime flights was smaller than that during daytime flights, which was consistent with the results obtained by Zhang et al. (2019). The higher cognitive workload as indicated by the larger fixation average pupil diameter could be due to more intensive attention allocation to the attitude indicator. During daytime flights, the attitude indicator was susceptible to external light reflection at high altitudes, making it difficult to read data. Hereby, the pilot attempted to increase their situation awareness by paying more attention to the attitude indicator. Nevertheless, in all flight phases, the average value of FAPD-AOI9 during nighttime flights was higher than that during daytime flights, which differed from the results of FAPD-AOI3. AOI 9 was the view out of the window, not an instrument area inside the cockpit, so it did not have its own light source. Using a simulated taxing task, Zhang et al. (2019) noticed larger fixation average pupil diameter in views outside of the window in the nighttime conditions compared to those in the daytime conditions. Decreased visibility at night would increase the pilot's difficulties to obtain and encode information from the environment (Viertler & Hajek, 2017). Larger fixation average pupil diameter in views outside of the window at night could be associated with the increased workload induced by information acquisition and encoding difficulties at night. Also, this finding was consistent with Blacker et al. (2018) who reported larger pupil sizes at night compared to in the daytime. Besides, the significant difference found in FPX and FPY metrics showed the various distribution of fixation points at different flight phases and visibility levels. This result needed to be validated with more sample data in the future, as it might be influenced by the pilot's sitting posture.

The results of the correlation analyses of all gaze behavior metrics revealed that the relationship among all gaze behavior metrics varies according to flight phase in daytime and nighttime flights. There was a strong and significant positive correlation among SD, SAV, and SPV in all flight phases of daytime and nighttime flights, all of which were saccadic metrics. This result indicated that both eyes of the pilot worked in a coordinated manner (Orduna-Hospital et al., 2023). In addition, in both daytime flights and nighttime flights, there was a strong and significant negative correlation between FPX-All and FPY-All in FP I and FP III and a weak and significant positive correlation in FP II. Previous studies have shown that compared with FP I and FP III, the workload level of pilots in FP II is the lowest, suggesting that the cognitive state of pilots varies according to the flight phase (Liu et al., 2023).

5. Conclusions

This study provided new insights into helicopter pilot gaze behavior by analyzing eye-tracking data collected in real flight conditions, contrasting daytime and nighttime flights. Unlike prior studies, which predominantly relied on simulator data, this research contributed to the field by utilizing data from real helicopter flights, highlighting the pilot gaze behavior patterns that emerge in authentic flight environments. Key findings indicated that pilot gaze behavior metrics crucial to aviation safety differed during daytime and nighttime flights. Regardless of whether it was a daytime flight or a nighttime flight, the pilot focused on the external view, the airspeed indicator, and the attitude indicator. However, the pilot paid more attention to the dual tachometer than the altimeter when flying during the nighttime. These results revealed distinctive patterns in pilot gaze behavior under low-light conditions, providing essential insights for strengthening nighttime flight training and ultimately contributing to improved flight safety standards. Additionally, this study's methodology and metrics provided a framework that is appropriate to evaluate pilot gaze behavior across other aircraft types and scenarios. A few limitations should be noted in this study. First, the authors collected data from only one pilot in multiple tasks, and the results obtained might be influenced by personal attributes. Future research will invite more pilots to participate in the research. Second, due to the involvement of real aircraft experiments, safety considerations limited the focus to regular flight tasks, excluding emergency scenarios. Future research, following more comprehensive evaluations, aims to explore pilots' gaze behavior during emergencies using real aircraft.

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Author contributions

CZ was responsible for the conceptualization and formal analysis and for preparing the original draft. CZ, JH, and CL were responsible for methodology and validation. CZ, WZ, and SL were responsible for data curation. CZ, WZ, and SL were responsible for editing and visualization. CJ was responsible for project administration and supervision.

Disclosure statement

All authors declare that they have not any competing financial, professional, or personal interests from other parties.

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