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Study on How Expert and Novice Pilots Can Distribute Their Visual Attention to Improve Flight Performance

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ABSTRACT To explore how pilots' distribution of visual attention affects flight performance, twenty male pilots (novices and experts with 407 ± 11.3 h and 4127 ± 77 h of flight experience, respectively) were enlisted to complete the instrument holding pattern and approach procedure on the DA-42 simulator. The distribution of visual attention was based on eye movement data recorded during the flight to investigate how pilots scan the flight instrument panel, which was divided into six areas of interest (AOIs). To evaluate the pilots' flight performance an expert scoring method was used. During the outbound-leg stage, experts paid significantly more visual attention to the airspeed indicator, altimeter and reference system, whereas for the approach phase, they devoted more attention to the airspeed indicator, altimeter and vertical speed indicator. Results showed that experts' proportions of gaze duration on different AOIs contributed to their better performance. An effective visual attention model can be developed on this study to improve air traffic safety.

INDEX TERMS Attention distribution, flight performance, areas of interest, gaze duration, air traffic safety, eye movement.

I. INTRODUCTION

The stable development of the civil aviation industry requires close considerations of many key factors. Among them, how aircrews behave plays an important role in ensuring efficient operation and aviation safety in case of emergency [1]–[3]. Holding pattern phase and approach phase are important to the whole flight process. In particular, the Global Fatal Accident Review [4] revealed that the majority of worldwide aviation mishaps in the years 2002 to 2011 happened during the approach phase. In addition, the 2013 International Civil Aviation Organization Safety Report showed that the number of flight accidents occurring during the approach phase accounted for 18% of total accidents, and is second only to those occurring during the landing phase [5]. More recently, according to the 2018 International Air Transport Association Safety Report on aircraft accidents from 2014 to 2018, the main cause of flight incidents is human error by pilots, and the number of fatal aircraft accidents occurring during the approach phase is only less than that in the en-route flight phase [6].

During the approach phase, pilots need to complete a series of complex operation procedures, such as adjusting the altitude, speed and attitude of the aircraft, and also ensure alignment with the runway. It is worth mentioning that prior to this phase, if air traffic is heavy, pilots are required to enter a holding pattern phase to wait for the traffic load to be eased: the entire holding pattern phase is divided into an

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outbound-turn, outbound-leg, inbound turn and inbound-leg. Pilots should strictly follow the instructions of the holding pattern for hovering, and control flight parameters in accordance with the instructions such as the type of entry procedure and the position of the holding point [7].

Generally, most of these operations rely on pilots' monitoring and analysis of various flight parameters in different displays, and this highly complex task could put pilots in a state of high cognitive load. Under different cognition loads, pilots have different visual-motor skills and capabilities, and this affects the accuracy of aircraft control [7]. High cognitive load may lead to illusion and misjudgment (i.e. spatial disorientation). Obviously, the most important channel to perceive information is vision, and so pilots' attention distribution mode largely determines the degree of information acquisition [8]. A pilot's reasonable visual field scanning strategy can provide reliable and accurate information related to aircraft attitude, motion and position, thereby preventing and responding to spatial disorientation [9]. On the contrary, if the attention resources allocated to various instruments are unreasonable, making some parameters to be ignored or forgotten, the operational safety of aircraft will be seriously threatened [10]. Moreover, driver behavior in post-congestion situations became more aggressive, more focused in the forward area but less focused in the dashboard area [11].

Recently, eye movement technology has been widely adopted in studies about pilot's attention distribution [12]. Many scholars have investigated whether eye movement indicators can objectively reflect the regularity of attention distribution. As early as 1950, Fitts *et al.* [13] analyzed the eye movement trajectory of pilots while landing with both instrumentation and ground control systems, and this analysis laid the foundation for the measurement of pilot's attention distribution behavior. Wanyan *et al.* [14] believed that human gaze behavior can reflect attention distribution to a large extent, and used eye movement data during the cruise and holding pattern phases to verify the effectiveness of the pilots' attention distribution model, which was built on the basis of hybrid entropy. Liu *et al.* [15] monitored attention distribution strategies of pilots in different flight phases by measuring eye movement indexes in terms of fixation, sweep and pupil size, and noted that eye movement indexes could be used to assess pilots' workload influence on flight performance. They reported that pilots had more fixation duration, smaller sweep amplitude and more pupil diameter under high workload. Further, great effort has been made to explore and establish more efficient and reasonable attention distribution modes. For example, the US Air Force required pilots to repeatedly scan between the runway and the airspeed indicator during training in the landing phase [16]. The US Aircraft Owners and Pilots Association recommended that pilots should observe the exterior and interior of the cockpit at a 2:1 ratio [17]. Niu [18] analyzed the eye movement patterns of pilots in flight movement simulation exercises, and concluded that pilots with better flight performance exhibited faster scanning speed and higher scanning frequency, which enabled them to complete information acquisition and processing within a shorter time. Hu *et al.* [19] collected a large amount of eye movement data and flight performance data of excellent pilots, and evaluated attention allocation in flight tasks under the National Aeronautics and Space Administration-task load index (NASA-TLX) scale to obtain the standard of attention distribution. Moreover, Zhang *et al.* analyzed the pilots' fixation rate, average fixation duration, and dwell time percentage in each AOI during the turning maneuvers near four examined intersections [20]. Li *et al.* revealed that intersection types made differences on drivers' scanning behavior [21]. Besides, a review [22] of eye-tracking data in aviation demonstrated that pilots' visual attention distribution is useful for high-workload conditions or for detecting fatigue and investigating the flight status of hypoxia and spatial disorientation.

Furthermore, many researchers have also explored the differences in the distribution of visual attention between experts and novices. Fitts *et al.* [23] found that experienced military pilots had more frequent fixations and shorter fixation durations on instruments. Bellenkes *et al.* [24], Rayner [25] and Wierda *et al.* [26] also came to the same conclusion and pointed out that expert pilots' better scanning strategies enable them to obtain information more effectively, which gives them more flexibility in their task requirements. Kim *et al.* [27] adopted eye-movement technology to compare the attention distribution of novices and experts in a simulated flight landing process under varying daylight conditions. Ottati *et al.* [28] and Kasarskis *et al.* [16] reported that there were differences between expert and novice pilots in regard to attention allocation and flight performance. Moreover, Ziv [29] reviewed series of studies relating to gaze behavior and flight performance, and confirmed the above conclusion, arguing that specific gaze behaviors can be used to differentiate between expert and novice pilots. However, experts are able to distribute their attention over areas of interest (AOIs) during flying tasks that require approach-to-landing maneuvers [9]. In addition, Liu *et al.* [30] found that expert pilots' eye movement patterns, expressed by eye movement indices such as fixation frequency and saccade frequency, reflect a lighter psychological load and enable them to produce better flight performance. By simulating the visual landing process, Kasarskis *et al.* [16] found that expert pilots possess a more efficient and reasonable attention distribution model than novices. The above work, however, rarely investigated the differences between experts and novice in how they exactly allocate their attention on different AOIs of the visual display, and how their allocation modes influence flight performance were also not fully analyzed.

Taking the above factors into account, in this study, we focused on determining effective strategies for searching the field of view (crosscheck) during the approach phase to increase the effectiveness and timeliness of acquiring flight parameters (such as attitude, airspeed, altitude, or vertical velocity), and enhance the pilot's ability to acquire spatial orientation. Thus, an experiment using the DA-42 simulator was carried out to assess student pilots' training progress and to check whether their visual attention distribution ability during these two selected flight phases (holding pattern and approach to landing) is consistent with that of expert pilots. We hypothesized that pilots with good flight performance have a more unified strategy for searching the field of view, and that it is feasible to develop a better attention allocation model for both the holding pattern phase and the approach phase. By comparing the attention allocation modes of expert and novice pilots, we explored how expert pilots reasonably distribute their attention over different AOIs, thereby improving their flight performance. Thus, training in the area of effective attention strategies may greatly improve technical and operational skills of novices, and thereby ensure flight safety.

II. METHODS

A. APPARATUS

1) FLIGHT SIMULATOR

The experiment was carried out on the Diamond DA-42 twin star simulator (Diamond Aircraft Industries GmbH, Austria), which complies with European Union Aviation Safety Agency and Federal Aviation Administration regulations, and has been certified by Civil Aviation Administration of China. The out-the-window (OTW) visual display of this fixed-based simulator is a cylindrical screen with a total field-of-view of approximately 200° horizontally by approximately 35° vertically. The simulator's instrument panel is fitted with the original Garmin G1000 NXi avionics suite and standby instruments, which can simulate the whole flight phase from takeoff to landing, and allow one to choose the landing airport and weather conditions that meet the experimental requirements. (See Figure 1)

2) EYE-TRACKER

Participants wore an EyeSo Glasses head-mounted eye-tracker (Braincraft Technology Co., Ltd, China) with a sampling frequency of 100 Hz and eye movement accuracy of 0.5°. The eye tracking system includes two sets of camera devices, an Eye Camera and a Scenery Camera. The Eye Camera captures the eye movement of pilots through infrared dark pupil tracking, and the Scenery Camera records the interior image of the flight simulator. During the experiments, the eye tracker was worn without restricting the participants' field of view and head movement, thus introducing no physical and cognitive load. The eye-tracker is also shown in Figure 1.

3) AOIS DIVISIONS

Researchers often divide AOIs into instruments related to navigation, technical conditions, and out-the-window [31], [32]. However, for these experiments, we divided AOIs according to different instrument area functions. Thus, for eye movement data analysis, the simulator display screen was divided into six AOIs: airspeed indicator (ASI), attitude director indicator (ADI), altimeter (ALT), vertical speed indicator (VSI), heading indicator (HI) and reference system (RS). In terms of eye movement data indexes, Rayner [25] proved that the duration of fixation provides information on the amount of cognitive processing devoted to capacity of AOIs, and the proportion of fixation time on a specified AOI, can also be used to measure the distribution of visual attention during flight [7], [9]. Hence, the gaze duration (sum of fixation durations on a specific AOI [33]) was selected as the basis for evaluating visual attention distribution, and analysis helped determine which part of the visual scene was the most explored. (See Figure 3).

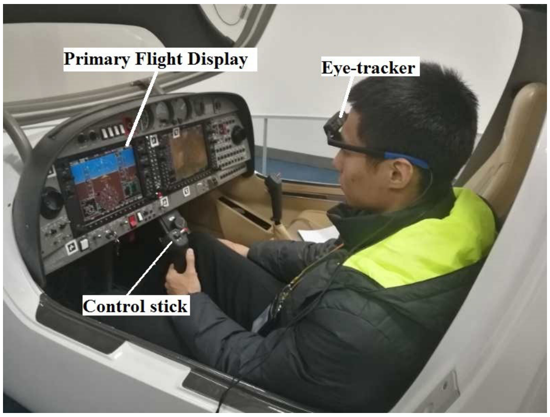

FIGURE 1. Apparatus used in the experiment; The DA-42 simulator and EyeSo Glasses head-mounted eye tracker.

B. PARTICIPANTS

Participants selected for the experiment were twenty male pilots, who included 10 student pilots (novices), with an average age of mean value Mean = 22.1 years (standard deviation, SD = 0.7; range = 21-23 years), and 10 instructors (experts), with an average age of Mean = 34.2 years (SD = 2.2; range = 30-38 years). All of the pilots were from the Chaoyang Flight College of Civil Aviation University of China (CAUC). The student pilots' flight duration was between 400 to 420 hours (Mean = 407, SD = 11.3), and they were skilled in the operation of the simulator and could complete the simulated flight task independently. Each of the instructors had more than 4000 hours of flight experience (Mean = 4127, SD = 77, range = 4007-4300), and previous experience on the DA-42 flight simulator.

All pilots had normal vision (or normal vision after correction) and no clinical history of vestibular symptoms (vertigo, dizziness, or disorientation) and neurological disorders. Since it was necessary to wear a head-mounted eye tracker for the entirety of the experiment, the pilots were allowed to wear contact lenses but not glasses. Prior to the study, each pilot declared to have had adequate sleep (more than 8 hours of sleep) the night before the experiment and had not taken any psychoactive medication (e.g. antihistamines, antidepressants, sleep aids, etc.) recently. All pilots had qualifications for Instrument Flight Rules (IFR) in Instrument Meteorological Conditions and could complete instrument flight tasks independently. They then signed the informed consent form before the experiment, and were paid for their participation

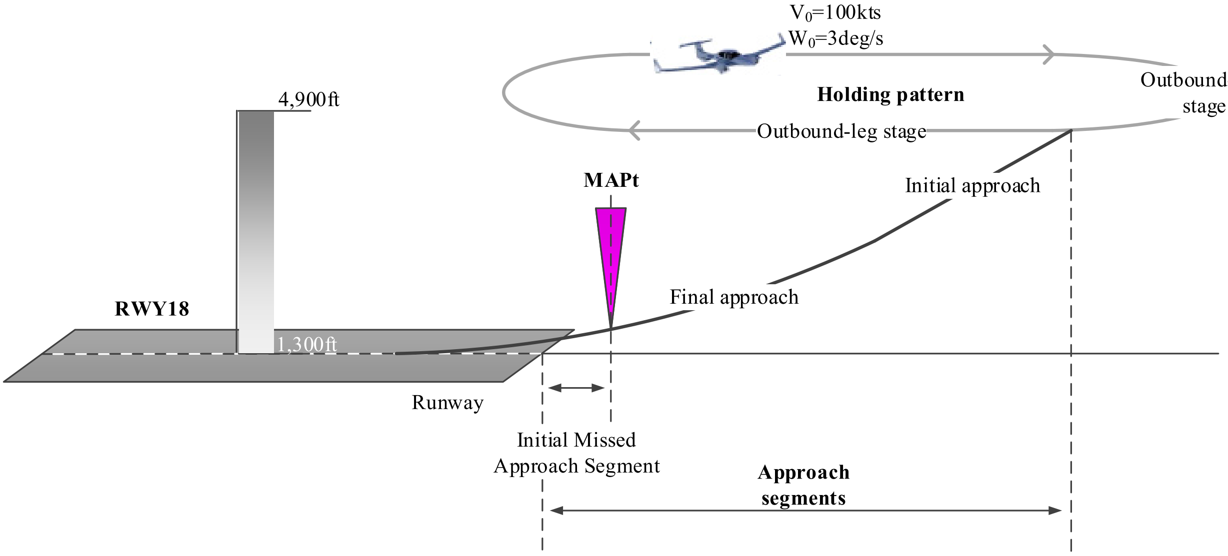

FIGURE 2. Schematic diagram of the flight mission.

FIGURE 3. Areas of interest on the flight simulator's Primary Flight Display. Note: ASI – airspeed indicator, ADI – attitude director indicator, ALT – altimeter, VSI – vertical speed indicator, HI – heading indicator, and RS – reference system.

(200 yuan per person). The experiment was conducted with the approval of the Academic and Ethics Committee at General Aviation College of CAUC.

C. FLIGHT PROFILE

According to the study design, the experiments were divided into two phases: the holding pattern phase and approach phase. The pilots were required to enter a non-standard holding pattern at 4900 feet over Chaoyang Airport at a speed of 100kts, turn rate of 3°/s, and a standard course of 156°. They needed to conduct a complete holding pattern procedure: a. Outbound-turn, b. Outbound-leg, c. Inbound-turn, d. Inbound-leg. The starting approach point heading was 355 °, and the end position of the flight was set at Missed Approach Point (MAPt). (See Figure 2)

D. PROCEDURE

After checking the experimental equipment to ensure they were in working state, all pilots were given 5 minutes of ''free-flight'' to familiarize themselves with the operational characteristics of the simulator and the eye tracker. This also helped to minimize the impact of individual differences [34]. The simulator could hold one person at a time. The scoring instructors, who did not attend the test, watched the actual operation of the flight from outside the simulator. The scoring instructors declared in advance that they didn't know any of the participants or their roles (instructor or student pilot).

Participants performed the following two tasks: the flight of the holding pattern and approach in the DA-42 simulator. The pilots' eye-movement activity was continuously recorded during the flight. The participants were asked to perform a specific standard flight profile according to the flight instructions. All participants carried out the holding pattern phase and the approach phase in the same flight profile, and they were required to perform standardized operation. Participants performed Very High Frequency Omni directional Range (VOR) non precision during the instrument approach procedure. They focused their attention solely on correctly performing these tasks. All participants completed the study at the same time of day (between 8:00 and 12:00) within a period of five days. The weather was windless during the simulation flights. Pilots were required to follow the flight rules strictly. There was no strict restriction on completion times of the experiments. However, the average total time for completing the whole experiment was about 820 seconds (SD = 68.0; range = 663-916 s).

E. MEASUREMENTS

Measurements were taken for two types of data, namely data about flight performance, and all eye-movement metrics recorded by eye tracker.

1) FLIGHT DATA

To record the real-time flight parameters, EZVIZ C6Tc 1080P monitoring system (Hikvision Digital Technology Co., Ltd, China), which included a camera and a monitor, was used. Then, PotPlayer (Daum Communications Corp, Korean) software was used to capture the experimental display screen every second, and the ABBYY FineReader 12 (ABBYY Corp, Russia) software was used to obtain the data during the holding pattern phase. However, the flight performance data of the holding pattern phase was quite different from that of the approach phase. For the former, we recorded the deviation, caused by pilots, in the holding speed, height, course, and turning rate; whereas, for the latter, the scores were directly awarded by three experienced instructors. During the flight operations, three experienced instructors observed the operation process from outside the cabin. After completing the specified flight mission, the flight trajectory of each participant was outputted. The operation performance of approach process was evaluated by an expert scoring method.

2) Eye-movement data

The core of this article is to analyze the eye movement data. As mentioned earlier, for purposes of analysis of eye movement data, the Primary Flight Display (PFD) was divided into six AOIs, namely airspeed indicator (ASI), attitude director indicator (ADI), altimeter (ALT), vertical speed indicator (VSI), heading indicator (HI), and reference system (RS). During the flight operations, the pilots had no access to OTW visual stimuli, and the flight was conducted solely using flight instruments. This means OTW was not included in the AOIs. (See Figure 3)

More importantly, since the eye tracker recorded each fixation to any AOI, it is possible to obtain almost all the eye-movement metrics, such as gaze duration (sum of fixation durations on a specific AOI), and fixation frequency (number of fixations on a specific AOI), which are the focus of this study. By analysis (details are given in sections II-G STATISTICAL ANALYSIS and III RESULTS), the index gaze duration can help to distinguish experts from novices. Thus, consistent with the index "mean dwell time" [7], we used the proportion of gaze duration on AOI$_k$ (k = 1,2,3,4,5 and 6 represent ASI, ADI, ALT, VSI, HI and RS, respectively), denoted by P_k, as the core index for this study. Then,

$$P_k = \frac{T_k}{\sum T_k}, \tag{1}$$

where T_k is the gaze duration on a specific AOI$_\mathrm{k}$, and $\sum T_k$ is the sum of gaze duration on all AOIs. Gaze duration T_k was obtained by calculating the sum of fixation durations on a specific AOI$_\mathrm{k}$ (details are given in section II-F-2) EYE-MOVEMENT DATA).

Besides, for each participant, the total gaze duration on all AOIs, $\sum T_k$, and the fixation frequency of AOI$_k$, θ_k, were also calculated.

F. DATA PROCESSING

1) FLIGHT DATA

By analyzing the flight performance data, we can calculate the performance scores in order to establish an advanced model of distribution of visual attention on AOIs during the holding pattern phase and the approach phase. Specifically, we assumed that if a "perfect" model exists, it should meet the following two conditions: (1) it can attain high performance scores; (2) it is performed by experts (since they are more experienced).

The holding pattern phase. Considering that the stabilizations of speed, altitude, course and turning rate are all important to ensure the flight attitude and route, we assumed these factors have the same weight when evaluating flight performance during this phase. Using i to represent the ranking of a participant (range = 1-20), then, for participant i, the mean speed v_i, mean height h_i, mean course H_i, and mean turning rate w_i can be obtained by averaging the data recorded by the ABBYY FineReader 12 software (with a frequency of 2Hz). Then, the speed deviation degree Δv_i, height deviation degree Δh_i, course deviation degree ΔH_i, and turning rate deviation degree Δw_i can be calculated as follows:

$$\Delta v_i = v_i - v_0, v_0 = 100kts \tag{2}$$

$$\Delta h_i = h_i - h_0, h_0 = 4900ft \tag{3}$$

$$\Delta H_i = H_i - H_0, H_0 = 156^\circ \tag{4}$$

$$\Delta w_i = w_i - w_0, w_0 = 3^\circ/s \tag{5}$$

These four values can be normalized as follows:

$$\overline{\Delta x_i} = (\Delta x_i - \Delta x_{\min})/(\Delta x_{\max} - \Delta x_{\min}) \tag{6}$$

where $\Delta x_{\min}$ is the minimum deviation value, which is 0 under ideal conditions; $\Delta x_{\max}$ is the maximum deviation allowed for the flight test. Based on the assessment completion criteria, we set $\Delta v_{\max} = 10kts$, $\Delta h_{\max} = 100ft$, $\Delta H_{\max} = 10^\circ$, $\Delta w_{\max} = 1^\circ/s$. The deviations of the four dimensions are normalized and then summed up to obtain the flight performance score:

$$F_i = 4 - (\overline{\Delta v_i} + \overline{\Delta h_i} + \overline{\Delta H_i} + \overline{\Delta w_i}) \tag{7}$$

Obviously, the higher the score F_i, the better the performance of pilot i.

The approach phase. Different from the holding patter phase, subjective assessment was adopted during the approach phase (see subsection 1) FLIGHT DATA of E. MEASUREMENTS). The three scoring instructors assessed each participant's flight performance based on two indicators: the standardization of the participant's flight operation, and the deviation of his flight trajectory diagram from the "perfect" trajectory the instructor considered. The grading system adopted a ten-point system, and the performance of each participant was indicated by the average of the scores awarded by the three instructors. Consistent with the holding pattern phase, in the approach phase, the higher the score, the better the performance.

2) EYE-MOVEMENT DATA

EyeSo Glasses was equipped with recording software, and we designated the 6 AOIs in this software in advance. After each experiment, the software exported the recorded data. We filtered and analyzed this data using EyeSo Studio3.0 software (Braincraft Technology Co., Ltd, China). Data with loss rate (the ratio of the number of packets lost to the data groups sent) exceeding 20% was generally considered unusable and filtered out. After filtration, the data was then processed further.

If the coordinate axis of the eye tracker is placed in the glasses, then head movement needs to be put into consideration [35]. However, the eye tracker in our experiment did consider the head movement of the participants when calculating the fixation times. In other words, the data of the outputted fixation times was already processed by a compensation algorithm for head movement. Moreover, the eye tracker recorded each fixation on any of the six AOIs. Consistent with a previous work [36], fixation in this case refers to a sequence of at least 10 coulometer samples with an inter-sample distance of less than 1° of visual angle. In this study, the minimum fixation time was set to 100ms. This means that when a fixation time is longer than 100 ms [37], [38], it is considered as a fixation duration with conscious processing of visual information. Finally, the key index, i.e. gaze duration ($k = 1,2,3,4,5$ and 6 represent ASI, ADI, ALT, VSI, HI and RS, respectively), was obtained by calculating the sum of fixation durations on a specific AOI_k. Then, the proportion of gaze duration on AOI_k was calculated according to Eq. (1).

It is worth noting that there was no change in altitude during the holding pattern phase, meaning the vertical speed in this phase is 0. Therefore the AOI VSI was regarded as a part of ALT when analyzing the eye movement data. Thus, VSI was not considered in this phase.

G. STATISTICAL ANALYSIS

Statistical analysis was conducted using the SPSS22 (SPSS Inc., Chicago, IL, USA) software. Since the main task is to compare the flight performance of experts and novices, an independent sample T-test was used to check the difference between the mean proportion of gaze duration of both the experts and novices on different AOIs. Besides this key index, the differences in total gaze duration on all AOIs, proportion of AOIs fixated, and fixation frequency of AOI_k were also checked ($k = 1,2,3,4,5$ and 6 represent ASI, ADI, ALT, VSI, HI and RS, respectively). Moreover, we analyzed the correlation coefficient between gaze duration and flight performance. In our study, for the proportion of gaze duration, the variances between the experts group and novices group showed no significant difference. In addition, using fewer than 50 participants is not recommend [37]. For our experiment, with α at 0.05, and power at 0.8 ($\beta = 0.2$), the sample size needed is less than 20, which meets the minimum requirement.

III. RESULTS

A. THE PILOTS' FLIGHT PERFORMANCE

The holding pattern phase. By calculating the scores using (2)-(7), it was found that the maximum score of experts was significantly lower than the minimum score of novices (see Figure 4. (a)). This means the flight performance of the instructors (Mean = 2.72, SD = 0.191) was better than that of the student pilots (Mean = 1.97, SD = 0.181) during this phase ($F(9, 9) = 0.459$, $df = 18$, $p < .001$).

The approach phase. For this phase, not all the 10 instructors performed better than the student pilots. Therefore, two under-performing instructors (No 12 and No 17) were excluded from the experts group. Similarly, two student pilots who attained supernormal scores (No 3 and No 16) were excluded from the novices group. The scores of the remaining pilots are presented in Figure 4. (b). The scores of the experts (Mean = 9.21, SD = 0.617) were significantly higher than those of the novices (Mean = 7.00, SD = 0.436) ($F(7, 7) = 3.071$, $df = 14$, $p < .001$).

B. THE DISTRIBUTION OF VISUAL ATTENTION

1) EYE MOVEMENT DATA DURING THE HOLDING PATTERN PHASE

Outbound-turn

stage. For this stage, there was no significant difference between experts and novices in regard to the total gaze duration on all AOIs ($p = 0.381$). Comparison of the results also showed no significant differences between experts and novices in respect to the fixation frequency for different AOIs ($p > 0.05$): specifically, for ASI, ($p = 0.522$) between experts and novices; for ADI, $p = 0.131$; for ALT, $p = 0.905$; for HI, $p = 0.241$; for RS, $p = 0.092$. Taking all pilots as a whole, the correlation between flight performance and gaze duration, r_1, and the correlation between flight performance and fixation frequency, r_2, were checked: gaze duration, when compared with fixation frequency, was more related to flight performance. (Table 1 and Table 4)

As for the key index, i.e. gaze duration $\mathrm{P_k}$(k = ASI, ADI, ALT, HI, RS), the ranking for the experts was $\mathrm{P_{ADI}} = \mathrm{P_{HI}} > \mathrm{P_{ALT}} = \mathrm{P_{ASI}} > \mathrm{P_{RS}}$. (Table 3), and the ranking for novices was $\mathrm{P_{HI}} > \mathrm{P_{ADI}} > \mathrm{P_{ALT}} > \mathrm{P_{ASI}} > \mathrm{P_{RS}}$. There existed no significant differences between experts and novices in respect to the proportion of gaze duration P_k on different AOIs (p>0.05): for ASI, $p = 0.108$ between experts and novices; for ADI, $p = 0.054$; for ALT, $p = 0.657$; for HI, $p = 0.632$; for RS, $p = 0.124$. (See Figure 5. (a))

Outbound-leg

stage. Similarly, there was no significant difference between experts and novices in respect to the total gaze duration on all AOIs ($p = 0.375$). However, experts and novices showed significant differences in the fixation frequency for ASI and ALT; specifically, for ASI, $p = 0.027$ between experts and novices; and for ALT, $p = 0.009$. However, for other AOIs, there existed no significant differences in the fixation frequency: for ADI, $p = 0.361$; for HI, $p = 0.522$; for

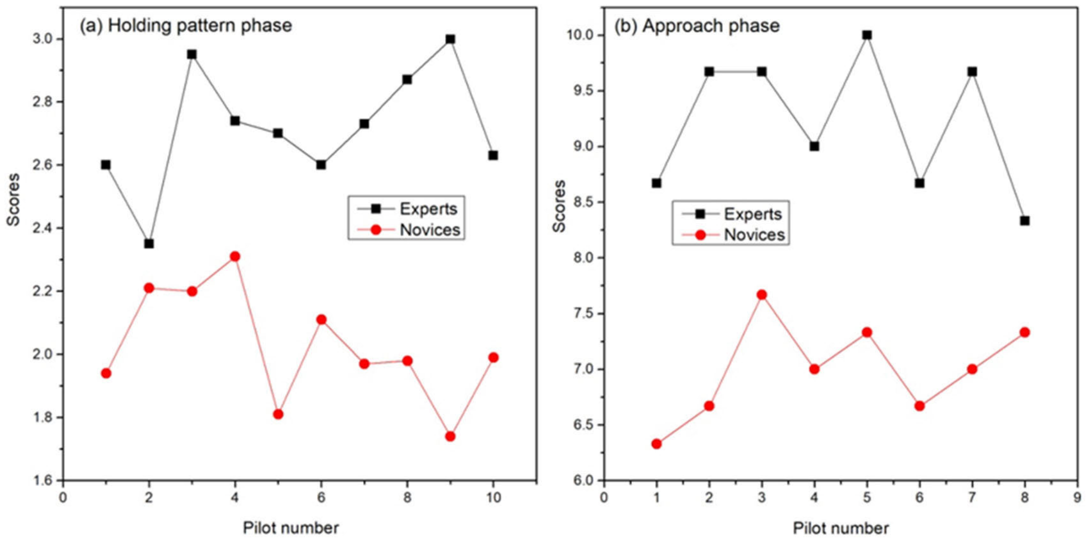

FIGURE 4. The scores of expert and novice pilots' flight performance during (a) the holding pattern phase and (b) the approach phase.

TABLE 1. The differences in eye-movement activity between novice pilots (n = 10) and expert pilots (n = 10) during the holding pattern phase.

Flight Phase	Eye-movement Metric	Area of Interest	Pilot				Between-Subjects Effects (novices vs. experts)		
			Novice		Expert				
			Mean	SD	Mean	SD	*F*	*df*	*p*
Outbound-turn stage	Proportion of gaze duration	ASI	0.10	0.012	0.11	0.011	0.820	18	0.108
		ADI	0.37	0.046	0.38	0.027	0.342	18	0.054
		ALT	0.11	0.018	0.11	0.022	1.590	18	0.657
		HI	0.40	0.025	0.38	0.037	2.241	18	0.632
		RS	0.02	0.040	0.02	0.024	0.371	18	0.124
	Fixation frequency	ASI	11.64	0.527	10.41	0.801	2.314	18	0.522
		ADI	46.28	2.095	47.01	2.477	1.398	18	0.131
		ALT	16.06	0.727	15.27	1.212	2.779	18	0.905
		VSI	0.03	0.035	49.87	3.740	2.761	18	0.241
		HI	49.71	2.250	3.49	0.278	2.015	18	0.091
	Total gaze duration (seconds)	n/a	47.58	11.580	45.63	7.423	0.412	18	0.381
Outbound-leg stage	Proportion of gaze duration	ASI	0.08	0.024	0.15	0.014	0.353	18	<.001
		ADI	0.37	0.019	0.30	0.034	3.122	18	0.031
		ALT	0.37	0.031	0.33	0.031	1.038	18	0.007
		HI	0.11	0.025	0.15	0.034	1.812	18	<.001
		RS	0.07	0.018	0.07	0.024	2.427	18	0.969
	Fixation frequency	ASI	22.03	1.999	25.41	3.050	2.328	18	0.027
		ADI	49.62	5.128	47.71	7.420	2.095	18	0.361
		ALT	53.90	11.010	48.10	7.241	0.434	18	0.009
		VSI	17.96	5.527	16.66	3.433	0.386	18	0.522
		HI	17.77	1.966	18.45	3.437	3.056	18	0.073
	Total gaze duration (seconds)	n/a	58.99	7.260	61.47	10.784	2.206	18	0.375

Note: ASI–airspeed indicator, ADI–attitude director indicator, ALT–altimeter, HI–heading indicator, and RS–reference system, n/a–not applicable.

RS, $p = 0.073$. The correlations r_1 and r_2 showed that gaze duration and fixation frequency were both closely related with flight performance, almost for each AOI. (Table 1 and Table 4)

The ranking of P_k for experts was $P_{ALT} > P_{ADI} > P_{ASI} = P_{HI} > P_{RS}$, and the ranking for novices was $P_{ADI} = P_{ALT} > P_{HI} > P_{ASI} > P_{RS}$. As for the proportion of gaze duration P_k, we found that experts paid significantly more attention to ASI and HI than novices: for ASI, $p < .001$; for HI, $p < .001$. Meanwhile, experts' proportions of gaze duration on ADI and ALT were significantly lower than that of novices: for ADI, $p = 0.031$ between experts and novices; for ALT, $p = 0.007$. There was no significant difference between experts and novices in respect to RS ($p = 0.969$). (See Figure 5. (b))

TABLE 2. **The Differences in eye-movement activity between novice pilots (n = 8) and expert pilots (n = 8) during the approach phase.**

PHASE

Flight Phase	Eye-movement Metric	Area of Interest	Pilot				Between-Subjects Effects (novices vs. experts)		
			Novice		Expert				
			Mean	SD	Mean	SD	*F*	*df*	*p*
Initial approach stage	Proportion of gaze duration	ASI	0.09	0.021	0.10	0.021	0.965	14	0.037
		ADI	0.36	0.030	0.34	0.029	0.965	14	<.001
		ALT	0.12	0.015	0.18	0.022	2.393	14	<.001
		VSI	0.03	0.006	0.03	0.007	1.224	14	0.013
		HI	0.37	0.027	0.32	0.047	3.148	14	<.001
	Fixation frequency	ASI	94.72	14.175	93.21	9.697	0.468	14	0.097
		ADI	337.13	51.234	336.54	62.918	1.510	14	0.721
		ALT	174.25	64.730	179.69	36.580	0.319	14	0.172
		VSI	37.81	13.981	44.53	7.640	0.299	14	0.092
		HI	327.15	72.310	331.14	62.773	0.754	14	0.084
		RS	57.25	5.814	56.91	5.752	0.979	14	0.911
	Total gaze duration (seconds)	n/a	322.45	111.770	313.74	79.484	0.506	14	0.017
Final approach stage	Proportion of gaze duration	ASI	0.12	0.026	0.12	0.038	2.174	14	<.001
		ADI	0.33	0.045	0.32	0.082	3.296	14	<.001
		ALT	0.13	0.015	0.16	0.013	0.796	14	<.001
		HI	0.34	0.029	0.31	0.053	3.274	14	<.001
		RS	0.04	0.010	0.04	0.013	1.598	14	0.045
		VSI	0.04	0.006	0.04	0.010	2.725	14	0.015
	Fixation frequency	ASI	72.37	8.950	79.61	16.002	3.197	14	0.031
		ADI	201.27	42.780	196.65	41.313	0.933	14	0.909
		ALT	92.06	11.562	98.15	16.500	2.037	14	0.007
		HI	190.87	1.127	179.54	24.470	1.338	14	0.014
		RS	44.73	7.230	45.70	8.340	1.331	14	0.296
		VSI	20.44	6.170	22.28	10.080	2.670	14	0.413
	Total gaze duration (seconds)	n/a	203.70	25.980	212.50	35.120	1.833	14	0.572

Note: ASI – airspeed indicator, ADI – attitude director indicator, ALT – altimeter, HI – heading indicator, and RS – reference system, n/a – not applicable.

2) EYE MOVEMENT DATA DURING THE APPROACH PHASE

The initial approach stage. In this stage, the expert pilots' total gaze duration on all AOIs was significantly lower than that of novices ($p = 0.017$). Experts and novices showed no significant difference in respect to fixation frequency of different AOIs ($p > 0.5$): for ASI, $p = 0.097$ between experts and novices; for ADI, $p = 0.721$; for ALT, $p = 0.172$; for VSI, $p = 0.092$; for HI, $p = 0.084$; for RS, $p = 0.911$. The correlations r_1 and r_2 showed that the fixation frequency was more weakly related to flight performance than gaze duration. (Table 2 and Table 4)

For experts, the ranking of P_k was $\mathrm{P}_{\mathrm{ADI}} > \mathrm{P}_{\mathrm{HI}} > \mathrm{P}_{\mathrm{ALT}} > \mathrm{P}_{\mathrm{ASI}} > \mathrm{P}_{\mathrm{VSI}} > \mathrm{P}_{\mathrm{RS}}$, whereas for novices it was $\mathrm{P}_{\mathrm{HI}} > \mathrm{P}_{\mathrm{ADI}} > \mathrm{P}_{\mathrm{ALT}} > \mathrm{P}_{\mathrm{ASI}} > \mathrm{P}_{\mathrm{RS}} > \mathrm{P}_{\mathrm{VSI}}$. Then, the T-test results showed that P_k of experts at ASI, ALT and VSI was significantly higher than that of novices: specifically, for ASI, $p = 0.037$ between experts and novices; for ALT, $p < .001$; for VSI, $p = 0.013$. However, for ADI and HI, the conditions were reversed: for ADI, $p < .001$; for HI, $p < .001$. (See Figure 6. (a))

The final approach stage. For this stage, there was no significant difference between experts and novices in respect to the total gaze duration ($p = 0.572$). Experts and novices showed significant differences in fixation frequency for ASI, ALT and HI: for ASI,$p = 0.031$ between experts and novices; for ALT, $p = 0.007$; for HI, $p = 0.014$. The correlations r_1 and r_2 showed that fixation frequency was more weakly related to flight performance than gaze duration. (Table 2 and Table 4)

For experts, the ranking of P_k was $\mathrm{P}_{\mathrm{ADI}} > \mathrm{P}_{\mathrm{HI}} > \mathrm{P}_{\mathrm{ALT}} > \mathrm{P}_{\mathrm{ASI}} > \mathrm{P}_{\mathrm{VSI}} = \mathrm{P}_{\mathrm{RS}}$, whereas for novices it was $\mathrm{P}_{\mathrm{HI}} > \mathrm{P}_{\mathrm{ADI}} > \mathrm{P}_{\mathrm{ALT}} > \mathrm{P}_{\mathrm{ASI}} > \mathrm{P}_{\mathrm{RS}} = \mathrm{P}_{\mathrm{VSI}}$. This demonstrates that experts paid significantly more attention to ASI, ALT, VSI and RS compared with novices: specifically, for ASI, $p < .001$ between experts and novices; for ALT, $p < .001$; for VSI, $p = 0.015$; for RS, $p = 0.045$. Although ADI and HI take up most of the attention in this stage, experts put less focus on ADI and HI than novices did: for ADI, $p < .001$; for HI, $p < .001$. (See Figure 6. (b))

IV. DISCUSSION

In this study, we aim to ascertain three important issues: a. whether the expert and novice pilots have distinct characteristics of attention allocation, and if these characteristics are established; b. whether there is an inevitable relationship between strategies for searching the field of view and flight performance; c. whether a model of attention allocation for better flight performance can be determined. Motivated by this, using DA-42 simulator and EyeSo Glasses, we carried out a flight experiment to explore how pilots' distribution of visual attention affects flight performance. The results are discussed in the following four subsections.

TABLE 3. Gaze duration for expert pilots (n = 10 during the holding pattern phase, n = 8 during the approach phase).

Flight phase	Effect (more > less in AOIs)	*F*	*df*	*p*
Outbound-turn stage	ADI> HI	0.533	18.0	0.308
	HI >ALT***	2.733	18.0	<.001
	ALT < ASI	3.423	17.6	0.197
	ASI > RS*	0.250	16.2	<.001
Outbound-leg stage	ALT>ADI	0.821	18.0	<.001
	ADI> ASI	5.898	12.3	<.001
	ASI=HI	0.173	13.6	0.487
	HI > RS	1.449	18.0	<.001
Initial approach stage	ADI>HI	0.383	14.0	0.039
	HI>ALT	4.440	11.3	<.001
	ALT>ASI	1.138	14.0	<.001
	ASI>VSI	9.824	10.9	<.001
	VSI>RS	0.467	14.0	0.041
Final approach stage	ADI>HI	2.422	14.0	0.027
	HI>ALT	16.060	7.3	<.001
	ALT>ASI	0.120	10.2	<.001
	ASI>VSI	13.360	10.9	<.001
	VSI=RS	0.630	14.0	0.019

Note: ASI – airspeed indicator; ADI – attitude director indicator; ALT – altimeter; VSI – vertical speed indicator; HI –heading indicator; and RS – reference system; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

TABLE 4. The correlations between flight performance and gaze duration (r1)/ fixation frequency (r2).

Flight phase	Area of Interest	$r1$	$r2$
Outbound-turn stage	ASI	0.920	0.570
	ADI	0.734	0.219
	ALT	-0.931	-0.482
	HI	-0.872	-0.111
	RS	-0.340	0.014
Outbound-leg stage	ASI	0.997	0.970
	ADI	-0.950	-0.850
	ALT	-0.876	-0.923
	HI	0.940	0.673
	RS	0.179	0.900
Initial approach stage	ASI	0.594	-0.019
	ADI	-0.971	-0.131
	ALT	0.998	0.111
	VSI	0.550	0.213
	HI	-0.836	-0.270
	RS	-0.277	-0.004
Final approach stage	ASI	0.946	0.279
	ADI	-0.932	-0.178
	ALT	0.962	0.817
	VSI	0.770	0.180
	HI	-0.949	-0.930
	RS	0.326	0.072

Note: ASI – airspeed indicator; ADI – attitude director indicator; ALT – altimeter; VSI – vertical speed indicator; HI – heading indicator; and RS – reference system; $r1$ – the correlations between flight performance and gaze duration; $r2$ – the correlations between flight performance and fixation frequency.

A. DIFFERENT CHARACTERISTICS BETWEEN EXPERT AND NOVICE PILOTS

It is worth noting that this study focused more on the differences between experts and novices. As shown in section III RESULTS, how the total gaze duration is distributed on different AOIs plays a decisive role in determining flight performance. In accordance with the "mean dwell time" [7] or "percentage of gaze duration" [9], we used the key index, proportion of gaze duration, which is a "stable" and representative index according to statistical analysis (see section III RESULTS). Thus we can further explore the attention distribution model of experts to better understand why they performed well in the flying tasks.

For the holding pattern phase, novice pilots is significant different from expert pilots in attention allocation during the outbound-leg stage (but not during the outbound-turn stage). During the outbound-turn stage, there almost existed no differences between the attention distribution model of experts and that of novices (See Figure 5). Thus, we can infer that experts do not have obvious advantage over novices during the outbound-turn stage. However, after entering the outbound-leg stage, experts put more focus on controlling the

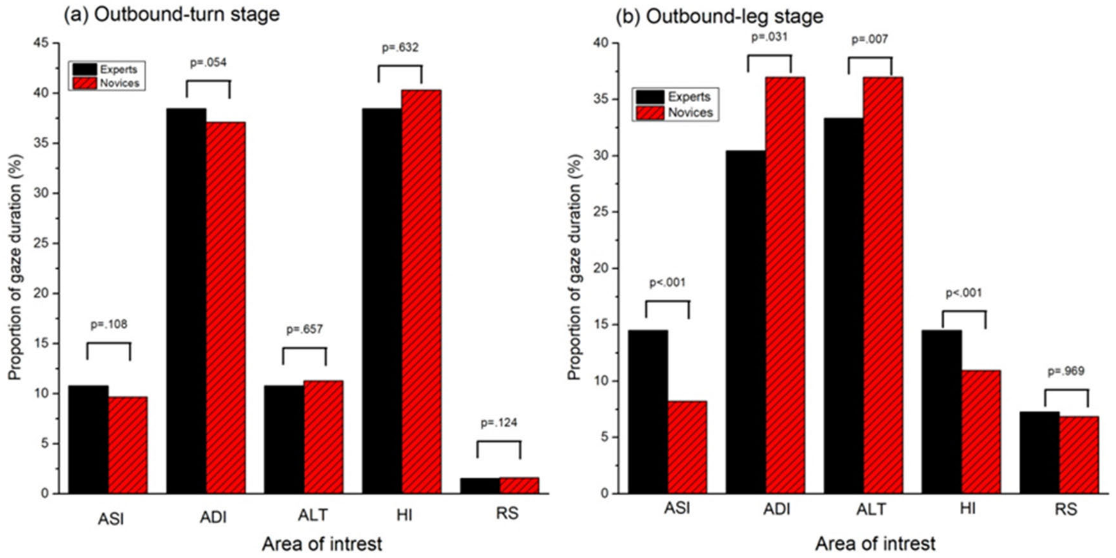

FIGURE 5. The proportion of gaze duration on a specific AOI for expert and novice pilots during the holding pattern phase (a) outbound-turn stage and (b) outbound-leg stage. Note: ASI–airspeed indicator, ADI–attitude director indicator, ALT–altimeter, HI–heading indicator, and RS–reference system.

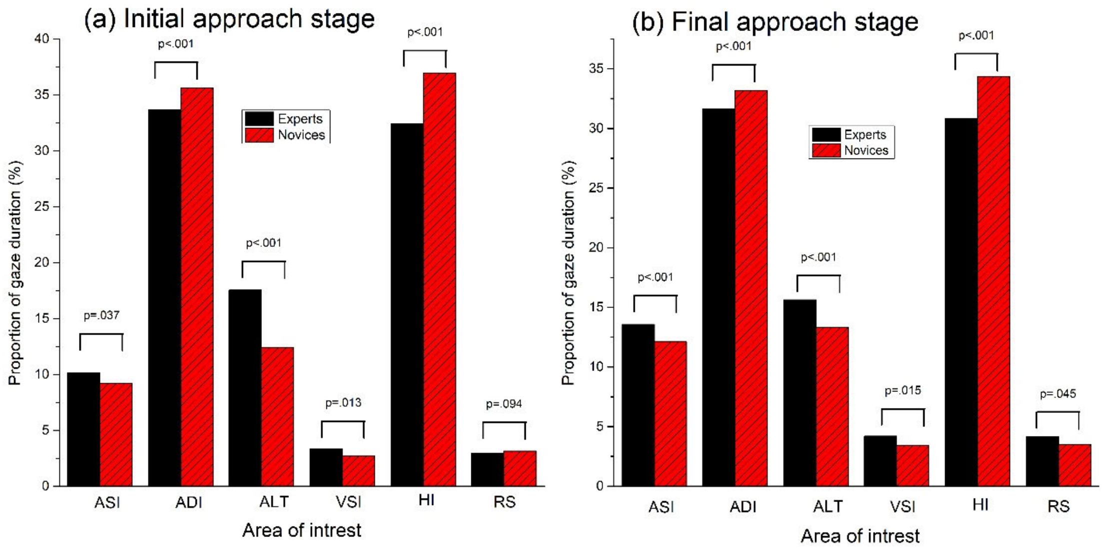

FIGURE 6. The proportion of gaze duration on a specific AOI for expert and novice pilots during the approach phase a) initial stage, b) final stage. Note: ASI – airspeed indicator, ADI – attitude director indicator, ALT – altimeter, VSI – vertical speed indicator, HI – heading indicator, and RS – reference system.

speed and direction of the aircraft (See Figure 5), which helps to improve their flight performances. Thus, pilots should appropriately increase their attention to the airspeed indicator (ASI) and heading indicator (HI) during the outbound-leg stage, in order to complete the holding pattern better.

Then, throughout the whole approach phase, all participants need to devote most of their attention to ADI and HI, because they keep on making horizontal flight and turn operations in this phase. However, regardless of the initial or final stage, the proportion of gaze duration of experts on both ADI and HI was significantly lower than that of novices. For novices, their over-focused attention distribution may easily result in the omission of other flight information and threaten the operational safety of the aircraft [10]. In contrast, it seems that the attention experts take from ADI and HI is directed at other AOIs. In other words, experts have a more ‘‘balanced’’ focus on the entire visual display, which might explain their better performance. In fact, it has been well accepted that, compared with novices, experts pay more attention to ASI due to the increased concern about a stall at a potentially high angle of attack and the need to retract flaps with regard to specific speed values [7], [42], [43]. In this sense, our results were consistent with these observations. Furthermore, besides ASI, experts also paid more attention to ALT and VSI during the approach phase, indicating that they did not ignore changes in the vertical direction. Note that this does not mean that the more attention is paid to ASI, ALT or VSI, the better the flight performance, since even the worst-performing novice had at least 400 hours of flight experience, and thus the instructions adopted a very narrow parameter range, particularly for the highly ''experienced'' pilots.

B. CORRELATION BETWEEN FLIGHT PERFORMANCE AND ATTENTION ALLOCATION

Our study revealed that experts' flight performance exceeded that of novices in both the holding pattern phase and the approach phase. This is partially consistent with the findings of most previous works [9], [16], [23]–[28], [30], [39], [40]. However, Bellenkes *et al.* [24] reported that expert pilots performed better than novices in vertical and longitudinal control, but not in lateral control. This may be ascribed to the fact that these studies adopted different criteria for distinguishing ''experts'', and participants in this current study were not as experienced as those in Bellenkes's study [16], [24], [28].

Interestingly, there were close correlations between flight performance and gaze duration on different AOIs during both the holding pattern phase and the approach phase (most correlation coefficients $r > 0.8$, see section III RESULTS), which proves that appropriate attention allocation can efficiently facilitate flight performance of experts [16], [28], [41]. However, besides the outbound-leg stage of the holding pattern phase, the correlations between flight performance and fixation frequency were relatively weaker (see section III RESULTS). Moreover, it seemed that there was no significant difference between experts and novices in respect to the index of fixation frequency. This differs with the conclusion that experienced pilots had significantly more fixation times than novices [23], [24], [28]. This difference may be because there was no outside scenery (no OTW stimuli) in this study. Pilots directed their visual attention to only the cockpit and flight instruments. Moreover, as mentioned above, the criteria for distinguishing ''experts'' may also affect the results. However, with respect to dwell time on flight instruments, experts had significantly lower total gaze duration than novices during the initial approach, which was consistent with findings of previous studies [23], [24], [27], [28] and showed that expert pilots needed less effort to complete the approach phase [26].

C. IMPLICATIONS OF THE FINDINGS IN THIS STUDY

Clearly, experts performed better than novices throughout the whole experiment. Experts allocated their gaze duration on different AOIs in a different way from novices, which mainly accounts for their better flight performance from a statistical point of view. Specifically, for the holding pattern phase, experts put more focus on controlling the speed and direction of the aircraft during outbound-leg stage; while for the approach phase, experts paid more attention to ASI, ALT and VSI. Overall, it seems that experts, compared with novices, have established a more balanced and non-extreme model of attention allocation.

However, it was worth noting that the changes in the gaze durations between the experts and novices, although statistically significant, seem small in this experiment. To verify the robustness of our main results, we have also checked all other eye-movement data from the same apparatus (see II. METHODS) from 2016-2020. Interestingly, the conclusions remain qualitatively unchanged that gaze duration on different AOIs is most closely related to flight performance in all the eye movement indexes, and experts has a significantly different attention allocation model from novices. Thus, it is important and necessary to ''carry over'' the attention allocation mode of experts to novices in the daily training.

D. LIMITATIONS AND FUTURE WORK

First of all, a major problem is that participants in this study were from the same school, which might, to some extent, have led to the ''consistency'' of some of the eye-movement indexes. In fact, this is also a huge problem for other similar studies [26], [28]. More importantly, Wu *et al.* found that differences in cultural attitudes made Beijing students to behave completely differently from Boston students under the same experimental setting [44]. Thus, it is important to increase the diversity of participants to make the results more ''universal''.

Next, in our study on the use of the IFR (Instrument Flight Rules) procedure, OTW was not considered as part of the AOIs, which is quite different from the way to AOIs were divided in some previous works [7], [16], [42], [45]. There can also be some ''statistical deviation'' when our observations are compared with these studies.

Last but not least, simulator-induced flight environment is limited by many factors, and researchers are not always able to take all of the factors into account. For example, our study did not include fatigue associated with the performance of flight maneuvers. Therefore operation details were neglected, and it was not clear whether similar variations in gaze behavior would occur if different flight maneuvers were to be performed. Another serious problem is that the instructions obtained from simulator-based experiments are likely to deviate from reality. For example, novices may not be able to maintain balanced focus on all AOIs, and if forced to behave like experts, their flight performance would likely worsen. Therefore, a real flight experiment is needed for comparison purposes in the future.

V. CONCLUSION

Considering the complexity of both the holding pattern phase and approach phase, which usually make pilots have a large psychological load, we were curious as to how novice and expert pilots distribute their visual attention during these flight stages and how it affects their flight performance. Motivated by this, based on eye movement technology, 20 pilots were enlisted to complete the instrument holding pattern and approach procedure on the DA-42 simulator. The display of DA-42 simulator was divided into 6 AOIs according to different functions during flying. The conclusions are as follows.

i. In view of the eye movement data, it is clear that there exist significant differences in eye movement patterns between expert and novice pilots. Specifically, experts have established an effective attention allocation mode which makes them out-compete novices.

ii. Data analysis shows that compared to other eye movement indexes, the proportion of gaze duration on different AOIs is more closely related to flight performances. The experts' proportions of gaze duration on different areas of interests contributed to their better performance.

iii. Overall, experts have a more "balanced" focus on the entire visual display, which might explain their better performance. Specifically, during the outbound-leg stage, pilots will appropriately increase their attention to the airspeed indicator (ASI) and heading indicator (HI); as for the whole approach phase, although putting a lot of focus on the attitude director indicator (ADI) and heading indicator (HI) is unavoidable, pilots also concentrate more on other instruments to avoid ignoring other flight information.

iv. We recommend that the attention allocation mode of experts be adopted in daily flight training, as conscious visual behavior training can enable pilots to improve their flight performance.

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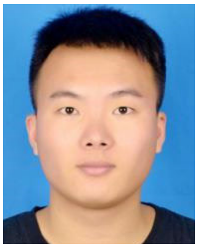

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