Pilots' Visual Scanning Behaviors During an Instrument Landing System Approach

Yanyu Lu; Yiyuan Zheng; Zhen Wang; Shan Fu

BACKGROUND: Since eye movement can provide a reliable index of the attention allocation, which can assist in understanding pilots' cognitive state, this study investigated the effect of pilots' experience and the autopilot mode on their attention allocation on the Primary Flight Display (PFD) and Multi-Function Display (MFD) during an approach task.

METHODS: There were 16 pilots who were classified into two levels of aviation expertise depending on the flight hours, and required to fly an Instrument Landing System approach. Their visual scanning behaviors were recorded through an eye tracker and analyzed based on fixation number and dwell time.

RESULTS: The results revealed that the pilot experience level, instrument panel and autopilot mode all had significant impact on the fixation time ratio and dwell time. The pilots fixated most often on the PFD and had shorter dwell time. Furthermore, they had a lower fixation number and shorter dwell time on the PFD and MFD when the autopilot was off that they should allocate visual resources to the others (e.g., out-of-the-window) and obtain more information to maintain overall situation awareness under higher time pressure. Compared to pilots with more expertise, pilots with less expertise had an increased fixation number and decreased dwell time on the airspeed after turning off the autopilot.

DISCUSSION: The present study indicated that the pilots had different visual scanning modes according to the flight mode and their experience. We expect that pilots' visual scanning behaviors during tasks will help the training and the design of the human-machine interaction.

KEYWORDS: Visual scanning behaviors, pilots' experience, flight deck.

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Human factors in aviation have matured as they have been integrated into all aspects of aircraft design and flight operation. The importance of effective human-machine interfaces and the cognitive model have been widely accepted in flight deck design. In commercial aviation, the pilot is the operational center of the system, as he/she is responsible for not only flight safety but also the integration of air traffic service, maintenance, dispatch and other systems.[8] Therefore, understanding pilots' behavior and cognitive state is necessary to study and improve human factors in aviation.

Visual scanning pattern has been applied in laboratory settings and real environments in various fields as a means of studying human factors because eye movement can provide a reliable index of attention allocation and can be captured continuously and measured objectively without interrupting the operators' activities.[24] Commonly used eye movement and performance variables are fixation, saccades (rapid eye movements), dwell duration (also called fixation duration and is the interval between two successive saccades), blink rate and pupil diameter. In the field of aviation, studies have primarily focused on eye movements in relation to mental workload,[5,9] display design,[21] cockpit monitoring strategies[4,17] and air traffic control.[10,11]

Eye movements have also been used to compare performance between experienced and novice pilots to identify effective scanning strategies and cognitive processes. Experts' cognitive performance is understood as superior performance by "rapid access to a well-organized body of conceptual and procedural knowledge."[1] Studies of experts' cognitive performance aim to reveal the development of advanced cognitive capabilities and

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their influencing factors, which have great significance for training novices and improving the human-machine interfaces. Bellenkes et al.[3] examined the differences between visual scanning and attentional flexibility in experienced and novice pilots, and their results revealed that experienced pilots had shorter dwell times and more frequent visits to most instruments. Huemer et al.[12] examined the differences in scanning behavior between experienced (astronauts) and novice (airline transport pilots) operators by measuring eye movements and recording performance parameters in a part-task space shuttle cockpit simulator. The study showed that the experienced pilots had fewer errors and faster reaction times, and both the novice and experienced group similarly modified their scanning strategies. Kasarskis et al.[13] compared scanning behavior between experienced and novice pilots via several simulated approaches and landings and found that experienced pilots had shorter dwells, more total fixations and airspeed fixation with fewer altimeter fixations than novices. Sullivan et al.[19] investigated potential improvements to training simulations by analyzing the influence of flight expertise on visual scan patterns. They found that gaze parameters and scan management skills were predicted by expertise level and that experienced pilots scanned more out-of-the-window (OTW) than novice pilots.

Many previous studies focused on the comparison of the pilots' visual scanning behaviors with different experience levels during a flight task. The fixation allocation on the different instrument panels and the effect of the different flight tasks should also be critical issues for the design of the flight deck and for training pilots. Among the panels in the flight deck, a Primary Flight Display (PFD) is a modern aircraft instrument dedicated to flight information critical to flight, including calibrated airspeed, altitude, attitude, vertical speed, etc. The PFD is designed to improve a pilot's situational awareness by integrating this information into a single display, reducing the amount of time necessary to monitor the instruments. Meanwhile, a Multi-Function Display (MFD) is used in concert with a PFD. The MFD displays navigational and weather information from multiple systems. Moreover, MFDs can also display information about aircraft systems such as fuel and electrical systems. These two panels provide most of flight information to pilots during the flight, and should draw most of their attention. The attention allocation between the two panels might reflect pilots' cognition skills.

In addition to instrument panels, the flight tasks performed by the pilots, such as monitoring, manual control, communication and so on, also have an impact on the pilot's attention. We hypothesize that pilots with difference experience should have different attention allocation on the PFD and MFD when performing different tasks/functions. The tasks/functions performed by the pilot can be differentiated by changing the autopilot mode. The pilot is mainly responsible for monitoring with the autopilot engaged, while he needs to manually control the flight with the autopilot disengaged. Therefore, this study aimed to investigate the effect of pilots' experience level and the autopilot mode on their foveal attention allocation on the PFD and MFD during an approach mission. Meanwhile, the attention allocation among Attitude Indicator (ADI), airspeed and altitude was further studied, since they are most important indicators of pilots' control during an approach mission.

METHODS

Subjects

Fourteen Chinese male commercial airline pilots participated in the experiment. The participants' age range was 30–53 yr (mean $\pm$ SD $=$ 38.4 $\pm$ 8.22 yr). They had 1000–18,000 h of total flight time and 0–89 flight hours in the two weeks before the experiment. Seven pilots were the captains of a CRJ-200, while the others were the co-captains. Each pilot has been the captain or co-captain of a CRJ-200 for more than 1 yr. The experiments were approved by the Academic Committee of the School of Aeronautics and Astronautics, Shanghai Jiao Tong University (Approval number: 2014-019) and adhered to the tenets of the Declaration of Helsinki. Before the experiment, all subjects were informed of the purpose and procedures of the experiments and signed an informed consent form prior to participation.

There were 14 pilots who were classified into 2 levels of aviation expertise depending on their total flight hours and the responsibility in a CRJ-200: less expertise and more expertise, with the threshold of 5000 flight hours. In the more expertise group, 7 pilots had 10,857.1 $\pm$ 5177.3 (mean $\pm$ SD) flight hours and were the captains of a CRJ-200; the other 7 pilots were in the less expertise group with 1677.8 $\pm$ 1177.5 flight hours and were the co-captains. The groups differed significantly in mean age, as expected with less experienced pilots being younger (35.4 $\pm$ 6.8 yr) and more experienced pilots being older (39.0 $\pm$ 7.4 yr).

These pilots were paired into 14 flight crews in which one pilot served as the Pilot Flying (PF) and the other pilot as the Pilot Monitoring (PM). Because the PF controlled the aircraft and was responsible for the navigation of the aircraft and the monitor of the systems, the study focused on the characteristics of the PFs' eye movements. Since each pilot performed as a PF, each expertise group had equal opportunity to engage with the PFD and MFD during the task.

Apparatus

The experimental apparatus included a CRJ-200 full-flight simulator and an eye tracker. The simulator was a qualified simulator (level D) conforming to the guidelines presented in the Federal Aviation Administration Advisory Circular (AC120-40B) – Airplane Simulator Qualification, which has also been used for pilot training for commercial airlines. Three areas of interest [AOIs: Attitude Indicator (ADI), airspeed, and altitude] were developed according to the information on the PFD (**Fig. 1** and **Fig. 2**).

The eye movements of the pilots were recorded with a Tobii glasses eye tracker (Tobii Technology, Stockholm, Sweden) at a sampling rate of 30 Hz. A series of infrared markers were mounted in the flight deck to define the areas of analysis and aggregate gaze data for the analysis. The gaze points would automatically be aggregated through the selected recording. The results of whether the gaze point is located inside of the AOI

Fig. 1. The flight deck of the CRJ-200.

could be exported. The infrared marker emitted invisible infrared light which did not interfere with the pilots during the flight.

Procedure

The pilots were briefed on the routes, weight, and balance of the aircraft for the simulation runs. Then, a training test, including a straight and level flight and an Instrument Landing System (ILS) approach into the runway at Xi'an Xianyang International Airport, was performed to help familiarize the pilot with the experimental procedure, reduce the bias between the groups, and accommodate them to flight with the glasses eye tracker. In the formal experiment, all the pilots were required to perform the same ILS approach into Xi'an Xianyang International Airport's runway. The flight mission started from straight and level flight at 10,000 ft, i.e., no takeoff was included. The autopilot was engaged at the beginning. The airplane was kept descending to the initial landing point, where the height was 1500 ft at a speed of 250 kn. Then, the flight crew executed a landing according to the "standard instrument landing procedure." The autopilot was turned off when the pilots had adequate visual reference of the landing environment. A manual landing procedure was required for the pilots. The whole mission lasted about 10 min, with about 5 min with autopilot off. A flight instructor participating in the experiment was responsible for the configuration of the scenario and served as an Air Traffic Controller.

Fig. 2. The Primary Flight Display (PFD), Multi-Function Display (MFD), and three areas of interest (AOIs).

Data Analysis

In the study, the fixation data were calculated according to the gaze points in the AOIs provided by the eye tracker. The threshold of a fixation was determined to be 100 ms.[6,14,22] Therefore, three or more temporally sequential gaze point samples in the AOI were classified as a fixation according to the sample rate of the eye tracker (30 Hz). The dwell time (fixation time) (T_{dwell}) in an AOI was calculated as

$$T_{dwell} = \frac{\sum_i^N end\_t_i - start\_t_i}{N}$$

where $start\_t_i$ was the start time of the i^st^ fixation and end_t_i was the end time. N was the fixation number in the AOI.

Wickens and McCarley[24] summarized that the eye movements in selective attention could be measured by fixation, dwell duration, percentage dwell time, event fixation latency, and so on. These measures were widely used in the study of visual attention, including situation awareness,[7,15] evaluation of advanced display technology,[23] reading on web pages,[18] and other research. Therefore, the fixation number (the ratio between the selected areas and the number of all display systems in the flight deck) and dwell time of Pilots Flying were analyzed in the study to measure the visual scanning behaviors of pilots. The data represented the mean number and standard deviation for the combined data from two groups and were analyzed with analysis of variance (ANOVA) to examine the effects of different factors on the fixation number and time. A three-way mixed-model ANOVA was used in the results with experience as between-subject factor and autopilot mode and panels/AOIs as the within-subject factors. All significant interactions were evaluated with tests of simple effect.

RESULTS

PFD vs. MFD

The fixation number rate and dwell time were compared between pilots with different experience levels on the selected instrument panels (PFD and MFD) when the pilots performed the different flight tasks (autopilot engaged or disengaged, **Table I**).

The fixation number rate and dwell time were analyzed using three-way mixed-model ANOVA, with experience (more expertise or less expertise) as between-subject factor and autopilot mode (engaged or disengaged) and panels (PFD or MFD) as the within-subject factors.

The statistical results revealed that there were no significant three-way interactions, but a significant main effect of experience, autopilot mode, and panels on the fixation number. The pilots with less expertise fixated significantly less than those with more expertise [$F(1, 6) = 10.645$, $P = 0.002$, $\eta^2 = 0.275$]. The fixation number on the PFD was significantly more than that on the MFD [$F(1, 6) = 61.304$, $P < 0.001$,

Table I. The Fixation Number Ratios and Dwell Time of Pilots with Different Experience on PFD and MFD When Autopilot Is On and Off.

		AUTOPILOT ON		AUTOPILOT OFF	
		LESS EXPERTISE	MORE EXPERTISE	LESS EXPERTISE	MORE EXPERTISE
Fixation Number Ratio	PFD	0.45 ± 0.12	0.50 ± 0.14	0.31 ± 0.14†	0.49 ± 0.13*
	MFD‡	0.24 ± 0.15	0.25 ± 0.06	0.08 ± 0.03†	0.23 ± 0.11*
Dwell Time	PFD	200.31 ± 52.05	214.18 ± 61.27	155.48 ± 31.50†	213.98 ± 29.91*
	MFD‡	287.16 ± 43.02	250.27 ± 45.12	167.20 ± 29.26†	236.67 ± 40.39*

All values are mean ± SE.
* Significantly different from the pilot with less expertise. †Significantly different from autopilot on. ‡Significantly different from PFD.

$\eta^2 = 0.315$] (**Fig. 3A and B**). The PFD was fixated on twice as much as the MFD. The pilots fixated significantly less on both the PFD and MFD when autopilot mode was off [$F(1, 6) = 5.803$, $P = 0.020$, $\eta^2 = 0.703$]. Meanwhile, there was a significant effect of interaction between the pilots' expertise and autopilot mode [$F(1, 6) = 4.952$, $P = 0.031$, $\eta^2 = 0.204$]. Tests of simple effects indicated that both expertise groups decreased their fixation number when the autopilot was not engaged, but the change of the fixation number was greater in pilots with less expertise than pilots with more expertise. Compared with the less experienced pilots, the pilots with more experience fixated much more both on the PFD and MFD without the autopilot, while with autopilot on, there was not an obvious difference between the pilots with different expertise levels.

The analysis of the dwell time (**Fig. 3C and D**) revealed a significant main effect of the instrument panels [$F(1, 6) = 9.081$, $P = 0.004$, $\eta^2 = 0.783$]. The dwell time of the pilots was significantly shorter on the PFD than on the MFD. Similar to the fixation number, the autopilot mode and pilot expertise significantly affected the dwell time [$F(1, 6) = 10.525$, $P = 0.002$, $\eta^2 = 0.494$; $F(1,6) = 5.061$, $P = 0.029$, $\eta^2 = 0.223$, respectively]. There was a significant effect of interaction between the pilots' expertise and panels [$F(1, 6) = 4.636$, $P = 0.002$, $\eta^2 = 0.593$]. Tests of simple effects indicated that both expertise groups had less dwell time on the PFD than on the MFD, but the difference between the two panels was greater in pilots with less expertise than pilots with more expertise.

AOIs on PFD

PFD is the most important display system in the flight deck and constitutes almost half of pilots' fixations. Therefore, three AOIs indicating the basic flight parameters (ADI, airspeed, and altitude) were defined to investigate pilot's attention allocation on the PFD (**Table II**).

The fixation number and dwell time were analyzed using three-way mixed-model ANOVA, with experience (more expertise or less expertise) as between-subject factor and autopilot mode (engaged or disengaged) and AOIs (ADI, airspeed, and altitude) as the within-subject factors (**Fig. 4A and B**).

There was a significant main effect of AOIs [$F(2, 12) = 3.343$, $P = 0.041$, $\eta^2 = 0.353$] and pilots' expertise[$F(1, 6) = 4.464$, $P = 0.038$, $\eta^2 = 0.480$] on fixation number. Meanwhile, there was a significant interaction of AOIs × expertise × autopilot mode for the fixation number [$F(2, 12) = 3.349$, $P = 0.041$, $\eta^2 = 0.301$]. Tests of simple effects indicated that there was a significant effect of the experience level when they fixated on the airspeed whether the autopilot was engaged and when they fixated on the altitude with the autopilot engaged. The fixation number of the pilots with less expertise presented a different mode from that of pilots with more expertise, that the pilots with less expertise fixated least on the altitude while the pilots with more expertise fixated least on the airspeed. When the autopilot mode was off, the pilots with less expertise fixated more often on the airspeed and less on the ADI, while there was less change for the pilots with more expertise.

Analysis of the dwell time revealed a significant main effect of autopilot mode [$F(1, 6) = 4.694$, $P = 0.034$, $\eta^2 = 0.290$] (**Fig. 4C and D**). The pilots had significantly shorter dwell time with the autopilot off. The pilots with different expertise had a different mode of the dwell time with the autopilot off, although there was no main effect of expertise, no main effect of AOIs

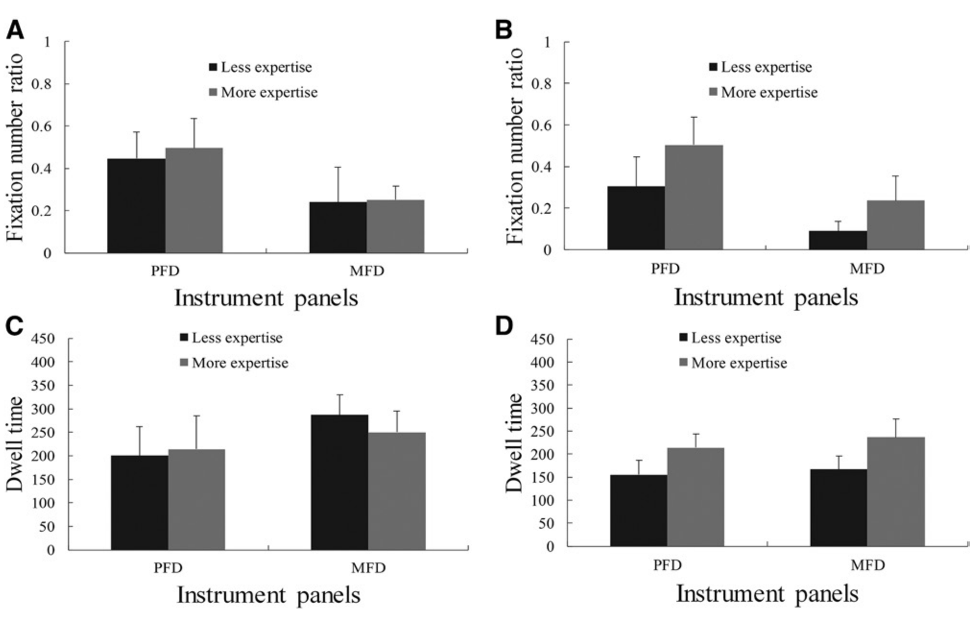

Fig. 3. The fixation number ratio and dwell time of pilots with different levels of experience on PFD and MFD: A) fixation number ratio with an autopilot; B) fixation number ratio with no autopilot; C) dwell time with an autopilot; and D) dwell time with no autopilot. Error bars represent the SE.

Table II. The Fixation Number Ratios and Dwell Time of Pilots with Different Experience on Three AOIs of PFD When Autopilot Is On and Off.

		AUTOPILOT ON		AUTOPILOT OFF	
		LESS EXPERTISE	MORE EXPERTISE	LESS EXPERTISE	MORE EXPERTISE
Fixation Number Ratio	ADI	0.13 ± 0.05	0.15 ± 0.04	0.09 ± 0.06†	0.15 ± 0.04
	Airspeed	0.12 ± 0.05	0.05 ± 0.02*	0.12 ± 0.1	0.05 ± 0.03*
	Altitude	0.05 ± 0.04	0.14 ± 0.04*	0.05 ± 0.04	0.11 ± 0.04*
Dwell Time	ADI	230.02 ± 62.01	246.25 ± 79.44	172.15 ± 33.63†	189.91 ± 28.67†
	Airspeed	217.40 ± 59.26	205.44 ± 73.04	133.21 ± 40.78†	189.87 ± 22.64†
	Altitude	195.71 ± 54.14	180.52 ± 74.51	173.21 ± 35.74†	159.76 ± 55.02†

All values are mean ± SE.
* Significantly different from the pilot with less expertise. †Significantly different from autopilot on.

and no interaction effect. Among the three AOIs, the greatest decline of the dwell time for the pilots with less expertise was on the airspeed, while for the pilots with more expertise, the fixation allocation remained more stable.

DISCUSSION

This study focused on the attention allocation of pilots with different levels of expertise on different instrument panels in the flight deck while they performed different tasks separated by the autopilot mode.

All pilots in the study fixated more often on PFD than on MFD, regardless of whether the autopilot was engaged or not. PFD presents the most basic flight information at a update rate of at least 15 Hz, while MFD shows the aircraft's current route plan and weather information with a update rate no less than 1 Hz.[26] Pilots tend to look more at places where there is a lot of "action."[25]

The study revealed that there was a significant difference between the dwell time on the PFD and MFD, i.e., the pilots had shorter dwell time on PFD, especially for those with less expertise. This result may be attributed to the differences between information formats and presentations between the two instrument panels. The PFD presents basic flight parameters (e.g., airspeed, attitude, and altitude) in a fixed location with a distinct and fixed format, and pilots adopt a strategy of detecting deviations from a particular position rather than reading the precise value. However, the MFD has more information formats, such as navigation route and a moving map, which require pilots to spend more time to extract information.

After turning off the autopilot, the change of attention allocation proved that the flight tasks performed by the pilots have an impact on their attention allocation. The fixation number on the PFD and MFD both decreased, especially on the MFD. According to the flight operating procedure, the pilots should turn off the autopilot when they establish visual reference to the landing environment. Therefore, the pilots paid less attention to the route and shifted it to OTW scenes.[2] Besides, the dwell time on the instrument panels was shorter when the autopilot was not engaged, especially for the pilots with less expertise. The shorter dwells meant that the pilots needed to allocate visual resources to the others, obtaining more information from other aspects and having a better overall situational awareness to help make more accurate decisions under higher time pressure constraints.[13]

The study revealed the interaction between the autopilot mode and the pilots' expertise and proved our hypothesis that the pilots with different experience levels had different attention allocation when performing different tasks, even if they all completed the tasks. When turning on the autopilot, there was not an obvious difference of visual scanning behaviors between two expertise levels of the pilots. The pilots with more expertise had slightly shorter dwell times and a higher fixation number, which was similar to the previous studies.[3,13] In this phase, the main task of the pilots was monitoring the systems. However, for the manual landing (without the autopilot), the visual scanning

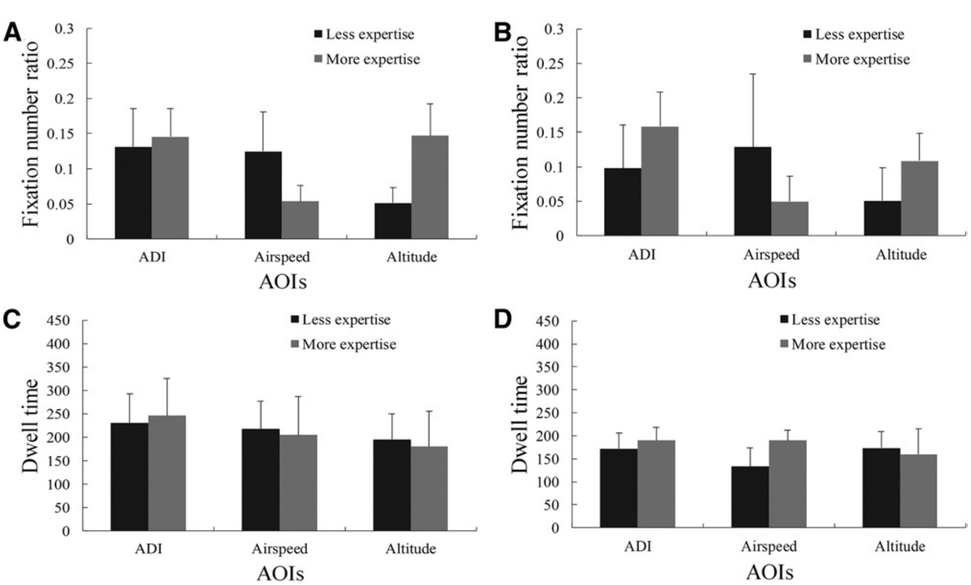

Fig. 4. The fixation number ratio and dwell time of pilots with different levels of experience on three AOIs: A) fixation number ratio with an autopilot; B) fixation number ratio with no autopilot; C) dwell time with an autopilot; and D) dwell time with no autopilot. Error bars represent the SE.

behavior of the pilots with less expertise changed more (less fixation time on the instrument panels and shorter dwell time) relative to that of the pilots with more expertise whose scanning behaviors had less changes. This result may be attributed to the experienced pilots' ability that their additional flight experience helped them adapt to the change of flight demands and maintain a relatively stable cognitive state.[3] Meanwhile, it suggested that the pilots with more expertise had a better situation awareness, since fixation rates and dwell times as information acquisition indicators in pilots could reflect the perceptual level of situation awareness.[15,16]

The results concerning the attention allocation on the three AOIs further proved our hypothesis. The pilots with more expertise had a more stable distribution mode of their scan behaviors on the three AOIs whether autopilot was engaged or not, i.e., they fixated most on ADI and least on the airspeed panel. Otherwise, when the autopilot was not engaged, the pilots with less expertise had an increased fixation number and decreased dwell time on the airspeed. At the end of the approach phase, the uncertainty of the airspeed could make them adjust their visual scanning behavior and pay more attention to the airspeed panel. This result was consistent with the findings of Taylor et al.[20] that there was an advantageous effect of prior experience and specialized expertise on older pilots' cognitive performance, because more pilot experience was associated with older age in the study. It was suggested that the stable visual scanning behavior may be an effective index for training novice pilots since expert's cognitive performance represents advanced cognitive capabilities and their influencing factors.

The out-of-the-window scanning characteristics were not considered in the study for two reasons. First, the pilots paid more attention to instruments than OTW during the ILS approach, especially with the autopilot engaged. Second, unlike the head-down display, there were no specific quantitative data and no status information in the OTW scene, meaning that it was difficult to define an appropriate AOI and determine a fixation.

In future research, the difference between pilots with different experience levels (more experienced pilots vs. student pilots) in more difficult flight tasks (such as severe weather or alert conditions) will be considered to explore more expertise characteristics. Meanwhile, we will concentrate on developing different training strategies for pilots with different experience levels based on the results of this study and improve the design of the flight deck.

In conclusion, the present paper aimed to study the effect of the pilots' experience on the visual scanning strategies on the PFD and MFD when performing different tasks. The results proved our hypothesis that attention allocation strategies of the pilots with different experience levels would be changed in a different way with their tasks. It revealed that pilots fixated more often on the PFD and had shorter dwell time, and their visual scanning behavior has obvious differences when autopilot is engaged or not. Compared with pilots with less experience, pilots with more experience had more stable visual scanning behaviors. We could expect that the pilots' visual scanning behaviors during tasks will help the training and design of the human-machine interaction.

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