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Research Article

A Real-Time Measurement Model of Attention-Allocation Level and Its Application in Simulated SPO Task

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Most human-caused flight accidents can be attributed to a pilot's attention deficit and monitoring errors. Accordingly, pilots' attention allocation is strongly related to their task performance. This study is aimed at analyzing pilots' fixation characteristics and attention-allocation levels. First, we proposed a model for measuring attention-allocation level based on the salience, effort, expectancy, and value (SEEV) model. Second, a low-fidelity single-pilot operation (SPO) cockpit environment was constructed, and 20 pilots were recruited for an experiment to compare their fixation characteristics between SPO and double-pilot operation (DPO) scenarios. The results showed slight differences in the attention levels allocated by SPO and DPO pilots under a scenario of one-engine failure. It concluded that Human-centered flight deck design can enhance a pilot's attention allocation level. These findings can be used to optimize future flight deck designing and flight training for improving pilot's task performance.

1. Introduction

The reliability of modern aircraft cockpit equipments continues to be improved in the past decades, and the proportion of flight accidents caused by mechanical or system problems also keeps decreasing, human factors have become the primary threat to flight safety [1]. Pilots are gradually shifting from manual operation to monitoring aircraft status and making decisions based on cockpit automation. Aviation has long been concerned about breakdowns in human–automation interactions [2], which require receiving a large amount of information. Human–computer interactions often fail as a result of monitoring errors [2, 3]. In the cockpit environment, the primary channel through which pilots obtain information is the visual system. Experienced pilots are able to reduce monitoring errors and obtain more accurate information [4]. A report by the National Aeronautics and Space Administration (NASA) indicated that 77% of automated driving accidents were related to pilot inattention, and other studies have shown that attention is closely related to monitoring task performance [5, 6].

Attention is a key psychological regulatory mechanism in information processing and the allocation of limited resources. It has been shown that almost half of crew errors are caused by pilots' attention-allocation problems [7]. Dismukes et al. [8] found that pilots' attention allocation played a significant role in their cognitive processes. A complex and dangerous flight environment is one factor that can threaten flight safety [1]. In the case of system failure, a pilot faces an increased workload, which requires more visual searching and processing. However, a pilot's attentional resources are limited, and attention-allocation level is therefore an important factor affecting a pilot's access to and cognition of information in the scenario. This, in turn, has a significant effect on task performance and safety, thus highlighting the importance of studying pilot attention allocation in failure scenarios.

A pilot's mental workload is strongly correlated with situational awareness, and an excessive mental workload could lead to poor situational awareness [9]. Even if the information is accurate, excessive information can result in mental overload and might not improve decision quality. Visual

attention can provide insights into cognitive processes [10], information processing, and the effect of an interface on a pilot's visual characteristics. By optimizing the *Quick Reference Handbook* search and presenting the actions and recommendations, pilot operations and decision-making can be facilitated, and search times can be reduced [11, 12]. Pilot operating time can be reduced by new designs that can reduce pilot workload and improve task performance.

Attention allocation has mostly been modeled by combining cognitive mechanisms and information processing. Dehais et al. [13] developed the ADAPT model to predict pilots' attention allocation and behavior. The salience, effort, expectancy, and value (SEEV) model proposed by Wickens et al. [14] is among the most widely used models in the field of flight piloting. SEEV was subsequently improved and refined to increase noticing time and the probability of noticing, forming the NT-SEEV model [15]. Further, Wickens et al. [16] combined situational awareness and attention allocation as part of the attention–situational awareness model. It has been shown that simulation participants cannot handle all visual information [17]. In this regard, highlighted information attracts attention and enables operators to make quick decisions [18, 19]. Different monitoring tasks, such as flying [16] and driving [20], have been validated using the SEEV model.

Most attention-allocation research focuses on behavioral prediction as opposed to establishing a quantitative model of attention allocation. The level of automation and intelligence of airborne systems is increasing, and single-pilot operation (SPO) has emerged as a future trend in aviation. Research on SPO human factors has focused on SPO design solutions, onboard system updates, personnel communication and collaboration, pilot incapacitation, and airworthiness certification, among other topics. Three main factors affect passengers' attitudes toward SPO: pilot performance, passengers' trust in technology, and ticket price [21]. Research on SPO has been conducted by NASA [22], the European Aviation Safety Agency [22], and aircraft manufacturers such as Airbus [23]. In consideration of flight safety and ergonomic concerns, researchers have favored a "cockpit+ground station" solution [24, 25], resulting in the formation of a collaborative "single pilot+onboard automation system+ground operator" system [26]. The limited existing research does not provide enough evidence to verify the optimal SPO. It has been demonstrated, however, that pilots can manage certain abnormal flight scenarios with the support of onboard systems and ground operators [24, 27]. In addition to eliminating decision-making conflicts caused by cognitive biases and inconsistent operation under double-pilot operation (DPO), SPO might be able to improve pilots' decision-making efficiency. SPO might also optimize the human–machine interface in the cockpit and enhance pilot attention allocation.

Based on the SEEV model, we propose a quantitative model of attention allocation that incorporates fixation characteristics, eye-movement data, and task-performance indicators as quantitative factors. It is capable of assessing pilots' attention-allocation levels during malfunction scenarios. We specifically aimed to do the following:

(1) Develop a quantitative model of attention allocation

(2) Analyze differences in fixation characteristics between SPO and DPO pilots under malfunction scenarios

(3) Compare pilots' attention-allocation levels between the two modes of operation using the attention-allocation quantification model

2. Model Construction

2.1. SEEV Model. Based on flight operation, Wickens [28] proposed the SEEV model, which includes four factors: salience, effort, expectancy, and value. A linear weighted relationship between them is established as follows:

$$A = aS - b\mathrm{Ef} + c\mathrm{Ex} + dV, \tag{1}$$

where A is the amount of attentional resources of pilots in the area of interest (AOI); S is the information salience in the AOI; Ef is the effort pilots invest in acquiring information; Ex is pilots' expectation of information in the AOI; V is the value of information in the AOI; and a, b, c, and d are the weighting coefficients of the factors.

It has been demonstrated that the SEEV model is consistent with both the top-down and bottom-up attention mechanisms of humans; it is capable of accurately predicting the attention allocation of a category of drivers [29]. Nevertheless, there are no quantitative indicators for the model's factors and no explanation for the weight coefficients.

2.2. Attention-Allocation Measurement Model Construction. The model's factors include salience, effort, and situational attributes.

2.2.1. Salience. Human physiological conditions and external stimuli contribute to the emergent nature of the SEEV model, which is controlled from the bottom up by the mechanism of attention control. While the color, size, and luminance of an AOI can affect physiological conditions, this varies from individual to individual. AOI is defined as the area in which the subject must gaze to receive information; salience is defined as the target object's own property, which is a fixed value. The mean pupil diameter reflects the physiological state of the individual and the influence of external stimuli [30]. Mean pupil diameter can therefore reflect an individual's workload. According to other physiological data that objectively reflect the workload, disposing of the malfunction in the SPO does not significantly increase the pilot's workload. Therefore, we used mean pupil diameter as an indicator of prominence, and the quantitative value of prominence was recorded as V:

$$V = \frac{P_E - P_{E-\min}}{P_{E-\max} - P_{E-\min}}, \tag{2}$$

where V is the participant's prominence in the experimental situation, P_E is the experimental value of the participant's mean pupil diameter, $P_{E-\min}$ is the minimum value of the participant's mean pupil diameter in the experimental situation, and $P_{E-\max}$ is the maximum value of the participant's mean pupil diameter in the experimental situation.

2.2.2. Effort. Human attention has limited resources [31]. Obtaining more information requires a corresponding sweeping effort that suppresses attention allocation. In the SEEV model, effort is affected by the distance between the visual center and each AOI. The participants were in the same environment, and the distance between their visual center and each AOI did not differ significantly. Thus, we considered using situational durations that reflect effort. However, situational durations can adversely affect attention allocation. The equation can be expressed as follows:

$$E_f = \frac{T_E - T_{\text{Min}}}{T_{\text{Max}} - T_{\text{Min}}}, \tag{3}$$

where E_f is the degree of effort participants put into acquiring information, T_E is the experimental measurement of the participants' situational duration, T_{Min} is the minimum value of situational duration in the experiment, and T_{Max} is the maximum value of situational duration in the experiment.

2.2.3. Situational Attributes. In the SEEV model, expectancy and value are top-down factors influencing the attention allocation. The quantitative model integrates expectancy and value into situational attributes, and a close correlation exists between fixation duration and information processing. In addition, there is a correlation between fixation duration and fixation counts [32]. Thus, the percentages of fixation duration and fixation counts were selected as influencing factors. This is expressed by the following equation:

$$S_i = I_{C-i} \times u_i \times (P_{\text{FT}-i} + P_{\text{FC}-i}), \tag{4}$$

$$S = \sum_{i=1}^{n} S_i, \tag{5}$$

$$S_n = \frac{S - S_{\min}}{S_{\max} - S_{\min}}, \tag{6}$$

where S_i is the i AOI situational attribute, I_{C-i} is the amount of visual information in the i AOI, u_i is the combined rating of the importance and validity of visual information in the i AOI, $P_{\text{FT}-i}$ is the percentage of fixation duration in the i AOI, $P_{\text{FC}-i}$ is the percentage of fixation counts in the i AOI, S is the total value of the participant's situational attribute in the experimental scenario, and S_n is the quantitative value of the participant's situational attribute.

The amount of visual information in AOI, I_{C-i}, took values from 0 to 10. The integrated evaluation value of the importance and validity of visual information in AOI, u_i, took values from 0 to 1, both influenced by the task scenario. The I_{C-i} and u_i of each AOI were evaluated by experts.

2.2.4. Attention-Allocation Level. In summary, participants' attention-allocation levels in scenario A can be expressed as follows:

$$A = V - E_f + S_n, \tag{7}$$

where A is the participant's attention-allocation level in the experimental scenario, V is the participant's salience in the experimental scenario, E_f is the participant's effort to obtain information in the experimental scenario, and S_n is the quantitative value of the participant's situational attributes in the experimental scenario.

3. Materials and Methods

In the past few decades, civil aviation has transitioned from five to two pilots. It will eventually transition from two to one pilots and finally to unmanned aircraft. To ensure safety, SPO cockpits must be optimized for human–machine interaction, workload reduction, and physiological indicator monitoring, which can improve pilot attention distribution [33, 34].

3.1. Participants. To reduce the effect of flight experience on attention allocation [35], 20 B737 aircraft pilots were grouped equally based on flight rating. There were one female and 19 males, aged 20–50, with total flight times of 2000–18,000 h (mean: 6771.8; standard deviation: 4297.02). All participants were in good physical health and had normal vision and hearing. They were asked to avoid alcohol, caffeine, and medications for 24 h prior to the test. They were also asked to get adequate sleep.

3.2. Apparatus and Materials. The A320 quasi-five-level fixed flight simulation platform was used for the flight simulation experiment. The flight simulation platform's components include the main control system, simulation system, environment and vision system, and flight data acquisition and processing system [34]. The main control system allows for selecting an airport and runway, adjusting the aircraft's position and status, and setting different weather conditions and aircraft malfunctions (see Figure 1).

The experimental equipment included a head-mounted eye-tracking device (Tobii Pro Glasses 2; see Figure 2) and a behavior recorder.

3.3. Experimental Design. The experiment involved two cockpit environments in which the changes in ambient light were consistent. In cockpit, the light sources were consistent and unchanged after taking off. Through this way, we made sure that participants experienced a consistent effect due to the AOIs' light source. One was SPO, which provided intelligent assistance systems and ground operating station support; the other was DPO, which was based on existing cockpit systems. In the SPO cockpit, a copilot was isolated from the cockpit of the A320 and was used as a ground station. According to flight experience, we divided the participants into two groups, one for SPO operation and the other for DPO operation. All participants were in the role of the PF during the whole experiment; PM in the DPO was acted by the same person.

The experimental scenario selected one-engine failure in the clean configuration, as shown in Figure 3.

3.4. Selection of Indicators. The cockpit visual information interfaces were divided as follows: AOI 1 primary flight display (PFD), AOI 2 navigation display (ND), AOI 3 engine/

Figure 1: A320 quasi-five-level fixed flight simulation platform.

Figure 2: Tobii Pro Glasses 2 head-mounted eye-tracking device.

warning display (E/WD), AOI 4 system display (SD), AOI 5 central console, AOI 6 flight manual, and AOI 7 outside window (see Figure 4). However, the participants did not gaze at AOI 7.

The fixation duration, fixation count, mean fixation duration, fixation duration percentage, and fixation count percentage of AOI were selected as the indicators of individual visual attention allocation. Fixation duration is the length of time an individual gazes at an AOI, fixation count is the number of points an individual gazes at within an AOI, mean fixation duration is the ratio of the time an individual gazes at an AOI to the number of points gazed at, fixation duration percentage is the percentage of the time an individual gazes at an AOI to the total fixation duration, and fixation count percentage is the percentage of the number of points gazed at within an AOI to the total number of points gazed at.

Mean pupil diameter and malfunction duration were also selected. Mean pupil diameter reflects the effect of the flying task on the participant; malfunction duration reflects the participant's task performance.

3.5. Experimental Procedure. Each participant read and signed an informed consent form before participating in the experiment and then provided basic personal information. They spent 10 min familiarizing themselves with the flight simulator. Then, the participants put on Tobii Pro Glasses 2 head-mounted eye-tracking devices with assistance from the researchers. Once the equipment was in place, the experiment began, and the results were recorded. We used the situation awareness global assessment technique (SAGAT) to assess participants' situation awareness. We assessed participants' situational awareness by a questionnaire that included experienced scenarios, related operations, and parameter recollection.

Participants flew an A320. They completed takeoff checks and received instructions prior to takeoff. When the clean configuration form was reached, an unknown single-engine failure scenario occurred. Participants were asked to follow standard operating procedures for malfunction disposal, while the aircraft's status remained in autopilot mode at the time of the malfunction. After the malfunction was resolved, they were asked to spend 5 min assessing their situational awareness. The entire experiment lasted approximately 20 min.

4. Data Analysis

4.1. Fixation Characteristics. IBM SPSS Statistics 23.0 was used to analyze the fixation characteristic indicators; the Shapiro–Wilk test was used to test normality. For indicators that meeting the normality requirement, an independent-sample t-test was used; the Mann–Whitney U-test was used for indicators that did not meet the normality requirement. In the experiment, the indicators of meeting normality distribution were analyzed by using t-test, including the AOI 1 (PFD) mean fixation duration; the AOI 2 (ND) fixation duration percentage and fixation count percentage; the AOI 3 (E/WD) fixation duration, fixation counts, fixation duration percentage, and fixation count percentage; the AOI 5 (central console) fixation duration, fixation counts, fixation duration percentage, and fixation count percentage; and the AOI 6 (flight manual) fixation counts, mean fixation duration, fixation duration percentage, and fixation count percentage. For other indicators that do not meet the normal distribution, the Mann–Whitney U-test is used to analyze.

Figure 5 shows the differences in fixation characteristics between the two cockpit environments.

Between the two cockpit environments, the fixation duration percentage ($p = 0.035$, $z = -2.08$) and fixation count percentage ($p = 0.043$, $z = 2.004$) for AOI 1 (PFD) showed statistically significant differences. The fixation duration for AOI 3 (E/WD) showed statistically significant differences ($p = 0.02$, $t = -2.6$, $d = -1.163$). The fixation counts ($p = 0.015$, $t = -2.873$, $d = -1.285$), fixation duration percentage ($p = 0.042$, $t = -2.277$, $d = -1.102$), and fixation count percentage ($p = 0.009$, $t = 3.047$, $d = -1.36$) for AOI 6 (flight manual) showed statistically significant differences. The results for all other indicators showed no statistically significant differences between the SPO group and the DPO group ($p > 0.05$).

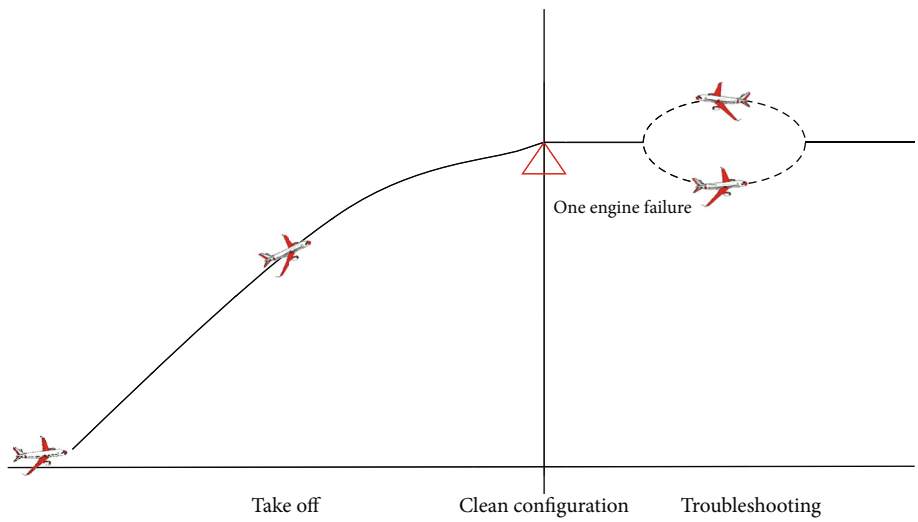


Figure 3: Experimental scenario.

Figure 4: AOI diagram.

4.2. Model Calculations

4.2.1. Salience Quantification. During the malfunction disposition phase, participants' pupil diameters were continuously measured with an eye-movement device to determine their mean pupil diameter. It was significantly larger for participants in the SPO cockpit than for those in the DPO cockpit ($p < 0.05$), as shown in Figure 6.

The mean pupil diameters of individual participants were extracted and calculated using equation (1). Table 1 shows the results.

4.2.2. Effort Quantification. A behavioral recorder was used to extract participants' situational durations. Statistical analysis revealed significant differences between the situational durations of participants in the SPO cockpit and the DPO cockpit. Specifically, the situational duration of SPO pilots was shorter than that of DPO pilots, as shown in Figure 7.

The behavioral camera was used to record the participants' operation processes, from which situational duration was calculated and effort was quantified using equation (2). Table 2 shows the effort quantification results.

4.2.3. Situational Attribute Quantification. Experts were invited to subjectively score the I_{C-i} and u_i of the experimental scenario AOIs. The average value was taken as the result for the cockpit environment. Table 3 shows the results. The subjective score is provided anonymously by pilots, psychologists, and experts in fields related to civil aviation.

We calculated the quantified values of the participants' individual situational attributes by substituting the fixation duration percentage and the fixation count percentage of the AOIs into equations (4)–(6). Table 4 shows the results.

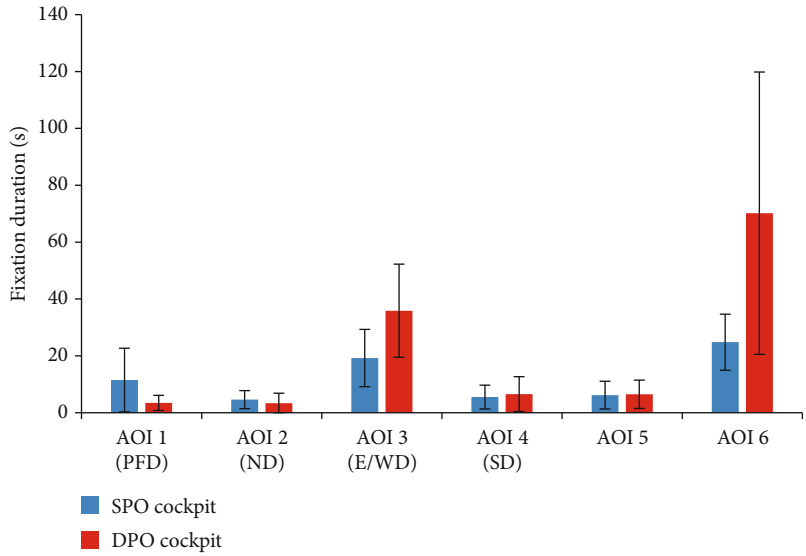
4.2.4. Attention-Allocation Quantification. We substituted the quantitative values of salience, effort, and situational attributes into equation (7) to calculate the attention-allocation levels of individual participants in the scenario of one-engine failure. Table 5 shows the attention-allocation results.

The average value of attention allocation was slightly higher for participants in the SPO cockpit than for those in the DPO cockpit, but the standard deviations of attention-allocation level in both cockpit environments were large (see Figure 8).

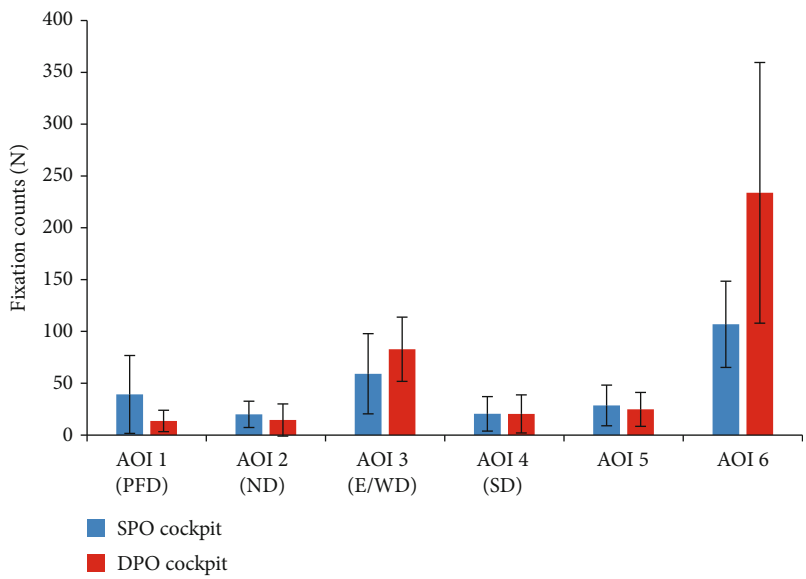
5. Discussion

Along with the amount and complexity of visual information presented to a pilot, the pilot's visual behavior can reflect their workload, attention allocation, and situational awareness of the scenario they find themselves in. This study constructed a low-fidelity SPO cockpit, analyzed participants fixation characteristics under SPO, and investigated the differences of fixation characteristics and attention-allocation levels in SPO group and DPO group. We also attempted to observe how the intelligent assistance system integrated with ground operation station support affected attention allocation and fixation characteristics.

5.1. Impact of SPO Cockpit on Pilot Fixation Characteristics. We selected fixation characteristics for fixation duration, fixation counts, mean fixation duration, fixation duration

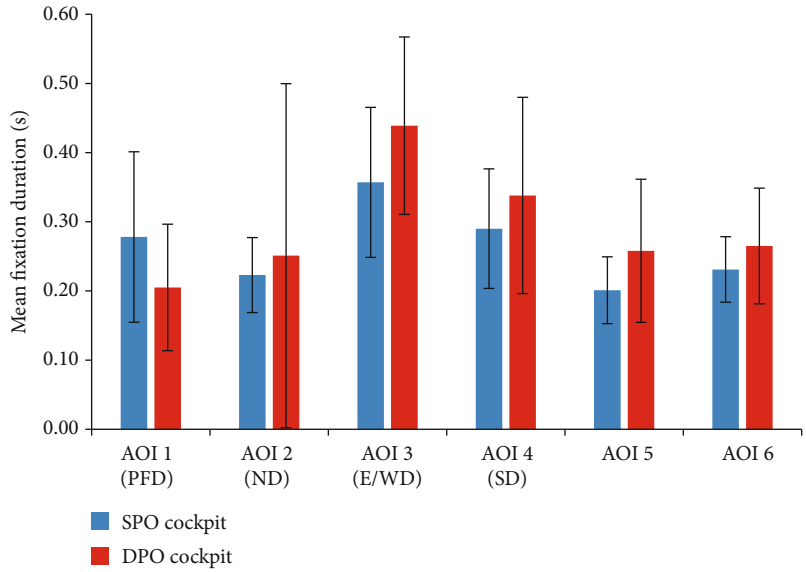


(a) Fixation duration

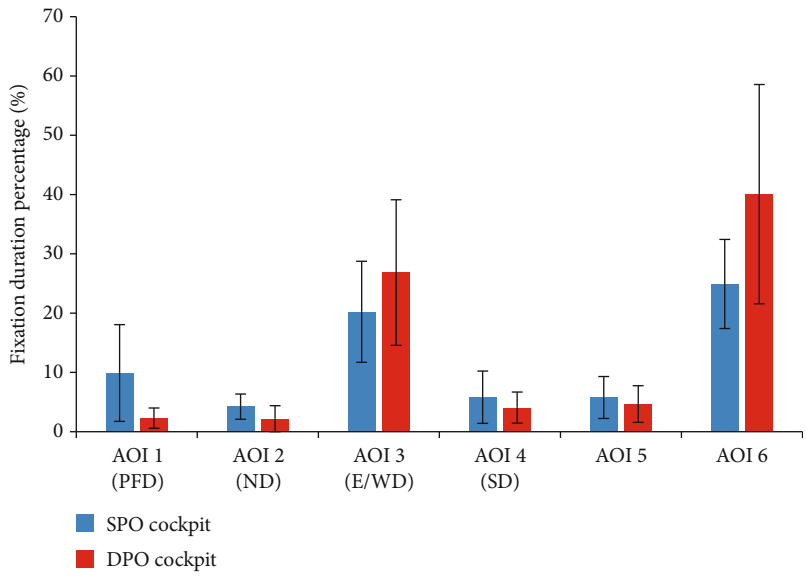


(b) Fixation counts

Figure 5: Continued.

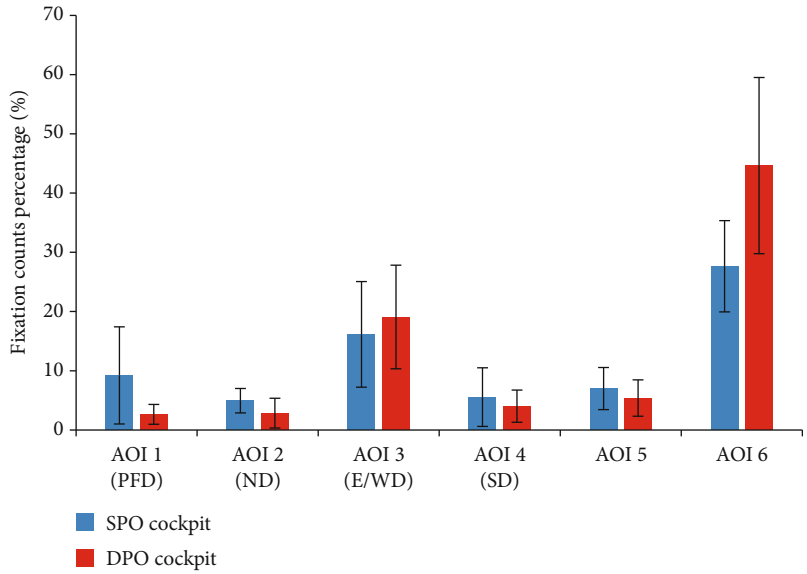


(c) Mean fixation duration



(d) Fixation duration percentage

Figure 5: Continued.



(e) Fixation count percentage

Figure 5: Participants' mean (standard deviation) of fixation characteristic indicators in SPO and DPO. SD is represented by the error bars.

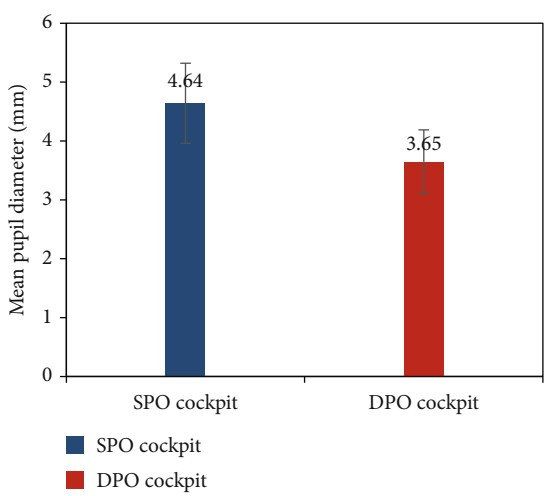


Figure 6: Participants' mean (standard deviation) of pupil diameter indicators in SPO and DPO.

percentage, and fixation count percentage. The number of fixation counts and the fixation duration can reflect the complexity of the information [36]. In order to operate effectively and make informed decisions, operators must have access to visual information about their environment and status [37]. Fixation duration and fixation counts are strongly correlated with human cognitive performance and performance on tasks [38]. In addition to indicating a pilot's skill level, attention allocation and fixation duration on important AOIs can be an effective indicator of situational awareness [7].

This experiment utilized an intelligent assistance system; the SPO group used it to executable operation. The result of the experiment shows the SPO group situational durations shorter than the DPO group. It was also found by Li et al. that the integrated design was faster than the traditional design when it came to identifying solutions and completing tasks [39]. SPO participants allocated their attentional resources saved by intelligent aids to other AOIs, with PFD receiving a significant amount of attention. This is because participants in the single-engine failure scenario perceived aircraft status information on the PFD as more important, and the intelligent assistance system helped participants understand the operational procedures while alerting them to aircraft failure information. Accordingly, both the fixation duration percentage and the fixation count percentage reflected the same conclusion, with the integrated design reducing the time participants spent identifying malfunction states and operating procedures. The DPO group participants' fixation characteristics differed more significantly than the SPO group, indicating that intelligent assistance systems may facilitate the capture of valid assistance information by participants. However, why does the use of the traditional flight manual differ greatly between individuals? This maybe participants are not unfamiliar with the cockpit environment and equipment, as well as the different flying experience of participants in the study which may also explain the individual differences. The design of the interface may also play a role in this phenomenon; a good interface design can reduce the cognitive workload on the user [40], which is related to the user's performance, policies, and subjective preferences [41, 42]. The preference for vertical menus is one example of this [43].

5.2. Attention-Allocation Level Model. Salience, effort, and situational attributes contribute to the quantification of attention-allocation levels. A malfunction scenario requires the pilot to access a large amount of information through the cockpit environment, which dictates that primarily visual information is processed cognitively and used to resolve the malfunction. In situations where time is limited

Table 1: Salience quantification in the SPO and DPO cockpits.

Group	Indicator	Mean ± standard deviation
SPO cockpit	Mean pupil diameter (mm)	4.636 ± 0.64
	Salience	0.468 ± 0.24
DPO cockpit	Mean pupil diameter (mm)	3.646 ± 0.51
	Salience	0.45 ± 0.31

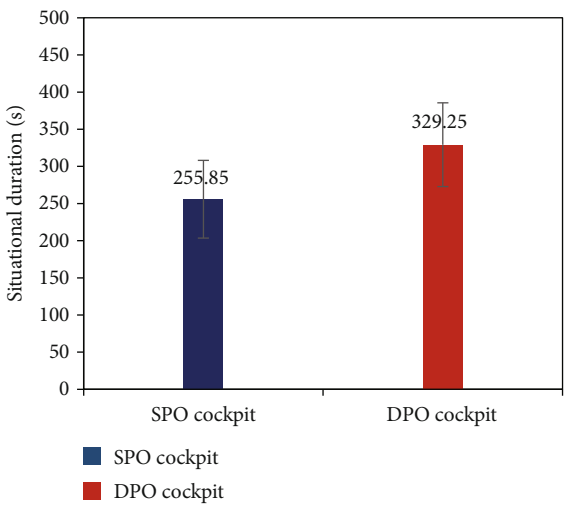


Figure 7: Participants' mean (standard deviation) of situational duration indicators in SPO and DPO.

Table 2: Effort quantification results for the SPO cockpit and DPO cockpit.

Group	Indicator	Mean ± standard deviation
SPO cockpit	Situational duration	255.85 ± 49.67
	Effort	0.281 ± 0.20
DPO cockpit	Situational duration	329.25 ± 53.45
	Effort	0.575 ± 0.22

and the workload is high, more salient information in the flight manual can assist the pilot in understanding and making decisions more quickly [11]. As the basis for salience, human physiological state and external stimuli are combined to produce a perceptual response. Pupil diameter is influenced by light, task difficulty, and one's own mental workload [30], and pupil diameter is a valuable indicator of visual attention and workload [41, 44, 45]; therefore, the mean pupil diameter was chosen as an indicator of salience. During the experiment, there were considerable differences in the cockpit environments between the SPO and DPO groups, so we calculated salience separately for each group. In addition to suppressing the participants' attention level, a lengthy situational duration can also negatively affect the participants' attention allocation, while it can also reflect the participants' performance on the task, as the attention-allocation level is also strongly related to the performance of the task, so situational duration was chosen as an indicator of effort. The human error rate was not added as a factor influencing effort in this study because the experimental segments were all in autopilot mode while following standard operating procedures for malfunction disposal. This individual human error rate was extremely low, and the differences in expressing it mathematically were very small, so the calculation of effort did not include it. Based on the analysis of objective physiological indicators measured during the study, we found that the SPO cockpit did not significantly increase the workload of the participants, so we quantified the effort level uniformly for both groups. The situational attributes refer to the participants' awareness of each AOI's importance in the scenario and how those AOI's relate to the task scenario. In light of the different durations of the experimental segments, the two groups were quantified separately. Participants' fixation duration percentage and fixation count percentage can be regarded as indicators of their situational awareness. The result shows that the quantitative values of the participants' attention-allocation level were higher in the SPO group than in the DPO group. It is possible that the participants' unfamiliarity with the SPO cockpit and intelligent assistance system is to blame for this. The SPO may be able to enhance the participants' attention-allocation level and enhance task performance once the operator has reached a certain level of familiarity. During the experiment, we implemented the flap handle lock task scenario, but the SPO group participants paid more attention to SD (AOI 4) in the flap handle lock task scenario than in the one-engine failure task scenario, which was closely related to the task scenario. Furthermore, we found that the effects of the integrated design were not always positive, which may be related to the design itself, the task situation, and individual differences.

These means are expectants which could be obtained from historical data. It can be calculated by simply collecting the values of a certain parameter during a certain period in the past. That is to say, if the more historical data accumulated in the past and the larger the sample space, then this expectant (mean) will be more accurate. So, as long as this mean is obtained in advance and inputted into the model, the model can calculate the attention-allocation level in real time. Meanwhile, this model also could be used for the assessment of pilot's attention-allocation skill level after flight training.

5.3. Limitations and Future Work. There are still some limitations in this study. The SPO cockpit environment based on the A320 simulated cockpit is compared with the actual SPO cockpit, and some differences exist in cockpit space and equipment. This experiment examined only the visual channel, and it did not examine the effects of other information channels on attention allocation. In the experiment, malfunction scenarios were designed and conducted in a simulated flight environment, in which the pilot's stimulation could not reach the state of a real flight.

Table 3: I_{C-i} and u_i scores in the experimental scenario. The weight coefficients are applied to the A320 and not to the other types of aircraft. Meanwhile, the SPO weight coefficient data is only suitable for the SPO simulation environment of the experiment.

Group	AOI	PFD		ND		E/WD		SD		Central console		Flight manual		Outside window	
	Indicator	I_{C-1}	u_1	I_{C-2}	u_2	I_{C-3}	u_3	I_{C-4}	u_4	I_{C-5}	u_5	I_{C-6}	u_6	I_{C-7}	u_7
SPO cockpit		8.00	0.85	2.00	0.43	7.20	0.75	2.10	0.42	1.00	0.12	3.50	0.85	1.40	0.12
DPO cockpit		8.00	0.45	2.00	0.22	6.70	0.60	2.10	0.20	1.00	0.12	5.80	0.43	1.40	0.04

Table 4: Situational attribute quantification results.

Group	Situational attribute (mean ± standard deviation)
SPO cockpit	0.469 ± 0.27
DPO cockpit	0.708 ± 0.26

Table 5: Participants' levels of attention allocation.

Group	Attention allocation (mean ± standard deviation)
SPO cockpit	0.66 ± 0.486
DPO cockpit	0.58 ± 0.492

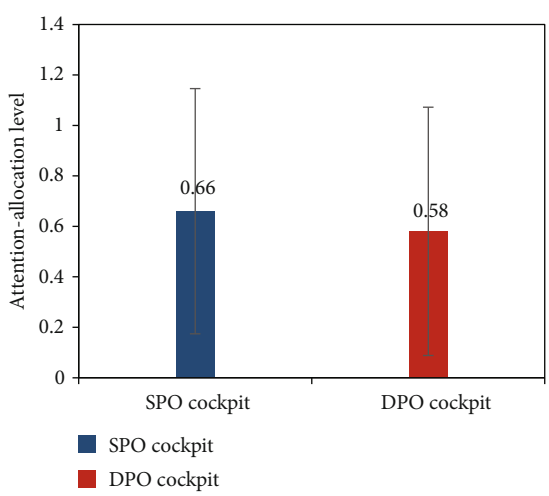


Figure 8: Participants' attention-allocation levels.

A quantitative model of attention-allocation level should be improved in future work by incorporating physiological data, eye-movement data, and other cognitive data, such as using functional near-infrared spectroscopy (fNIRS) to measure pilot cognitive activity. The design of the ground operation station and the intelligent and automated settings of the onboard equipment should be improved in the SPO cockpit environment. Secondly, only 20 airline pilots were recruited in this study, which is a relatively small number, and future experiments need more participants to reduce the impact of individual differences on experimental results. Moreover, factors such as flight experience and aircraft model can be examined and analyzed. Additionally, to improve data reliability, the number of scenarios maybe increased in the future.

6. Conclusion

To quantify pilots' attention-allocation levels, we proposed an attention-allocation level measurement model based on the SEEV model, taking salience, effort, and situational characteristics as the influencing factors. This model can be used to quantify pilots' attention-allocation levels. Using an eye-tracking device, flight simulation experiments were conducted in SPO and DPO scenarios to study the effects of the participants' fixation characteristics. The following conclusions can be drawn:

(1) Through optimal design, an intelligent assistance system can reduce the time required to find information and identify solutions in the experimental SPO environment, allowing the SPO group participants to devote more attentional resources to other important matters

(2) The optimized human–machine interface design in the SPO cockpit significantly affected participants' mean pupil diameter. However, this could be the result of a variety of factors, such as the lighting of the interface of the intelligent assistance systems. Furthermore, the SPO group disposition malfunction time was shorter in the case of one-engine failure. This indicates that the intelligent assistance system and ground station support provided effective participants assistance in the experiment

(3) We integrated eye-movement indicators, fixation characteristics, and task performance as influencing factors to quantify salience, effort, and situational characteristics. Using a linearly weighted model of the three indicators, we found that the SPO group had a slightly higher attention-allocation level than the DPO group

The purpose of this study was to explore the fixation characteristics of SPO pilots and analyze the differences in attention allocation between participants in SPO and DPO scenarios. We constructed a quantitative attention-allocation level model, incorporating salience, effort, and situational attributes as indicators. Eye-movement indicators, fixation characteristics, and task performance were used to reflect pilots' attention-allocation levels during malfunction disposal. Although this study could not fully reflect a true SPO scenario, it could nevertheless demonstrate the effectiveness of intelligent assistance systems and ground operating station support. This could be used as a reference for designing of future

intelligent SPO cockpit. This study can support assessing attention-allocation levels in pilot malfunction handling scenarios, which can be used for pilot selection and training. Attention allocation is related to individual preferences and habits, and a good search strategy does not necessarily result in good task performance. Therefore, task-performance indicators, eye-movement data indicators, and fixation characteristics can be added to the attention-allocation model to determine individual attention-allocation levels in the future research.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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