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Pilots' Scanning Behavior Between Different Airport Intersection Maneuvers in a Simulated Taxiing Task

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ABSTRACT Among flight crew errors, 54% occurred in the taxiing phase, especially near intersections in low visibility situations. This paper examines pilots' scanning behavior when executing different turning maneuvers at airport intersections both on clear days and in low visibility situations. The Beijing International Airport was reconstructed in an Airbus 320 simulator. Eight male pilots participated in this study. The pilots were required to take full manual control from the last approach point and to taxi according to the predetermined flight plan. The pilots' fixation rate, average fixation duration, and dwell time percentage in each area of interest (AOI) were analyzed during the turning maneuvers near four examined intersections. The results showed that the dwell time percentages in the electronic centralized aircraft monitoring (ECAM) area when executing right turn maneuvers were significantly higher than those when executing left turn maneuvers on clear days. In low visibility situations, the percentages of dwell time in the right view out of the window (OTWR) area when executing right turn maneuvers were significantly higher than those when executing left turn maneuvers. To examine if the scanning behavior reported in this study is safe or not, the pilots' responses to potentially dangerous situations should be further studied.

INDEX TERMS Air traffic safety, scanning behavior, intersection maneuver, taxiing, low visibility.

I. INTRODUCTION

According to an in-depth study on 415 commercial aviation accidents that occurred between 2010 and 2014, flight crew errors were found to be involved in nearly one-third of these accidents [1]–[3]. Among the errors, 54% occurred in the taxiing phase [4], [5] and accidents may also happen during the taxiing phase [6], [7]. For example, runway incursion is the leading cause of major accidents that occurred at the Linate Airport in 2001 (118 casualties), Omsk in 1984 (178 casualties), and Tenerifein in 1977 (583 casualties) [8]. The taxiing phase is a complex multitask process. During taxiing, pilots have to monitor the environment both inside and outside of the cockpit, communicate with the air traffic controllers, and maintain taxiing speed and direction. The high workload of pilots during the taxiing phase increases the probability of operational errors and accidents [5]. Therefore, it is of great importance to understand pilots' performances during the taxiing phase.

Weather conditions influence pilots' performances [9], [10]. Tamura *et al.* [11] conducted a simulation study to examine the differences in pilots' scanning behavior during takeoff in daytime and nighttime situations. Both eye movements and subjective perceptions were found to be different in the examined visibility situations. Kim *et al.* [12] analyzed pilots' eye movements in the landing phase in day and night lighting conditions and found that pilots made significant glideslope control errors in the nighttime situations. In addition to nighttime situations, low visibility weather (e.g., fog or smog day) is another element that may increase pilot workload and/or decrease performance [13], [14].

In addition to weather, pilots' performances may vary across different maneuvers at airport intersections. In surface transportation research, intersections have been identified as the most dangerous locations in urban traffic [15], [16]. The numbers of crashes that have occurred at different

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FIGURE 1. An overview of the simulator and eye tracker.

types of intersections (e.g., 3-leg or 4-leg) are different partially because of the geographic characteristics [17]. In [18], the duration a driver spent in each area of interest while turning left, going straight and turning right at unsignalized intersections was analyzed. The results showed that, when entering an intersection, drivers spent more time in the far left and central areas while turning left and more time in the far left, central and far right areas while going straight or turning right. However, the pilots' scanning behavior between different maneuvers at airport intersections has never been analyzed in air traffic safety research.

This paper aims to examine pilots' scanning behavior when executing different turning maneuvers at airport intersections in both clear day and low visibility situations. The main contributions of this paper include: (1) The innovative analysis of pilots' scanning behavior across different turning maneuvers at airport intersections will provide evidence for future strategies to enhance air traffic safety. (2) The examination of pilots' scanning behavior in the taxiing phase in low visibility conditions will give a better understanding of pilots' scanning behavior. These contributions can be used for better cockpit design and training programs.

The remainder of this paper is organized as follows: Section 2 introduces the simulation experiment and the executing of data collection, including the apparatus, participants, experiment procedure, etc. Section 3 presents the results using ANOVA and LSD analyses. Section 4 provides a discussion of the results and briefly explains the implications of the results for enhancing airline safety. Finally, the concluding remarks and future work are summarized in Section 5.

II. METHODS

A. APPARATUS

An Airbus 320 simulator located in Shanghai Eastern Flight Training Company Ltd. was used in this study. A head-mounted eye tracker (iView X HED, SMI) was employed to record pilots' eye movement data with a logging frequency of 200 Hz. The collected eye movement data included eye fixation, saccade, transition, etc. The raw data were processed

(a) clear day

(b) low visibility

FIGURE 2. Examples of the examined visibility scenarios.

by BeGaze 3.4 from SMI. See Figure 1 for an image of a pilot wearing the eye tracker in the simulator.

B. PARTICIPANTS

Eight male pilots were recruited from Shanghai Eastern Flight Training Company Ltd. to participate in this experiment. The pilots all had simulator experience. The ages of the pilots ranged from 27 to 40 years (mean = 33.0 years, SD = 4.9 years) with normal or corrected to normal vision.

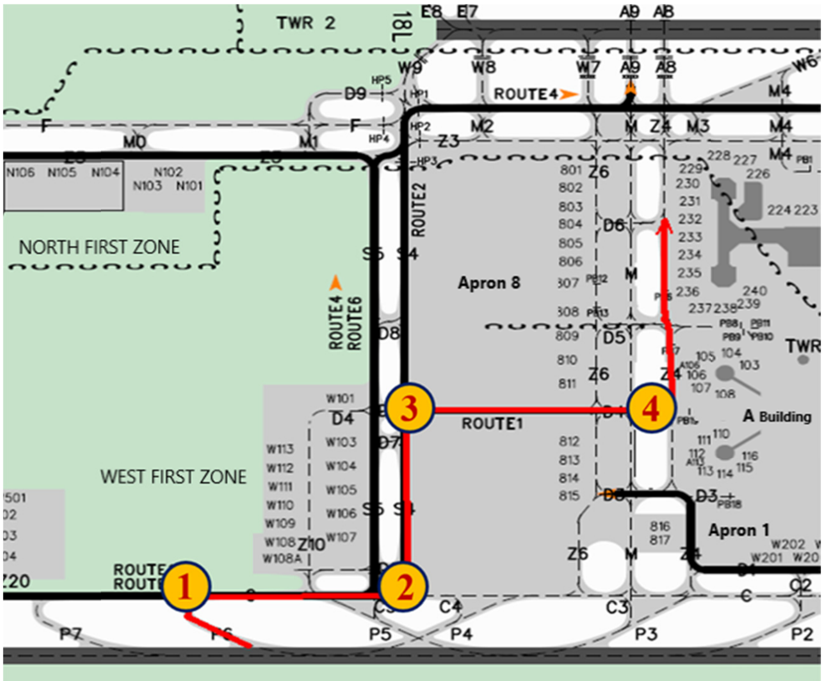

FIGURE 3. The taxiing route (red line) and the 4 examined intersections (orange circles) of the Beijing International Airport in the simulated taxiing task.

All of the participants had legal licenses. The flight hours of the pilots ranged from 1700 to 15000 hours (mean = 8000.0 hours, SD = 5204.1 hours).

C. VISIBILITY SCENARIOS

Two visibility scenarios were examined in this study, i.e., a clear day and a low visibility situation. See Figure 2. In the clear day situation, the airplane was operated in the visual meteorological condition (VMC) in which the pilots judged the flight situation, such as speed and altitude, with their own vision. In the low visibility situation, the visibility distance was limited to 200 m (the lowest number allowed for safe flight in China). The pilots had to operate the airplane in the instrument meteorological condition (IMC) in which the flight situation was mainly determined from instruments in the cockpit. Visibility was considered a within-subject factor. Each subject performed the taxiing task once under each of the visibility conditions. Half of the subjects started with the clear day condition, and the rest started with the low visibility condition.

D. TAXIING TASK AND EXPERIMENT PROCEDURE

The Beijing International Airport was reconstructed in the simulator for the experiments. Before the experiment, a senior instructor communicated with the pilots about the flight plan, and a consent form, approved by the local ethics committee, was signed by each participant. During the experiment, the pilots were first required to complete a 10-minute test trial to familiarize themselves with the simulator. Then, the pilots were required to take full manual control from the last approach point to complete the landing and to taxi to gate 232 according to the predetermined flight plan. See Figure 3 for the required taxiing route. The pilots needed to get off runway 36L from P6. The four intersections examined in this study are marked with circles in Figure 3. Each participant completed the taxiing task once under each visibility condition. The required maneuver to be executed at intersections 1 and 3 was a right turn, and the maneuver to be executed at intersections 2 and 4 was a left turn. Because the geographic characteristics were different among the examined intersections, the maneuvers executed near different intersections were analyzed independently. Thus, both visibility conditions (clear day versus low visibility) and intersection types (the four intersections marked with numbers in Figure 3) were within-subject factors.

E. AREAS OF INTEREST (AOIS)

Six areas of interest (AOIs) were selected for analysis, including electronic centralized aircraft monitoring (ECAM), navigation display (ND), primary flight display (PFD), left view out of the window (OTWL), middle view out of the window (OTWM), and right view out of the window (OTWR). The selection of the AOIs was made by a senior training instructor from Shanghai Eastern Flight Training Company See Figure 4 for a general overview of the AOIs. These AOIs provide the visual information necessary for pilots to perform the three main tasks in the taxiing phase. Specifically, ECAM is the AOI showing system states information, especially malfunction alarm information; PFD is the outer display providing information on altitude, guidance, airspeed, and vertical and lateral deviations; ND presents aircraft navigation information, including the flight plan route and a moving

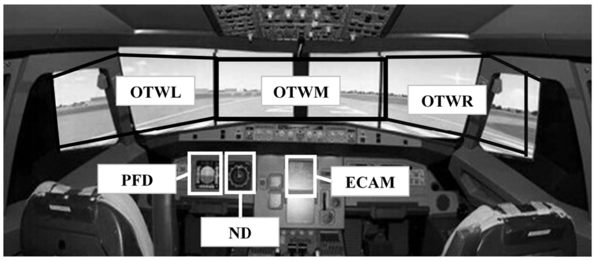

FIGURE 4. Areas of Interest (AOIs).

map of database waypoints; OTWM provides information about the centerline of the taxiing route and surface markings; OTWL provides information about environmental clues, such as surface markings, lighting and signage in the pilots' left view; and OTWR provides information about environmental clues in the pilots' right view.

F. EYE MOVEMENT MEASURES

The measures employed to describe the pilots' scanning behavior include fixation rate, average fixation duration, and dwell time percentage in each AOI. To generate the eye movement profiles for data analysis, the three measures were collected and computed for each intersection maneuver. According to [19], a fixation was defined as a dwell in an area of 10 by 10 pixels over 100 m. The fixation rate was defined by the number of fixations on an AOI per second, and average fixation duration was calculated as the average time duration of fixations in an AOI. The findings from a flight simulator experiment suggested that both fixation rate and average fixation duration were indicators of situation awareness [20] and were positively correlated with a working memory load [21].

G. DATA ANALYSIS

Based on the observation of taxiing operations during the experiment, the subjects began to operate the steering handle to turn approximately 15 seconds before the indicated point, and the aircraft turned to be parallel with the centerline of the taxiway approximately 15 seconds after the indicated point. Consequently, to reduce the effect of duration variability across the subjects and trials, eye movement data 15 seconds before and after the indicated point were used for analysis, as they can better reflect the fixation performance of a complete turn. The fixation counts and fixation duration in the AOIs were calculated separately at each intersection.

The independent variable was intersections and the dependent variables were pilots' eye movement measures including fixation rate, average fixation duration, and dwell time percentage in each AOI. The examinations in clear day and low visibility situations were conducted separately. The hypothesis was that all the examined eye movement measures significantly differed among the four examined intersections. Shapiro-Wilk test was conducted to assess whether the examined variables were normally distributed, and the normality of the eye movement measures were verified ($p > 0.05$). Repeated measures analyses of variance (ANOVAs) were used to analyze the effects of intersection on eye movement measures across AOIs and visibility scenarios. The ANOVAs were validated by Mauchly's sphericity test, and Greenhouse-Geisser-adjusted degree of freedom and p values were used upon the violation of the sphericity assumption. Post hoc multiple comparisons were performed with LSD adjustment where necessary. The statistical significance level was selected to be 0.05.

III. RESULTS

The tracking rates of the pilots' eye movement data were 82.4% and 84.8% in the clear day and low visibility situations, respectively. Table 1 presents the detailed results of the pilots' eye movement in each AOI among the examined intersection maneuvers for both the clear day and low visibility situations. Table 2 presents the ANOVA table numbers. Statistical significance was found in the fixation rate in OTWR in the clear day situation (p =0.043). See Table 1, the fixation rate in OTWR at intersection 2 was 126.5%, 126.4%, and 208.3% higher than those at intersections 1, 3, and 4, respectively. Post hoc comparison results showed that the mean fixation rate in OTWR at intersection 2 was significantly higher than all of the other three intersections that were examined (2-1: $p = 0.024$; 2-3: $p = 0.023$; 2-4: $p = 0.012$) (See Table 2). No significant differences were found among the intersection maneuvers at 1, 3 and 4. For the low visibility situation, no significant differences were found among the four intersection maneuvers that were examined.

Table 2 shows that the dwell time percentages in ECAM were significantly different among the examined intersection maneuvers in the clear day situation ($p = 0.028$). Post hoc results showed that the mean time pilots dwelled in ECAM at intersection 1 was 4.3 times that at intersection 2 ($p = 0.008$) and 3.3 times that at intersection 4 ($p = 0.020$). No significant differences were found between the two right turn maneuvers (1 and 3) or between the two left turn maneuvers (2 and 4). In the low visibility situation, no significant differences were found among the four examined intersection maneuvers.

Table 2 also shows that the dwell time percentages in OTWR were significantly different among the intersection maneuvers that were examined in the low visibility situation ($p = 0.032$). Post hoc results showed that the mean time that the pilots dwelled in OTWR at intersection 1 was 3.2 times that at intersection 2 ($p = 0.010$) and 3.1 times that at intersection 4 ($p = 0.011$). No significant differences were found between the two right turn maneuvers (1 and 3) or between the two left turn maneuvers (2 and 4). In the clear day situation, no significant differences were found among the four examined intersection maneuvers.

IV. DISCUSSION

The main tasks that need to be completed in the taxiing phase include monitoring the surrounding traffic environment,

TABLE 1. Pilots' eye movement measures in each AOI among the examined intersection maneuvers for both the clear day and low visibility situations: Mean (SD).

AOIs	Measures	Clear day				Low visibility			
		1	2	3	4	1	2	3	4
ECAM	Fixation rate (times/s)	2.4(0.8)	4.0(1.4)	1.7(0.7)	1.2(0.9)	3.4(1.2)	2.5(1.2)	2.7(1.1)	2.1(1.3)
	Average fixation duration (ms)	180.8(58.9)	180.7(78.3)	156.7(63.6)	110.2(77.8)	128.7(42.8)	123.5(52.8)	206.9(82.5)	82.9(45.4)
	Dwell time percentage (%)	**8.0(2.0)**	**1.8(0.6)**	**5.9(2.0)**	**2.4(0.5)**	2.2(1.3)	0.9(0.6)	1.1(0.4)	1.4(1.0)
ND	Fixation rate (times/s)	3.8(0.8)	2.3(0.8)	4.2(1.9)	2.2(0.8)	3.6(0.7)	4.6(0.8)	3.6(0.8)	2.4(0.7)
	Average fixation duration (ms)	245.6(64.0)	364.4(181.4)	340.7(105.5)	229.1(86.6)	235.7(44.6)	272.3(48.6)	255.3(59.1)	271.1(71.1)
	Dwell time percentage (%)	9.2(4.3)	7.0(4.0)	8.2(4.3)	12.1(4.0)	7.2(2.9)	9.2(5.6)	8.2(4.2)	14.4(6.8)
PFD	Fixation rate (times/s)	3.3(1.0)	2.7(1.0)	2.6(0.8)	1.7(0.8)	3.7(1.4)	2.2(0.9)	2.5(0.9)	2.0(0.8)
	Average fixation duration (ms)	229.3(78.4)	319.2(168.4)	311.0(117.6)	388.4(165.3)	215.4(66.2)	257.8(115.2)	380.0(152.9)	304.7(141.6)
	Dwell time percentage (%)	4.7(3.9)	5.0(2.2)	3.8(1.5)	14.4(7.0)	1.6(0.7)	6.8(3.4)	10.4(8.7)	8.3(3.4)
OTWL	Fixation rate (times/s)	2.6(1.8)	1.2(1.2)	1.2(1.2)	1.7(1.7)	2.1(2.1)	2.8(2.1)	1.7(1.7)	0.6(0.6)
	Average fixation duration (ms)	25.0(16.8)	17.1(17.1)	12.5(12.5)	16.7(16.7)	7.5(7.5)	29.7(22.4)	9.4(9.4)	28.3(28.3)
	Dwell time percentage (%)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.0(0.0)	0.4(0.4)	0.1(0.1)	0.2(0.2)
OTWR	Fixation rate (times/s)	**3.8(1.1)**	**8.6(2.5)**	**3.8(0.9)**	**2.8(0.4)**	3.1(0.6)	2.3(0.6)	2.5(0.6)	2.6(0.7)
	Average fixation duration (ms)	351.0(47.4)	205.7(57.2)	327.1(42.1)	386.4(46.1)	413.7(76.3)	269.4(71.0)	367.8(75.0)	275.4(86.2)
	Dwell time percentage (%)	8.2(2.5)	5.1(4.8)	6.5(5.5)	2.7(2.0)	**21.6(7.0)**	**6.8(1.9)**	**14.1(4.3)**	**6.9(2.6)**
OTWM	Fixation rate (times/s)	2.6(0.5)	2.0(0.4)	2.6(0.5)	1.8(0.3)	2.1(0.3)	1.9(0.3)	1.9(0.3)	2.3(0.3)
	Average fixation duration (ms)	778.6(347.8)	736.1(250.8)	850.8(433.8)	605.5(94.6)	685.6(229.0)	976.2(473.4)	652.9(122.2)	510.3(92.7)
	Dwell time percentage (%)	33.4(11.0)	42.4(15.8)	27.3(15.2)	23.3(14.3)	36.8(6.4)	54.5(8.5)	39.8(5.2)	38.8(6.6)

TABLE 2. ANOVA Table Numbers (*represents significance at 0.05 level).

AOIs	Measures	Clear day		Low visibility	
		F-value	*p*-value	*F*-value	*p*-value
ECAM	Fixation rate(times/s)	$F(3,21)=2.421$	0.095	$F(3,21)=0.234$	0.872
	Average fixation duration (ms)	$F(1.49,10.41)=0.105$	P=0.845	$F(3,21)=0.975$	0.423
	Dwell time percentage (%)	**$F(3,14)=4.112$**	**0.028***	$F(3,28)=0.659$	0.584
ND	Fixation rate(times/s)	$F(1.21,8.46)=0.593$	0.493	$F(3,21)=1.735$	0.191
	Average fixation duration (ms)	$F(1.19,8.35)=0.412$	0.574	$F(3,21)=0.159$	0.923
	Dwell time percentage (%)	$F(3,14)=0.253$	0.858	$F(3,28)=0.260$	0.854
PFD	Fixation rate(times/s)	$F(1.33,9.31)=0.155$	0.772	$F(1.23,8.63)=0.653$	0.472
	Average fixation duration (ms)	$F(3,21)=0.412$	0.574	$F(3,21)=1.468$	0.252
	Dwell time percentage (%)	$F(3,14)=1.385$	0.288	$F(3,28)=0.529$	0.666
OTWL	Fixation rate(times/s)	$F(1.18,8.24)=0.340$	0.610	$F(1.53,10.70)=0.333$	0.668
	Average fixation duration (ms)	$F(1.58,11.04)=0.192$	0.778	$F(1.30,9.09)=518$	0.536
	Dwell time percentage (%)	$F(3,14)=0.843$	0.490	$F(3,28)=0.701$	0.560
OTWR	Fixation rate(times/s)	**$F(3,25)=3.138$**	**0.043***	$F(3,28)=0.253$	0.859
	Average fixation duration (ms)	$F(3,25)=2.457$	0.086	$F(3,28)=0.840$	0.483
	Dwell time percentage (%)	$F(3,25)=0.330$	0.801	**$F(3,28)=3.384$**	**0.032***
OTWM	Fixation rate(times/s)	$F(1.28,8.94)=2.416$	0.153	$F(3,21)=3.01$	0.053
	Average fixation duration (ms)	$F(1.06,7.41)=0.995$	0.356	$F(1.06,7.44)=1.124$	0.327
	Dwell time percentage (%)	$F(3,25)=0.349$	0.790	$F(3,28)=1.065$	0.380

controlling the aircraft speed, and maintaining an updated representation of the real-time position on the taxiing surface and the location of the destination [22]. The last two tasks do not strongly correlate with the visibility outside of the cockpit. For the task of monitoring the traffic environment while turning, pilots need to carefully assess the environment in the target lane [23]. On clear days, pilots could easily observe the traffic environment in the target lane, and therefore, the pilots' workloads were lower in this situation compared to that in the low visibility situation [10], [24]. Meanwhile, as the AOIs dynamically changed with the turning of the aircraft [25], [26], the pilots' behavior in scanning the outside areas near the examined intersections was similar between the two situations. Interestingly, the results illustrated in Table 2 showed that the pilots' fixation rate in OTWR at intersection 2 was significantly higher than the fixation rate at either of the other three intersections on clear days. This result is probably because when turning left at intersection 2, the pilots need to frequently check the traffic situation of the taxiway on the right side. However, in the left turn process, the initial left area OTWL would gradually move into the OTWM area as the aircraft turns. This difference contributes to the relatively higher fixation rate in the OTWR area at intersection 2.

One interesting finding is that the pilots applied different scanning strategies at different intersections for the same direction. For example, the scanning behavior at intersections 2 and 4 was different. Although intersection 4 required the same left turn as intersection 2, the fixation rate in OTWR at intersection 4 did not show the same trend as that at intersection 2. This may be caused by the taxiing phases. Intersection 2 was the busiest phase while taxiing. The pilots needed to find the taxiing target in the taxiing road and monitor the signs to maintain situation awareness. As for intersection 4, it was the last phase of the taxiing route. The pilots already had a good understanding of the airplane position and the clear gate, thus the signs in OTWR were not that informative to ensure taxiing safety.

As for the AOIs in the cockpit, ECAM is the area that shows information about the state of the system, especially malfunction alarm information [20]. On clear days, since it was easy for the pilots to be aware of the surrounding traffic environment, they spent more time checking the system status presented in the ECAM area [27]. According to the scanning patterns found in [1], short distance transitions between the adjacent AOIs were the primary glance transition patterns the pilots preferred, especially the back and forth transitions between the OTWM and its adjacent areas. When turning left, since the pilots worked in the left side of the cockpit, the transition distance between OTWL and ECAM was relatively longer than the transition distance between OTWR and ECAM in the right turning process. The shorter transition distance and the pilots' short-distance scanning patterns contribute to the longer dwell time in the ECAM area when turning right.

It was difficult for the pilots to see the traffic environment around the cockpit clearly in low visibility situations [4]. Therefore, pilots observed the traffic environment outside the cockpit with longer dwell times for taxiing safety than on clear days [27]. As the perception of the traffic environment was not as easy as on clear days, the pilots' eye movement behavior deviated between the left and right turn maneuvers. When turning right, pilots needed to concentrate more in the OTWR area for better awareness of the traffic situation in the target lane. However, when turning left, pilots worked in the left side of the cockpit, and the initial left area OTWL would gradually move into the OTWM area during the turning process. Hence, pilots' glance behavior in the OTWL and OTWM areas did not show significant differences between the intersection maneuvers that were examined.

A safe taxi to the target gate does not always mean a safe scanning pattern [28]. Unsafe scanning patterns would probably result in a safe taxiing process because dangers are not frequently present [13]. However, when dangers are present, with unsafe scanning patterns from pilots, there could be a terrible disaster. In the intersection maneuvers that were examined and presented in this study, no dangerous situations were included. To examine if the scanning behavior reported in this study is safe or not, the pilots' responses to dangerous situations should be further studied. From another perspective, the scanning behavior of experienced pilots could be regarded as safe scanning patterns [29]. If a pilot's scanning behavior largely deviates from the safe patterns, there could be a potential danger. The pilots may need to be trained repeatedly in a simulator to gain correct operation experience, and further systems for assistance could be designed to help pilots when necessary. In our future studies, we will recruit more pilots to categorize them into experienced and less-experienced groups according to their flight experience, and we will examine their responses to typical dangers that may happen near intersections. Feedback on the pilots' performance and suggestions for improving their flying skills would be given in order to promote better performances in their future training programs.

The findings of this study have practical implications for safe and accurate taxiing operations. (1) Airport traffic signs and landmarks in different turning directions are important for pilots to keep situation awareness for taxiing accuracy and safety [30]. Our findings suggest that different strategies for the design of signs and landmarks should be applied at different airport intersections according to the taxiing phase and intersection maneuver (turning left or right). (2) The taxiing style of a pilot can be estimated using the examined scanning measures. The scanning behavior of widely accepted safe and experienced pilots can be used as the standard scanning pattern [31], [32]. The safety level of other pilots' scanning behavior can be compared and evaluated for skills training or pilot selection. (3) The awareness level of air traffic controllers (ATCs) significantly affects air traffic safety [33]. The same examination method and results can be employed to investigate the scanning behavior of ATCs.

V. CONCLUSION

This study examines pilots' scanning behavior when executing different turning maneuvers at airport intersections both on clear days and in low visibility situations. The results show that different types of airport intersections significantly affect pilots' scanning behavior, and therefore influence air traffic safety. Even for the turning maneuvers to the same direction (left or right), the taxiing phase and intersection design may affect pilots' scanning behavior. Therefore, different designs of signs and landmarks should be applied at different airport intersections. Further assistance systems for pilots could be developed for precise help at different intersections for safety enhancement. In future studies, the following aspects need to be considered for improvement: (1) The evaluation criteria to estimate the safety level of pilots' scanning behavior needs to be designed to enhance air traffic safety. (2) The fatigue level of air traffic controllers (ATCs) significantly affects air traffic safety. By using eye tracking device and a method similar to that proposed in this study, the fatigue level of ATCs could be estimated. Alerts would be triggered when fatigue is detected, and substitute strategies would then be carried out to assure safety.

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