



Effects of time of day and taxi route complexity on navigation errors: An experimental study



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ABSTRACT

This study aimed to evaluate the effects of time of day and taxi route complexity on navigation errors. Nine pilots participated in the experiment. Four testing conditions defined by time of day conditions (i.e., nighttime versus daytime) and taxi route complexity (i.e., more complex versus less complex) were examined. Participants were instructed to perform simulated taxiing tasks in each of the testing conditions. Navigation errors during taxiing were counted. In addition, eye movement measures can reflect pilots' attention allocation, situation awareness and mental workload that are closely related to the risk of navigation errors. Thus, eye movement measures including fixation rate, average fixation duration and average pupil area were also selected as dependent variables. We found that navigation errors were fewer at night compared to in daytime. This could be explained by the finding that pilots paid more attention to the environmental clues out of the window at night, inducing better situation awareness for accurate taxiing. More complex taxi route was found to be associated with more navigation errors, but participants' visual behaviors were consistent between route complexity conditions, indicating that pilots' visual operation strategies did not contribute to the increased number of navigation errors in the more complex taxi route condition.

1. Introduction

Runway incursions are one of the leading causes for aviation accidents (Wilke et al., 2015; Mathew et al., 2017). The deadliest accident in aviation history happening in Tenerife in 1977 (583 fatalities) resulted from collisions due to runway incursions. A majority of runway incursions result from navigation errors that refer to failures to comply with the taxi clearance issued by air traffic control (Hooy and Foyle, 2006). According to the Federal Aviation Administration (2002), up to 58% of runway incursions were caused by navigation errors.

An effective way to control the risk of runway incursions is reducing exposures to causal factors for navigation errors. The majority of accident causal factors in aviation were related to pilots and the environment (Shappell et al., 2007). Among the pilot-related factors, excessive mental workload and inadequate situation awareness were constantly reported to lead to pilots' performance decrements and increase their chances of making errors (Michael and Alex, 2005; Shappell et al., 2007; Kilingeru et al., 2013). Morris and Leung (2006) reported that increased mental workload resulted in considerable decrements in manipulation and prioritization task performance among pilots. By

reviewing several aviation accidents (e.g., Air France Flight 447 on 1 June 2009), Kilingeru et al. (2013) summarized that loss of situation awareness due to pilots' failure to perceive information from the flight instruments was a contributor to all these accidents. van de Merwe et al. (2012) examined six pilots when they executed malfunction detection tasks during landing and found that pilots with poorer situation awareness made more errors. In a survey study by Chang and Wong (2012), loss of situation awareness and excessive workload have also been identified as major risk factors for navigation errors.

Environmental factors have also been identified as a major category of risk factors contributing to navigation errors (Shappell et al., 2007). Examples of these environmental factors include poor weather (Hunter et al., 2011), insufficient lighting (Michael and Alex, 2005), and ground navigation aid malfunction (Chang and Wong, 2012). The nighttime condition is an environmental factor that has been widely examined when evaluating pilots' behaviors. It was found that the nighttime condition was associated with decreased situation awareness and increased mental workload among pilots compared to the daytime condition (Andre, 1995; McCann et al., 1998). Specifically, by observing 35 pilots aboard, Andre (1995) found that pilots could easily lose situation

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awareness of aircraft's speed and position in the airport at night. In a simulation study with eight pilot participants, Hooey and Foyle (2006) reported that the nighttime condition induced increased workload among pilots. Nighttime effects may be associated with the "sea of blue" effect, which indicates that the blue lights marking the taxiways could cause pilots to become disoriented especially when viewing off-axis (Adam and Kelley, 1996; McCann et al., 1998). Though the nighttime condition has effects on pilots' behaviors, few studies have confirmed its effects on pilots' navigation errors. Therefore, there is lack of evidence for determining if the nighttime condition is a risk factor for navigation errors.

Researchers also reported that increased taxi route complexity (also a potential environmental risk factor) would make it more difficult for pilots' navigation operations (Wilke et al., 2015). Pilots were found to have more difficulties in maintaining an updated picture of the current aircraft position when taxiing on the taxiway with more intersections (Johnson et al., 2016). It is natural to expect that the chances of navigation errors are higher with a more complex taxi route that has more intersections and potential conflict points. However, besides taxi route characteristics (e.g., number of intersections and potential conflict points), it is also interesting to know whether pilots' behaviors could contribute to the increased likelihood of navigation errors in a more complex taxi route condition. In particular, we were interested in exploring if pilots would adopt different visual operation strategies between different route complexity conditions.

To address these research gaps, the present study aimed to explore the mechanisms for the effects of time of day (i.e., daytime versus nighttime) and taxi route complexity on navigation errors. Performance decrements and pilot errors often occur because of a lack of situation awareness (Kilingaru et al., 2013) or overload. Hooey and Foyle (2001) presented that a large proportion of navigation errors were accounted by overload and inadequate situation awareness. Therefore, increased mental workload and decreased situation awareness could be used as indicators of increased risks of navigation errors. To better understand the effects of time of day and taxi route complexity on navigation errors, there was a need to determine the mediating roles of mental workload and situation awareness in the relationship between these factors of interests (i.e., time of day and taxi route complexity in the present study) and navigation errors.

Mental workload and situation awareness can be assessed by using eye movement data for a variety of tasks (e.g., Dahlstrom and Nahlinder, 2009; Hankins and Wilson, 1998; Yu et al., 2016; Szczechura et al., 1998). Specifically, Moore and Gugerty (2010) found that in aviation monitoring tasks, longer fixation time spent in the relevant area of interest (AOI) was associated with better situation awareness. van de Merwe et al. (2012) conducted a malfunction detection experiment in a flight simulator and justified that more fixation rate in the relevant AoI suggested better situation awareness in the detection task. Fixation rate and average fixation duration were also reported to be positively correlated with working memory load in decision-making tasks (Orquin and Mueller, 2013). Besides fixation rate and average fixation duration, average pupil area was considered as a representative indicator of pilots' workload (He et al., 2012; Liu et al., 2014). In particular, larger pupil area suggests higher workload (van Orden et al., 2001; Ahlstrom and Friedman-Berg, 2006). Thus, eye movement measures were examined in the present study when evaluating the effects of time of day and taxi route complexity.

2. Methods

2.1. Participants

Nine male pilots (age: mean \pm SD = 33 \pm 4.0 years, median = 35 years; flight experience: mean \pm SD = 8689 \pm 4620 h, median = 10000 h) participated in the study. They were all recruited from Shanghai Eastern Flight Training CO., LTD and had experience of flying

Airbus 320 as a captain. This research was approved by the ethics committee at NWPU. Informed consent was obtained from each participant.

2.2. Apparatus

The experiment was conducted in an Airbus 320 simulator in Shanghai Eastern Flight Training CO., LTD. Eye movement data was recorded by an eye tracker (iView X HED, SMI) with the sampling rate set at 200 Hz. Raw eye movement data was collected and processed by the SMI BeGaze 3.4 software (SensoMotoric Instruments GmbH, Teltow, Germany). Two video cameras were placed beside the central control board and used to monitor pilots' operations.

2.3. The simulated taxiing task

Before the experiment, a senior training instructor from Shanghai Eastern Flight Training CO., LTD set the simulation scenarios and communicated with pilots about the flight plan. In the simulation task, participants took full manual control to perform landing from the last approach point and taxiing to the arrival gate in the Beijing International Airport according to the flight plan while following the instructions from a pseudo air traffic controller. An experimenter sat beside the pilot in the experiment to record pilot navigation errors based on their observations.

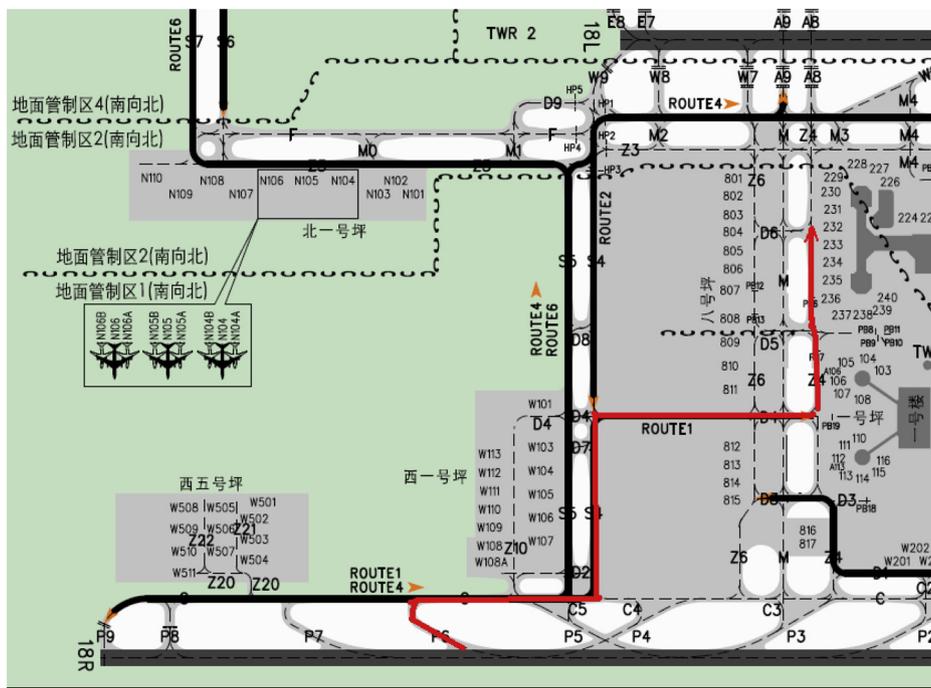
Two taxi routes differing in their complexity were selected in this experiment (Fig. 1). The less complex taxi route was 10.8 km long and included 10 separate intersection crossings. The more complex taxi route was 19 km long and included 18 separate intersection crossings. When taxiing on the less complex taxi route, the flight would get off the runway 36 L from P6, head for the north, and then arrive at Gate 232. When taxiing on the more complex taxi route, the flight would get off the runway 36 L from P7, head for the north, cross runway 18 L and wait for runway clearance for about 2 min, and finally arrive at Gate 520. Compared to the less complex taxi route, the more complex taxi route not only has more turns, but also involves situations that require more skillful operations. Specifically, taxiing on the more complex taxi route requires consecutive (short-distance) turning and crossing runway operations (Please see Fig. 1(b)).

The simulated taxiing tasks were completed in the daytime scenario and nighttime scenario, respectively. In the daytime condition, participants judged the flight speed and orientation using their own vision without the aid of instruments, to perform the task. In the nighttime condition, the airport was runs in the night mode while the other meteorological condition was normal.

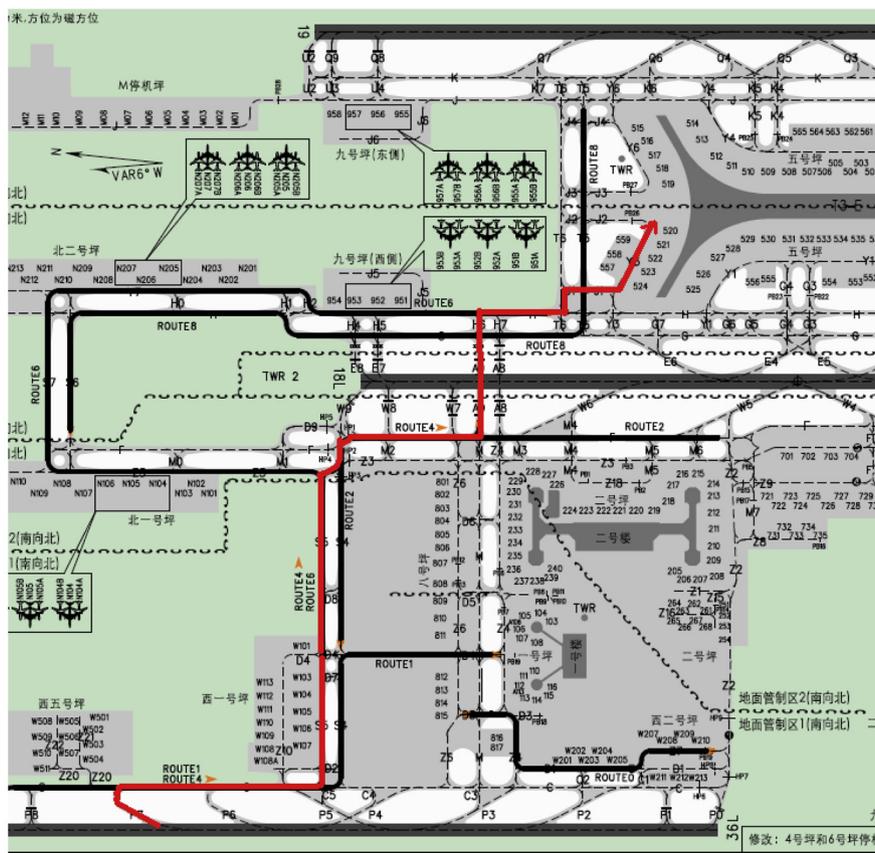
Both 'time of day' (i.e., daytime versus nighttime) and 'taxi route complexity' were defined as within-subject factors. Therefore, each participant performed taxiing operations in four testing conditions, corresponding to the four possible combinations of 'time of day' and 'taxi route complexity'. A simulated taxiing trial was performed in each testing condition. Participants were given a ten-minute break for their pupils to adjust between trials. Only standard devices (e.g., navigation display) were available in the cockpit, and the guidance capability was the same across the testing conditions. The order of these testing conditions was randomized across the participants.

2.4. Navigation errors

A navigation error was considered to occur if the flight was: 1) taxiing into an area where aircraft had not been cleared; or 2) deviating from the cleared taxiway centerline at least 50 feet by turning incorrectly or failing to turn (Hooey and Foyle, 2006; Hooey et al., 2000). After the experiment, the experimenter, together with an air traffic controller and the senior training instructor, reviewed the video recordings of the simulated task and counted the navigation errors according to their definitions. Navigation error counts were used as a



(a)



(b)

Fig. 1. Taxi routes. (a) Less complex taxi route; (b) More complex taxi route.

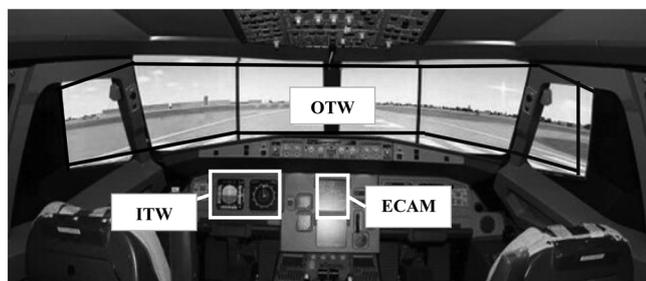


Fig. 2. Three AoIs.

dependent variable for analysis.

2.5. Eye movement measures

As visual information could be acquired during fixations rather than during intermediate saccades (Jacob and Karn, 2003; Rayner, 1998), fixation measures were chosen as dependent variables including fixation rate and average fixation duration in the areas of interests (AOIs). Fixation rate was defined by the number of fixations on an AOI per minute, and average fixation duration was calculated as the average time duration of fixations on an AOI.

A fixation was defined as a dwell in an area of 10 by 10 pixels over 100 ms (Jacob, 1991). The selection of AOIs in the present study was instructed by the senior training instructor. There are three main tasks operated by pilots during taxiing, including monitoring the surrounding visual scene, controlling the aircraft speed, and maintaining an updated picture of the current position of the aircraft on the taxiway and the location of the destination. Three AOIs were selected including the electronic centralized aircraft monitoring (ECAM), views in the window (ITW) and views outside of the window (OTW) (Fig. 2). These AOIs provide visual information necessary for pilots to perform the three main tasks during taxiing. In particular, ECAM is the AoI showing system states information, especially malfunction alarm information; ITW presents information about taxiing speed, airplane orientation, and taxiing route; OTW provides information about environmental clues outside of the cockpit (i.e., centerline of taxiing, signs and markings of airport) that is the most relevant with taxiing accuracy and helps pilots maintain their local awareness to avoid navigation errors (Schriver et al., 2008; Hasse and Bruder, 2015). Fixation measures were calculated based on the recorded eye movement data throughout the simulated taxing task.

Besides fixation rate and average fixation duration, average pupil area was also chosen as a dependent variable, as it has been reported to be an indicator of pilots' workload (He et al., 2012; Liu et al., 2014). The eye-tracking system provides pupil diameters (in pixels) along the x-axis (diaX) and the y-axis (diaY), respectively. Pupil size was computed as an ellipse area using the formula below:

$$\text{Pupil area} = \pi \times \text{diaX}/2 \times \text{diaY}/2$$

Note that average pupil area was not normalized by its corresponding baseline data, as the experiment was designed as a within-subject study.

2.6. Analysis

There were two independent variables that were 'time of day' and 'taxi route complexity'. Time of day had two levels: nighttime versus daytime. Taxi route complexity was also defined at two levels by the less complex route and more complex route. Chi-square test was performed to determine the main and interaction effects of 'time of day' and 'taxi route complexity' on navigation error counts. Two-way ANOVAs were performed to determine the main and interaction effects of 'time of day' and 'taxi route complexity' on eye movement measures.

Table 1
Data for each participant.

Subject No.	Total flight hours	Age (years)	No. of navigation errors	Conditions for navigation errors
1	15000	38	0	–
2	13800	40	2	D + MC & N + MC
3	11500	35	1	N + LC
4	11000	35	1	D + MC
5	10,000	36	0	–
6	6500	31	1	N + LC
7	4400	30	1	C + LC
8	4000	28	2	D + MC & N + MC
9	2000	29	2	D + MC & N + MC

D = daytime; MC = more complex route; N = nighttime; LC = less complex route.

Where significant interaction effects were identified, effects of route complexity would be examined for the nighttime and daytime conditions, respectively, by using paired t-tests.

In order to determine if the observed significant differences were practically meaningful, effect sizes quantified by partial-eta-squared were calculated. The effect size is the strength or magnitude of the difference between two data sets. The small, medium, and large effect sizes were suggested to correspond to 0.01, 0.06, and 0.14, respectively (Cohen, 1988). Level of significance was set at $\alpha = 0.05$ throughout the analysis.

3. Results

A total of 36 simulated taxiing trials were collected, given that each participant completed 4 trials. Ten out of the 36 simulation trials (27.8%) had a single navigation error. None of the trials contained more than one error. Conditions for the occurrence of navigation errors were presented in Table 1. In particular, navigation errors occurred more often in the daytime condition than in the nighttime condition (six errors in the daytime versus four errors at night, p -value = 0.005). Navigation error counts were also significantly higher in the more complex taxing route condition (three errors in less complex route versus seven errors in more complex route, p -value = 0.005). There was no significant interaction effect of 'time of day' and 'taxi route complexity' on navigation error counts. Regression was performed to determine the relationship between "flight hours" and "navigation errors", and the results showed that the relationship was not significant ($\beta = -0.481, R^2 = 0.231, p$ -value > 0.05).

Significant time of day effects were found in fixation rate in the areas of ECAM ($F(3, 32) = 7.989, p$ -value = 0.022) and OTW ($F(3, 32) = 13.503, p$ -value = 0.006) (Table 2). In particular, fixation rate was 92.3% higher in ECAM and 22.9% lower in OTW in the daytime versus at night, suggesting participants were more situationally aware during the nighttime. Besides, there existed significant time of day effects on average fixation duration and average pupil area in the areas of OTW (average fixation duration: $F(3, 32) = 12.886, p$ -value = 0.007; average pupil area: $F(3, 32) = 7.482, p$ -value = 0.026). Nighttime condition was found to be associated with 30.1% longer average fixation duration and 28.2% larger pupil area compared with daytime (Table 2), suggesting participants were more situationally aware and had higher workload during the nighttime.

There were no significant route complexity effects in fixation measures and average pupil area. However, the effect of route complexity on average pupil area in ECAM was found to be dependent on time of day conditions. In particular, average pupil area did not differ between the less and more complex taxi route conditions in the daytime, while significantly increased at night when taxing route became more complex ($t(1, 17) = -2.390, p$ -value = 0.022) (Fig. 3). This indicates that more complex taxi route led to higher workload only at night.

Effect sizes of the observed significant differences were all large,

Table 2
Eye movement data: Mean (SE).

Aols		Time of day conditions				Taxi Route Complexity				Time × Complexity
		Daytime	Nighttime	p-values	Effects size	Less complex	More complex	p-values	Effects size	p-values
ECAM	Duration (ms)	234.7(20.8)	183.8(23.6)	0.380	0.098	186.6(21.4)	231.8(23.2)	0.196	0.199	0.196
	Fixation rate (-)	5.08(0.29)	2.59(0.35)	0.022 [*]	0.500	3.68(0.41)	3.99(0.35)	0.604	0.035	0.829
	Pupil Area (mm ²)	5.77(0.51)	4.16(0.80)	0.260	0.155	4.63(0.77)	5.30(0.61)	0.254	0.159	0.009 [*]
OTW	Duration (ms)	486.6(34.5)	633.1(37.1)	0.007 [*]	0.617	555.4(32.8)	564.4(42.3)	0.865	0.004	0.142
	Fixation rate (-)	1.92(0.13)	2.36(0.11)	0.006 [*]	0.628	2.13 (0.13)	2.15(0.11)	0.895	0.002	0.179
	Pupil Area (mm ²)	5.86(0.41)	7.51(0.61)	0.026 [*]	0.483	6.49(0.59)	6.88(0.53)	0.458	0.071	0.088
ITW	Duration (ms)	280.3(21.4)	272.1(26.4)	0.854	0.004	274.6(22.3)	277.7(25.7)	0.816	0.007	0.211
	Fixation rate (-)	4.13(0.23)	3.57(0.38)	0.500	0.059	3.75(0.28)	3.96 (0.36)	0.424	0.081	0.084
	Pupil Area (mm ²)	5.56(0.46)	6.10(0.75)	0.606	0.035	5.64(0.61)	6.02(0.64)	0.512	0.056	0.083

* suggests statistical significance.

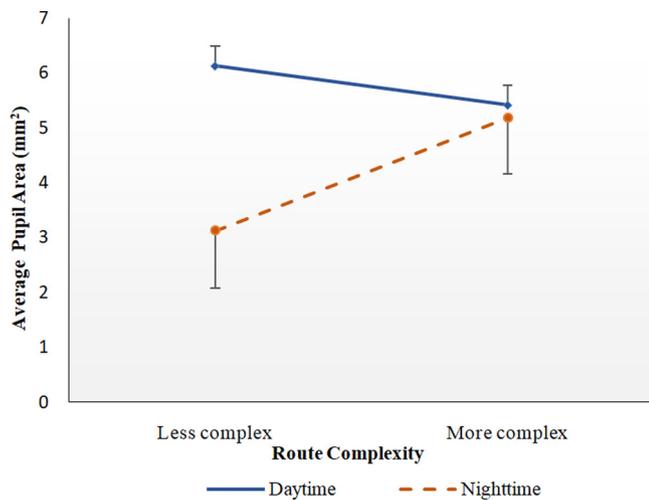


Fig. 3. Interaction effects of time of day conditions and taxi route complexity on average pupil area in the ECAM. Error bars indicate one SE.

ranging from 0.483 to 0.628 (Table 2).

4. Discussion

The nighttime condition was associated with poor visibility and the “sea of blue” effect, which would increase the difficulty of information acquisition for pilots. Therefore, it would have been natural to expect more navigation errors at night. However, in contrast to this, our findings showed that navigation errors were more in daytime versus at night. This finding is somewhat consistent with Cozza and Young (2013) who reported that there was a higher rate of runway incursions during daytime.

We noted longer average fixation duration, higher fixation rate and larger pupil area in OTW in the nighttime condition compared to those in the daytime condition. Decreased visibility at night would increase pilots’ difficulties of acquiring and encoding information from the environment (Viertler and Hajek, 2017). OTW presents the environmental information (i.e., centerline of taxiing, signs and markings of airport) that is the most relevant with taxiing accuracy and critical for pilots to keep their situation awareness to avoid navigation errors (Schriver et al., 2008; Hasse and Bruder, 2015). The observed pilots’ visual behaviors quantified by fixation duration and fixation rate suggest that pilots pay more attention to OTW at night. This could be explained as a visual operation strategy adopted by pilots to improve their situation awareness and maintain their ability to acquire and encode environmental information for taxiing accuracy at night. As a result, unnecessary errors could be more likely avoided at night. An implication from this finding is that pilots should be instructed to monitor OTW more often for better situation awareness and fewer navigation errors.

In addition, larger pupil area in OTW at night could be associated with the increased workload induced by information acquisition and encoding difficulties at night. This finding is consistent with Blacker et al. (2018) who reported larger pupil sizes at night compared to in the daytime.

We also found lower fixation rate in ECAM at night versus in daytime. ECAM is the AoI showing system states information, especially malfunction alarm information. Unlike OTW, ECAM does not provide much useful information for accurate taxiing in the normal situation. Lower fixation rate in ECAM at night may result from the attention trade-off between OTW and ECAM. In other words, pilots pay more attention to OTW at night because of the information acquisition and encoding difficulties caused by decreased visibility during night, and consequently less attention was allocated to ECAM.

We observed more navigation errors when taxiing on the more complex taxi route. More complex taxi route was associated with more intersections and conflict points. At the intersection, pilots need to decide if there is a turn and where to turn. Decision-making is cognitively demanding that will increase the difficulty of navigation operation. Johnson et al. (2016) reported that pilots was more likely to make mistakes at intersections. Therefore, it is natural to expect that increased number of intersections with the more complex taxi route would increase the probability of making errors. When looking at pilots’ visual behaviors, to our surprise, taxi route complexity did NOT affect eye movement measures that was considered closely related with navigation errors (Wilson et al., 2002; Bai et al., 2017). These findings could suggest that increased likelihood of making navigation errors on the more complex taxi route may not be attributable to the changes of visual behaviors, but just because there are more intersections and conflict points with the more complex taxi route. As our findings supported that complex taxi route could be a threat to navigation errors, attempts should be made to minimize the possibility of taxiing on a complex taxi route. A possible solution to this is using the follow-me vehicle that is able to guide the airplane taxiing to the gate according to the planned taxi route and help pilots clear the taxiing way.

Another interesting finding is that route complexity effects on average pupil area in ECAM were dependent on time of day conditions. In particular, more complex taxi route led to larger average pupil area in the nighttime condition, but made no difference in this measure in the daytime condition. Larger average pupil area suggests higher cognitive workload (van Orden et al., 2001; Ahlstrom and Friedman-Berg, 2006). The higher cognitive workload as indicated by larger pupil area could be due to more intensive attention allocation to ECAM. As ECAM presents system malfunction state information that is critical for safe taxiing, this finding may suggest that pilots attempt to increase their situation awareness by paying more attention to ECAM in a more challenging condition (i.e., taxiing on a complex taxi route at night). At the same time, though increased workload may impair taxiing safety, its negative effects could be compensated by increased situation awareness. This further explain why there were fewer navigation errors in the

nighttime condition.

There are several limitations in the present study. Firstly, the sample size is small ($n = 9$). Small sample size could result in increased type II error and decreased statistical power in statistical analysis. We should be cautious when generalizing the results from the present study. We also noted that effect sizes quantified by partial-eta-squared were all large. Therefore, the observed significant differences can be still considered practically meaningful. Secondly, to better understand the effects of taxi route complexity, each individual factor defining the route complexity (e.g., route length and number of intersections) shall be separately analyzed. However, only two taxiing routes were selected in the present study that makes separating these factors from each other impossible. This limitation should be addressed in the future work by evaluating more taxi routes with different levels of complexity. Thirdly, we realized that different guidance capabilities, such as follow-me vehicle in the airport and 3-D electronic map in the aircraft, may make differences in the effects of time of day and taxi route complexity. As only standard devices (e.g., navigation display) were available in the cockpit and the guidance capability was the same across testing conditions, it is impossible to compare the results with different guidance capabilities in the present study. It is worth examining the effects of guidance capabilities in the future.

In summary, the findings facilitate better understanding the effects of nighttime condition and taxi route complexity on pilots' navigation errors. Specifically, we found that navigation errors were fewer in the nighttime condition than in the daytime condition. This could be explained by the finding that pilots paid more attention to the environmental clues out of the window at night for accurate taxiing. More complex taxi route was found to be associated with more navigation errors, but participants' visual behaviors were similar between route complexity conditions. This indicates that pilots' visual operation strategies did not contribute to the increased number of navigation errors in the more complex taxi route condition. These findings suggest that taxi route complexity is a risk factor for navigation errors, but night condition is not due to pilots adjusting their behaviors in more challenging conditions. To control navigation errors, interventions should be applied to avoid exposures to complex taxi route.

Acknowledgements

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