Pilots' Fixation Patterns During Taxiing and the Effects of Visibility

Xiaoyan Zhang; Xingda Qu; Hongjun Xue; Jian Liu

INTRODUCTION: Visual performance is important for safe and accurate taxiing operations. Visibility is associated with navigation errors during taxiing. The main objective of the present study was to investigate the effects of visibility on pilots' fixation patterns during taxiing. The interaction between visibility and flight experience was also examined.

METHODS: Both experienced and less experienced pilots participated in the study. They were instructed to perform simulated taxiing tasks in two visibility conditions: clear day vs. low visibility. A mixed-model analysis of variance was performed to determine the main and interaction effects of 'visibility' and 'flight experience' on fixation data in each area of interest (AOI).

RESULTS: The results showed that experienced pilots' fixation counts reduced on the electronic centralized aircraft monitoring (ECAM) area, but increased out the middle view (OTWM) and right view out of the window (OTWR) in low visibility than in clear day, while fixation counts among less experienced pilots increased on the primary flight display (PFD) and ECAM areas, but did not change significantly OTWM and OTWR in low visibility. Fixation duration increased by 59.8%, 9.8%, and 7.9% in ECAM, OTWL, and OTWR, respectively, in low visibility than in clear day.

CONCLUSIONS: The findings suggest that pilots pay more attention and have higher perceptual load in the low visibility condition to maintain taxiing accuracy, and more experienced pilots make more visual efforts to extract information from AOIs outside the cockpit in the low visibility condition. These findings provide practical implications for safe and accurate taxiing operations.

KEYWORDS: visibility, flight experience, pilots, fixation patterns, taxiing.

Zhang X, Qu X, Xue H, Liu J. *Pilots' fixation patterns during taxiing and the effects of visibility*. Aerosp Med Hum Perform. 2019; 90(6):546–552.

The taxiing phase is a complex and dynamic process in flight.[12,23,30] During taxiing, pilots typically have to execute concurrent multitasks. For example, they need to simultaneously monitor visual scenes both inside and outside the cockpit, maintain taxiing speed and direction, and communicate with aircrews, air traffic controllers, and passengers. This imposes a very high workload onto pilots and increases the likelihood of operational errors and accidents. It was reported that there were 1460 runway incursions at U.S. airports between 1998 and 2001.[7] Therefore, there is an urgent need to understand pilots' performance during taxiing.

It was found that most information in the cockpit was presented visually and over 75% of pilot errors were caused by perceptual failures.[13] Safe and accurate taxiing operations are dependent on pilots' performance of encoding and extracting visual information inside and outside the cockpit,[1] which can be examined by fixation measures.[11,21,31] Fixation duration was found to be positively correlated with pilots' difficulty in understanding the areas of interest (AOI) or extracting information from an AOI.[19] It can also reflect the importance of the AOI to the pilots.[27] In addition, increased fixation counts on an AOI was suggested to be an indicator of increased attention allocation to the AOI.[20] Orquin and Mueller[17] showed that increasing working memory load leads to a linear increase in either fixation counts or fixation duration. Findings from a flight simulator experiment also suggested both fixation counts and fixation duration were able to reflect pilots' situation awareness.[27,31]

From the Institute of Human Factors and Ergonomics, Shenzhen University, Shenzhen, China; the School of Aeronautics, Northwestern Polytechnical University, Xi'an, China; and the Division of Applied Science & Technology, Marshall University, Huntington, WV, United States.

This manuscript was received for review in July 2018. It was accepted for publication in March 2019.

Address correspondence to: Xingda Qu, Ph.D., Institute of Human Factors and Ergonomics, Shenzhen University, 3688 Nanhai Avenue, Shenzhen City, Guangdong Province, China; quxd@szu.edu.cn.

DOI: https://doi.org/10.3357/AMHP.5206.2019

Low visibility is considered to be a factor compromising pilots' ability to encode and extract visual information.[3,14,15] Insufficient information due to low visibility may induce decision difficulty and situation awareness problems.[2,23,27] It may also increase operational stress, especially among less experienced pilots.[26] In fact, low visibility has been reported to be the cause for 17% of navigation errors during taxiing.[9] Though it is obvious that visibility affects taxiing operations, relevant emprical evidence is still missing.

The main objective of the present study was to determine the effect of visibility on pilots' visual performance during taxiing. In addition, it has been widely recognized that flight experience makes differences in pilots' visual performance.[29] For example, experienced pilots were found to fixate on the instruments for less time, but did visit the instruments more frequently, while their less experienced counterparts tended to dwell for a longer time on each instrument during a flight task.[18] Therefore, we would also like to examine the interaction between visibility and flight experience in the present study. Visual performance was examined by fixation measures, including fixation counts and fixation duration in the selected AOIs.

Decreased visibility limits pilots' encoding and extracting useful visual information from the airport environment,[29] which makes them pay more attention to the information outside the cockpit. Thus, we hypothesized that lower visibility would lead to more fixations and longer fixation duration in the areas outside the cockpit (e.g., traffic signs). It was also reported that experts tended to fixate on the instruments for less time, but had better automated skills in extracting information,[18,25] and fixation duration was positively correlated with pilots' difficulty in understanding the AOI or extracting information from that AOI.[19] Therefore, the second hypothesis was that less experienced pilots would have greater difficulty finding and extracting useful information from the instruments in the cockpit, and thus would have more fixations and longer fixation duration on the AOIs inside the cockpit compared to the experienced pilots, especially in the low visibility condition.

METHODS

Subjects

Eight male pilots participated in the study. They were all recruited from Shanghai Eastern Flight Training Co., Ltd., and had simulator experience. Four subjects were classified as experienced pilots as their flight hours were no less than 10,000 h (age: mean $\pm$ SD = 37.25 $\pm$ 2.22 yr; flight hours: mean $\pm$ SD = 12,450 $\pm$ 2340 h). The rest, who had flight hours less than 10,000 h, were classified as less experienced pilots (age: mean $\pm$ SD = 28.75 $\pm$ 1.71 yr; flight hours: mean $\pm$ SD = 3550 $\pm$ 2216 h). This research was approved by the local ethics committee at NWPU. Informed consent was obtained from each subject.

Apparatus

The experiment was conducted in an Airbus 320 simulator at Shanghai Eastern Flight Training Co., Ltd. Eye movements were recorded by an eye tracker (iView X HED, SMI, SensoMotoric Instruments GmbH, Teltow, Germany), with a sampling rate of 200 Hz. Raw data was collected and processed by the SMI BeGaze 3.4 software (SensoMotoric Instruments GmbH).

Procedure

Before the experiment, a senior training instructor from Shanghai Eastern Flight Training Co., Ltd., set the simulation scenarios and communicated with the pilots about the flight plan. The subjects played the role as a captain, sitting at the captain's seat on the right side of the cockpit, and took full manual control to perform landing from the last approach point and taxiing to the gate at Beijing International Airport according to the flight plan. The taxiing route is shown in **Fig. 1**, which indicates that the flight gets off the runway 36L from P6 heading north, passes seven intersections, and then arrives at Gate 232. Note that in the simulated task, the instructor who was assigned the task to communicate with pilots about their flight plan and observe pilots' operations sat in the second row on the left-hand side. Thus, the captain's seat was set on the right-hand side for the convenience of communication and observation.

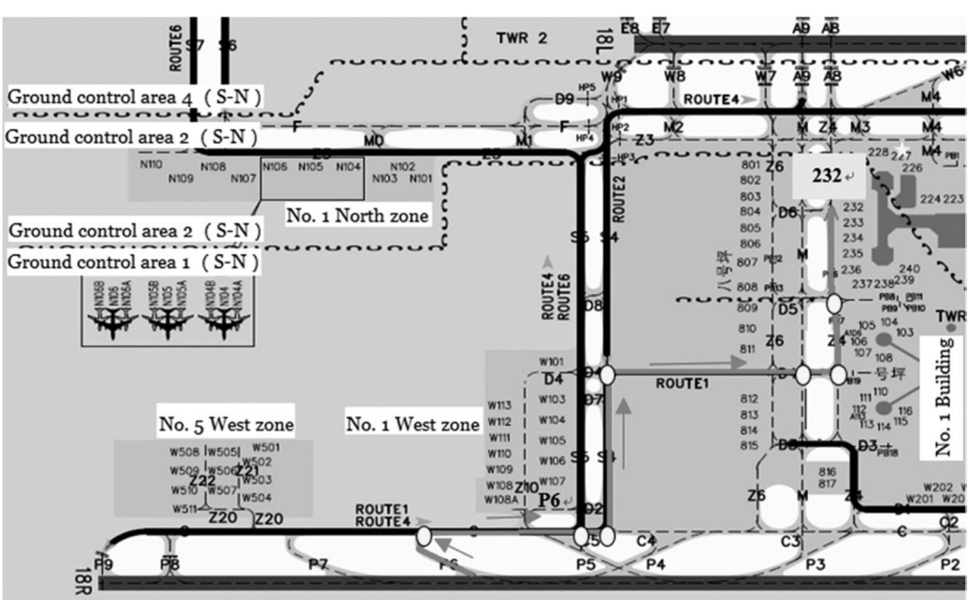

Fig. 1. Taxiing route (dark grey line) in Beijing international airport in the simulated taxiing task. White circles represent the intersections.

The simulated taxiing tasks were completed in two visibility scenarios corresponding to clear day and low visibility, respectively (**Fig. 2**). In the clear day condition, the subjects had unlimited visibility and the airplane was operated in the visual meteorological condition, in which the subjects judged the flight situation such as speed and attitude by their own vision. In the low visibility condition, the runway visibility was limited to 200 m (the lowest visibility allowed for safe flight in China) and the subjects had to operate the airplane in the instrument meteorological condition, in which flight situation was mainly acquired from the instruments in the cockpit. The taxiing tasks were the same in both visibility scenarios. Thus, effects of visibility would not be confounded by taxiing tasks. Visibility was considered as 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.

Dependent Variables

As visual information could be acquired during fixations rather than during intermediate saccades,[11,21] fixation measures were chosen as dependent variables, including fixation counts and fixation duration in the selected AOIs. According to Jacob,[10,11] a fixation was defined as a dwell in an area of 10 by 10 pixels over 100 ms.

The selection of the AOIs was advised by a senior training instructor from Shanghai Eastern Flight Training Co. The pilots needed to perform three main tasks during taxiing, including monitoring the surrounding visual scene, controlling the aircraft speed, and maintaining the updated information about the current position of the aircraft and the location of the destination. Six AOIs were selected, including electronic centralized aircraft monitoring (ECAM), navigation display (ND), left view out of the window (OTWL), middle view out of the window (OTWM), right view out of the window (OTWR), and primary flight display (PFD) (**Fig. 3**). These AOIs provide visual information necessary for pilots to perform the three main tasks during taxiing. Specifically, ECAM is the AOI showing system status information, especially malfunction alarm information. PFD and ND present information about taxiing speed, airplane orientation, and taxiing route. OTWM, OTWL, and OTWR provide information about environmental cues (e.g., surface markings, lightings, and signs) in pilots' front view, left view, and right view, respectively.

Pilots execute the most complicated manual and cognitive operations at the intersections during taxiing.[8,12] Therefore, we only looked at the dependent variables when passing intersections. We defined the moment when the airplane nose first entered the intersection as the marking point. Based on the observation of taxiing operations during the experiment, the subjects began to operate the steering handle for turning about 15 s before the marking point, and the aircraft turns to be parallel with the centerline of the taxiway around 15 s after the marking point. Thus, in order to reduce the effect of duration variability across the subjects and trials, eye movement data 15 s before and after the marking point were used for analysis as

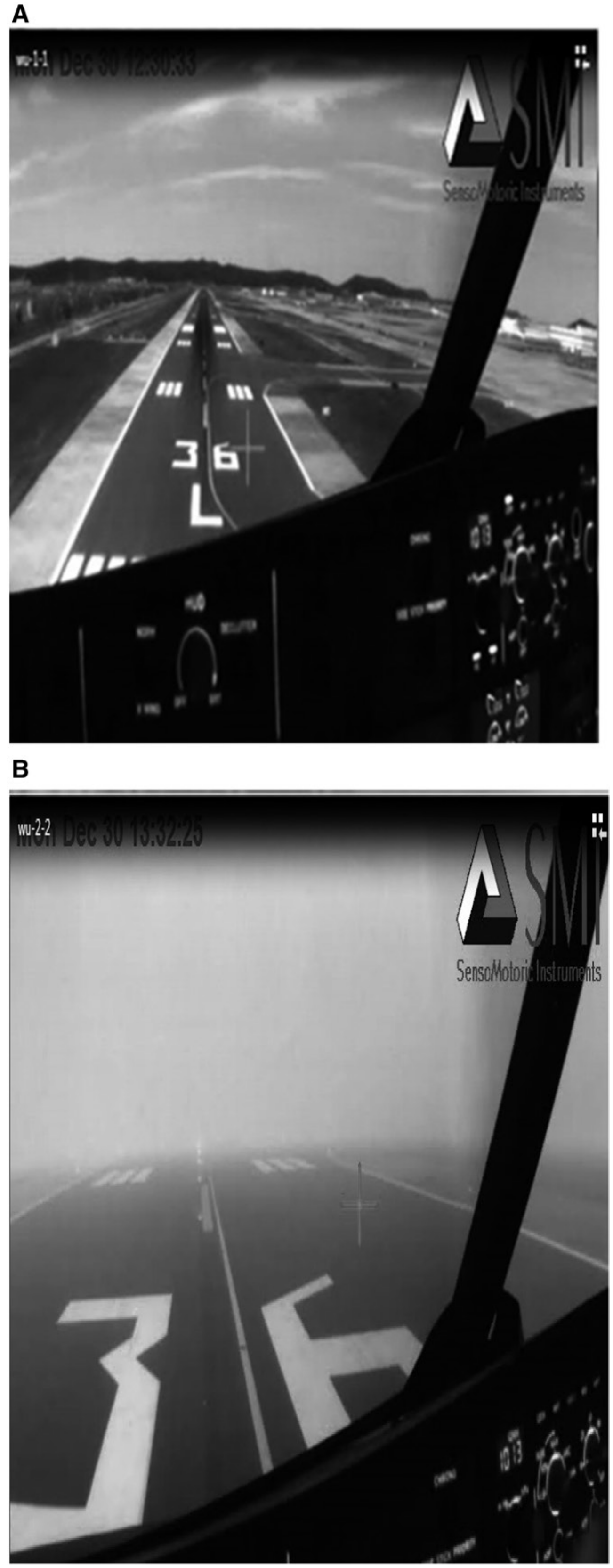

Fig. 2. Two visibility conditions. A) clear day; B) low visibility.

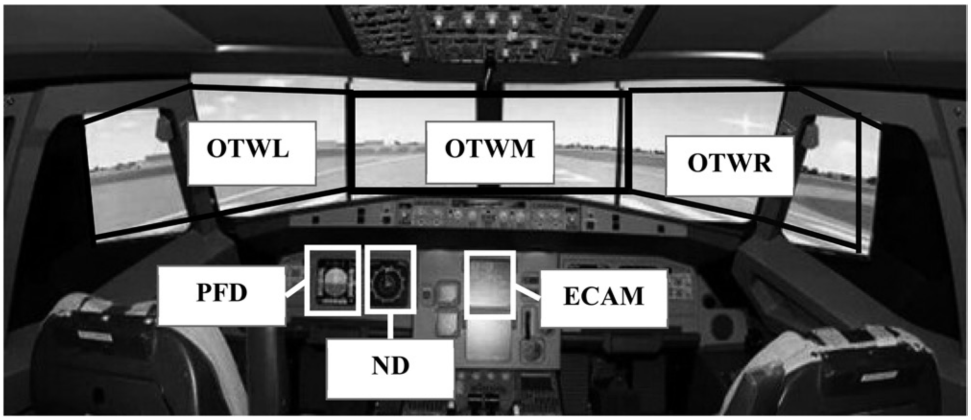

Fig. 3. Six AOIs.

they can better reflect the fixation performance of a complete turning. Fixation counts and fixation duration in the AOIs were calculated at each intersection, separately.

RESULTS

The independent variables were 'visibility' and 'flight experience'. As visibility was a within-subject factor and flight experience was a between-subject factor, a mixed-model ANOVA was performed to determine the main and interaction effects of 'visibility' and 'flight experience' on dependent variables in each AOI. In order to minimize interindividual differences, 'subjects' was considered as a random factor. Where significant interaction effects between visibility and flight experience were found, visibility effects were examined by using paired t-tests for each flight experience group, separately. As there were quite a number of comparisons in analyses, level of significance was set at $\alpha = 0.01$ to keep down the overall type I error. Note that since 'subjects' was a random factor, the data from each intersection were used in ANOVA.

Significant interaction effects of visibility and flight experience were found with fixation counts in the areas of ECAM [$F(1,108) = 8.978$, P-value = 0.003], PFD [$F(1,108) = 8.290$, P-value = 0.005], OTWM [$F(1,108) = 54.690$, P-value < 0.001], and OTWR [$F(1,108) = 21.300$, P-value < 0.001] (**Table I** and **Fig. 4**). Results from paired t-tests showed that fixation counts in the areas of OTWM and OTWR were significantly higher in low visibility than in clear day among experienced pilots [OTWM: $t(27) = 7.124$, P-value < 0.001; OTWR: $t(27) = 4.742$, P-value < 0.001], while such trend was not observed in OTWR [$t(27) = -2.439$, P-value = 0.022] and OTWM [$t(27) = -0.226$, P-value = 0.823] among less experienced pilots (Fig. 4). In addition, decreased visibility tended to lead to increased fixation counts in the area of ECAM and PFD among less experienced pilots [ECAM: $t(27) = 2.868$, P-value = 0.008; PFD: $t(27) = 2.914$, P-value = 0.007], while such measures significantly decreased with decreased visibility in ECAM [$t(27) = -2.872$, P-value = 0.008] and did not change significantly in PFD [$t(27) = -0.817$, P-value = 0.421] among experienced pilots (Fig. 4).

When significant interactions between visibility and flight experience were not present, longer fixation duration was observed in the areas of ECAM [$F(1,108) = 27.267$, P-value < 0.001], OTWL [$F(1,108) = 10.439$, P-value = 0.002], and OTWR [$F(1,108) = 10.597$, P-value = 0.002] in low visibility than in clear day (**Table II**). In particular, fixation duration increased by 59.8%, 9.8%, and 7.9% in ECAM, OTWL, and OTWR, respectively, in low visibility than in clear day. Besides, significant experience effects were found in the fixation duration in the areas of ECAM [$F(1,108) = 53.983$, P-value < 0.001], OTWL [$F(1,108) = 30.093$, P-value < 0.001], and OTWM [$F(1,108) = 15.259$, P-value = < 0.001] (Table II). In particular, experienced pilots had 80.4% longer fixation duration in ECAM, 15.3% shorter fixation duration in OTWL, and 35.6% shorter fixation duration in OTWM.

Significant visibility effects were found in fixation counts in the areas of OTWM [$F(1,108) = 30.592$, P-value < 0.001]

Table I. Fixation Counts: Mean (SE).

FACTORS/AOIs	ECAM	ND	OTWL	OTWM	OTWR	PFD
Experience						
Experienced	28.5(4.3)	36.7(7.5)	38.5(4.0)	268.8(19.6)	79.2(6.2)	32.5(4.2)
Less experienced	5.8(1.3)	24.3(3.4)	31.3(1.5)	297.5(7.3)	104.7(6.6)	30.8(4.3)
P-values	<0.001*	0.021	0.005*	0.010*	<0.001*	0.697
Visibility						
Clear day	17.2(3.7)	32.5(6.2)	37.0(1.2)	257.8(14.9)	101.9(9.0)	23.6(3.3)
Low visibility	17.1(2.7)	28.5(3.6)	32.8(3.4)	309.5(8.0)	82.0(4.0)	39.7(5.0)
P-values	0.435	0.227	0.905	0.000*	0.236	0.055
Experience ×Visibility						
P-values	0.003*	0.011	0.021	<0.001*	<0.001*	0.005*

* Indicates statistical significance.
AOIs: areas of interest; ECAM: electronic centralized aircraft monitoring; ND: navigation display; OTWL: out the window to the left; OTWM: out the window in the middle; OTWR: out the window to the right; PFD: primary flight display.

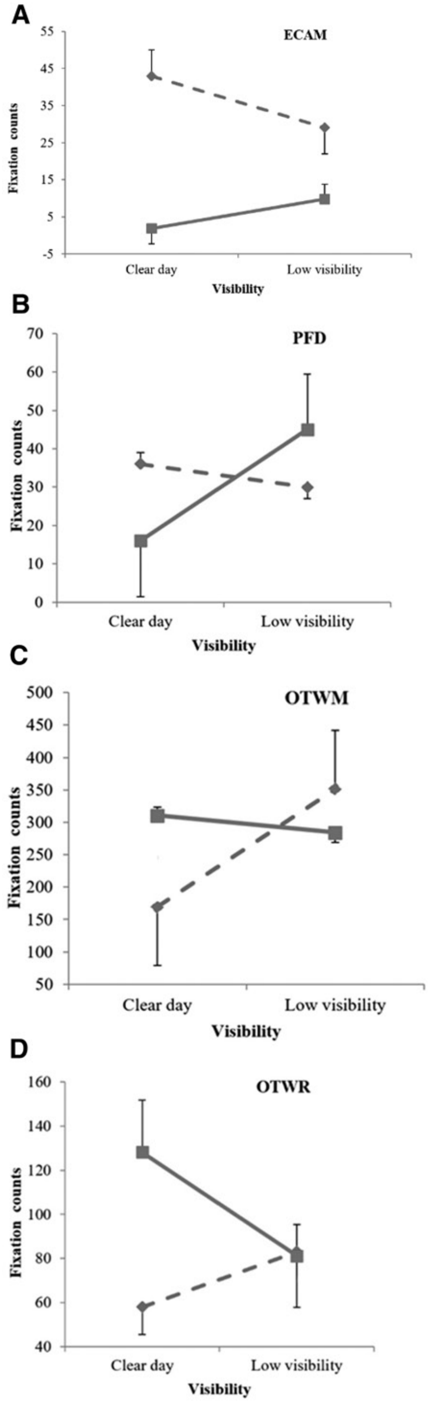

Fig. 4. Significant interaction effects of experience and visibility on fixation counts in the ECAM, PFD, OTWR, and OTWM. Error bars indicate 1 SE. Dashed line indicates experienced pilots; solid line indicates less experienced pilots.

(Table I). Pilots had 16.7% less fixation counts in clear day than in low visibility. Fixation counts in the areas of ECAM [$F(1,108) = 70.541$, P-value < 0.001], OTWL [$F(1,108) = 8.163$, P-value $= 0.005$], OTWM [$F(1,108) = 6.931$, P-value $= 0.010$], and OTWR [$F(1,108) = 14.021$, P-value < 0.001] were affected by experience (Table I). Compared with less experienced pilots, fixation counts increased by 391.4% and 23% in ECAM and OTWL, respectively, and decreased by 10.7% and 24.3% in OTWM and OTWR, respectively, among experienced pilots (Table I). Effect sizes of the observed significant differences were all large,[6] ranging from 0.160 to 0.669 (**Table III**).

DISCUSSION

The main aim of the present study was to improve the understanding of the effects of visibility on pilot's fixation performance during taxiing. To achieve this aim, we examined pilots' fixation patterns during taxiing in both low visibility and clear day conditions. As it has been widely recognized that flight experience makes differences in pilots' visual performance, both experienced and less experienced pilots were included in the study. Experience effects and experience-related differences in visibility effects were also examined.

One of our initial hypotheses was that less experienced pilots would have greater difficulty finding and extracting useful information from the instruments in the cockpit, and thus have more fixations and longer fixation duration in the AOIs inside the cockpit compared to the experienced pilots, especially in the low visibility condition. This hypothesis was supported by our results. We noted that with poorer visibility, experienced pilots had more fixation counts in the AOIs outside the cockpit (i.e., OTWM and OTWR). In contrast, among less experienced pilots, poorer visibility led to more fixation counts in the AOIs in the cockpit (i.e., PFD and ECAM). Experienced pilots' fixation pattern suggested that they had to make more visual efforts to extract information from AOIs outside the cockpit for taxiing accuracy because low visibility could result in information extracting difficulty and a stressful situation. Though fixating less on AOIs outside the cockpit in the low visibility condition, less experienced pilots had more fixation counts on the primary display (i.e., PFD) in low visibility than in clear day. This suggests that due to the lack of experience, less experienced pilots cannot extract enough information from AOIs outside the cockpit as effectively as experienced pilots in the low visibility condition. Consequently, they had to adopt an attention tradeoff and rely more on the information in the cockpit in the low visibility condition.

When significant interactions between visibility and flight experience were not present, we found that OTWL, OTWM, and OTWR had longer fixation duration in low visibility than in clear day. Decreased visibility reduces the range of vision, which limits pilots' encoding and extracting useful visual information from the airport environment. As a result, it would become more difficult for pilots to receive updated information about the current position of the aircraft. The information in OTWL, OTWM, and OTWR (e.g., centerline of taxiing, signs and markings of the airport) is most relevant with taxiing accuracy and helps pilots maintain their local awareness to avoid runway incursions.[24] Longer fixation duration observed in these AOIs in the low visibility condition suggested increased attention allocation to the taxi route and

Table II. Fixation Duration (ms): Mean (SE).

FACTORS/AOIs	ECAM	ND	OTWL	OTWM	OTWR	PFD
Experience						
Experienced	297.1(8.8)	249.7(6.7)	283.2(7.9)	247.5(9.0)	333.3(6.8)	282.0(9.2)
Less experienced	164.7(14.8)	262.2(11.5)	334.2(5.8)	384.1(5.2)	353.5(6.4)	281.4(15.0)
P-values	<0.001*	0.425	<0.001*	<0.001*	0.034	0.976
Visibility						
Clear day	165.0(17.8)	239.7(8.5)	300.4(7.1)	362.4(8.9)	332.8(6.3)	293.7(17.3)
Low visibility	263.7(11.6)	275.3(12.3)	329.9(7.2)	378.3(4.1)	359.1(6.9)	269.5(9.8)
P-values	<0.001*	0.032	0.002*	0.021	0.002*	0.456
Experience ×Visibility						
P-values	0.298	0.620	0.868	0.011	0.080	0.083

* Indicates statistical significance.
AOIs: areas of interest; ECAM: electronic centralized aircraft monitoring; ND: navigation display; OTWL: out the window to the left; OTWM: out the window in the middle; OTWR: out the window to the right; PFD: primary flight display.

more perceptual load to maintain taxiing accuracy.[20,22] This could be an attempt by pilots to maintain taxiing accuracy when the update of the information about the current aircraft position was compromised by low visibility.

Low visibility results in a lack of information in peripheral vision that will reduce the number of speed cues and make it more difficult for pilots' perception of speed and orientation.[8] They may not get enough information outside the cockpit to ensure safe and accurate taxiing.[23] ECAM is the display that shows system malfunction states, which is very important for safe taxiing. Longer fixation duration in ECAM was observed in low visibility than in clear day. This finding suggests that pilots adopted a visual operation strategy to rely more on ECAM in the decreased visibility condition for safe taxiing.

Fixation measures in ND and PFD were not affected by visibility. Important objects in scenes are fixated on more often and longer than less important objects.[5] In addition, more fixations and longer fixation duration might result from the AOIs with higher informativeness[21] and more relevant features.[16] Thus our findings indicated that ND and PFD became less informative and less important in the low visibility condition compared to the rest of the AOIs.

In the normal situation, ECAM appears not to provide much useful information (e.g., taxiing speed and taxiing orientation) for accurate taxiing. More experienced pilots were found to have longer fixation duration over ECAM than less experienced pilots. This could be explained from the perspective that more experienced pilots had more attentional resources available to monitor tasks with lower priority compared to their less experienced counterparts in the normal situation. Though less experienced pilots participating in the experiment were all well-trained pilots, some of them never played the role as a captain before joining the experiment. Due to the lack of flight experience as a captain, they may have ignored information about small probability events, e.g., system malfunction, during taxiing operations. This may suggest that less experienced pilots should be trained to pay more attention to ECAM for taxiing safety.

The findings from the present study aid in better understanding pilots' fixation patterns during taxiing and they can be used to derive practical implications for safe and accurate taxiing operations. In particular, the findings here suggested that the airport traffic signs and landmarks in the front view, as well as information about taxiing speed and orientation, become increasingly important for taxiing accuracy and safety, especially in the low visibility condition. Some researchers reported that visual augmentation methods can help pilots acquire information effectively in the low visibility situation.[4,28] Thus, the front view traffic signs and landmarks as well as the displays showing taxiing speed and orientation could be designed by visual augmentation methods. The new knowledge about experienced pilots' fixation patterns could guide less experienced pilots' fixation operations during taxiing. For instance, less experienced pilots should learn to monitor ECAM more often to improve their capability of handling unexpected off-normal events.

ACKNOWLEDGMENTS

This research was supported in part by the National Natural Science Foundation of China under grant #51705332.

Table III. Effect Sizes.

FACTORS/AOIs	ECAM	ND	OTWL	OTWM	OTWR	PFD
Experience						
Fixation counts	0.395	0.048	0.070	0.160	0.115	0.001
Fixation duration	0.626	0.503	0.548	0.660	0.999	0.024
Visibility						
Fixation counts	0.021	0.041	0.364	0.560	0.669	0.354
Fixation duration	0.486	0.568	0.323	0.372	1.000	0.560

AOIs: areas of interest; ECAM: electronic centralized aircraft monitoring; ND: navigation display; OTWL: out the window to the left; OTWM: out the window in the middle; OTWR: out the window to the right; PFD: primary flight display.

Authors and affiliations: Xiaoyan Zhang, Ph.D., and Xingda Qu, Ph.D., Institute of Human Factors and Ergonomics, Shenzhen University, Shenzhen, China, Hongjun Xue, Ph.D., School of Aeronautics, Northwestern Polytechnic University, Xi'an, China, and Jian Liu, Ph.D., Division of Applied Science and Technology, Marshall University, Huntington, WV, United States.

REFERENCES

1. Andre TA. Information requirements for low-visibility taxi operations: what pilots say. In: Jensen RS, Rakovan LA, editors. Proceedings of International Symposium on Aviation Psychology. Columbus: Ohio State University; 1995:484–488.
2. Chang YH, Yang HH, Hsiao YJ. Human risk factors associated with pilots in runway excursions. Accid Anal Prev. 2016; 94:227–237.
3. Cheung B, Craig G, Steels B, Sceviour R, Cosman V, et al. In-flight study of helmet-mounted symbology system concepts in degraded visual environments. Aerosp Med Hum Perform. 2015; 86(8):714–722.
4. Cheung B, Mckinley RA, Steels B, Sceviour R, Cosman V, Holst P. Simulator study of helmet-mounted symbology system concepts in degraded visual environments. Aerosp Med Hum Perform. 2015; 86(7):588–598.
5. Christianson SA, Loftus EF, Hoffman H, Loftus GR. Eye fixations and memory for emotional events. J Exp Psychol Learn Mem Cogn. 1991; 17(4):693–701.
6. Cohen J. Statistical power analysis for the behavioral sciences. Hillsdale (NJ): Erlbaum; 1998.
7. Federal Aviation Administration. FAA runway safety report: runway incursion trends at towered airports in the United States 1998–2001. Washington (DC): FAA; 2002.
8. Foyle DC, Hooey BL, editors. Human performance modeling in aviation. New York: CRC Press; 2007.
9. Hooey BL, Foyle DC. Pilot navigation errors on the airport surface: identifying contributing factors and mitigating solutions. Int J Aviat Psychol. 2006; 16(1):51–76.
10. Jacob RJ. The use of eye movements in human-computer interaction techniques: What you look at is what you get. ACM Trans Inf Syst. 1991; 9(2):152–169.
11. Jacob RJ, Karn KS. Eye tracking in human-computer interaction and usability research: ready to deliver the promises. In: Hyönä J, Radach R, Deubel H, editors. Proceedings of The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research. Amsterdam: Elsevier; 2003: 573–605.
12. Johnson ME, Zhao X, Faulkner B, Young JP. Statistical models of runway incursions based on runway intersections and taxiways. Journal of Aviation Technology and Engineering. 2016; 5(2):15–26.
13. Jones DG, Endsley MR. Sources of situation awareness error in aviation. Aviat Space Environ Med. 1996; 67(6):507–512.
14. Lapeyre B, Hourlier S, Servantie X, N'Kaoua B, Sauzéon H. Using the landmark-route-survey framework to evaluate spatial knowledge obtained from synthetic vision systems. Hum Factors. 2011; 53(6):647–661.
15. McCann R, Parke B, Andre A, Hooey B, Foyle D, Kanki B. An evaluation of the taxiway navigation and situation awareness (T-NASA) system in high-fidelity simulation. 1998 World Aviation Conference. Reston (VA): AIAA; 1998.
16. McColeman CM, Blair M. Task relevance moderates saccade velocities to spatially separated cues. Proceedings of the Annual Meeting of the Cognitive Science Society. 2014; 36:2627–2632.
17. Orquin JL, Mueller LS. Attention and choice: a review on eye movements in decision making. Acta Psychol (Amst). 2013; 144(1):190–206.
18. Ottati WL, Hickox JC, Richter J. Eye scan patterns of experienced and novice pilots during visual flight rules (VFR) navigation. In: Proceedings of the 43rd Human Factors and Ergonomics Society Annual Meeting. Santa Monica (CA): Human Factors and Ergonomics Society; 1999: 66–70.
19. Rahman MM, Strawderman L, Garrison T, Eakin D, Williams CC. Work zone sign design for increased driver compliance and worker safety. Accid Anal Prev. 2017; 106:67–75.
20. Ratwani RM, McCurry JM, Trafton JG. Single operator, multiple robots: an eye movement based theoretic model of operator situation awareness. In: Proceedings of the Fifth ACM/IEEE International Conference on Human-Robot Interaction. New York: Association for Computing Machinery; 2010:235–242.
21. Rayner K. Eye movements in reading and information processing: 20 years of research. Psychol Bull. 1998; 124(3):372–422.
22. Sarter NB, Mumaw RJ, Wickens CD. Pilots' monitoring strategies and performance on automated flight decks: an empirical study combining behavioral and eye-tracking data. Hum Factors. 2007; 49(3):347–357.
23. Schönefeld J, Möller DPF. Runway incursion prevention systems: a review of runway incursion avoidance and alerting system approaches. Progress in Aerospace Sciences. 2012; 51:31–49.
24. Schriver AT, Morrow DG, Wickens CD, Talleur DA. Expertise differences in attentional strategies related to pilot decision making. Hum Factors. 2008; 50(6):864–878.
25. Sullivan J, Yang JH, Day M, Kennedy Q. Training simulation for helicopter navigation by characterizing visual scan patterns. Aviat Space Environ Med. 2011; 82(9):871–878.
26. Thomas KM. The increasing risk of runway incursions - the most dangerous part of air travel may be the time spent on the ground. Journal of Air Law and Commerce. 2002; 67(2):545–591. Available at http://scholar.smu.edu/jalc/vol67/iss2/8.
27. van de Merwe K, van Dijk H, Zon R. Eye movements as an indicator of situation awareness in a flight simulator experiment. Int J Aviat Psychol. 2012; 22(1):78–95.
28. Viertler F, Hajek M. Evaluation of visual augmentation methods for rotorcraft pilots in degraded visual environments. Journal of the American Helicopter Society. 2017; 62(1):1–11.
29. Wang Z, Zheng L, Lu Y, Fu S. Physiological indices of pilots' abilities under varying task demands. Aerosp Med Hum Perform. 2016; 87(4):375–381.
30. Wilke S, Majumdar A, Ochieng WY. Airport surface operations: a holistic framework for operations modeling and risk management. Saf Sci. 2014; 63(3):18–33.
31. Yu CS, Wang MY, Li WC, Braithwaite G, Greaves M. Pilots' visual scan patterns and attention distribution during the pursuit of a dynamic target. Aerosp Med Hum Perform. 2016; 87(1):40–47.