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The Effects of Adaptive Automation on Pilots' Flight Control Performance and Visual Attention Distribution

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Abstract. Adaptive automation, the scheme to allocate power of control between the automation system and the human operator dynamically and flexibly depending on situations, has been studied in multiple disciplines recently. It is expected to alleviate the Out-Of-The-Loop (OOTL) phenomenon of human operators through occasional handover. However, the effectiveness and impacts of adaptive automation on human pilots in aviation scenarios are still unrevealed. To partially fill this gap, this study will investigate how the preset handover affects pilots' emergency-handling performance and psychophysiological alteration. The emergency-handling performance will be measured by the aircraft control behaviours recorded by the flight simulator, and the psychophysiological alteration will be assessed based on eye movements recorded by the eye-tracker. Twenty-six student pilots were recruited to participate in a comparative experiment consisting of two simulation flight tasks in a flight simulator. Compared with the control flight which performs autopilot during the whole cruising phase, the adaptive automation mode requires the pilots to conduct twice manual piloting at preset time points. Finally, an identical engine shutdown is triggered in each flight to assess the pilots' emergency-handling performance. As a result, the aircraft control behaviours data of the adaptive automation mode demonstrates a significant superiority and the eye movements data also presents several indicative divergences. This study reveals the natural human responses to the handover between autopilots and human pilots. The results can serve as a foundation for further developing the autopilot into the adaptive automation paradigm.

Keywords. Adaptive automation, flight safety, pilot performance, visual behaviours

Introduction

The development of sophisticated autopilot systems and flight management functions in aviation has mitigated the risk of human errors by taking over pilots' manual flight operations [1]. Using autopilots and flight management systems (FMS), many flight operations are automated, such as maintaining aircraft control, navigation, information presentation and fuel management, to reduce pilot workload and reduce the possibility of human-caused air accidents [2]. Nevertheless, pilots may be gradually disconnected from the loop of control as a result of advanced automation. Studies have found that pilots exposed to high levels of automation may lose focus, vigilance, and situational

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awareness over time, resulting in increased fatigue and lower skill levels [3]–[5]. These detrimental impacts on human performance brought on by the absence of human operation are described as Out-Of-The-Loop (OOTL) phenomenon.

The OOTL phenomenon appears in numerous fields where automated technologies take over duties that were originally performed by human operators [6]. Though the operators' overall operation skill level is maintained or even enhanced through years of routine training and experience accumulation, the OOTL impairs their performance in the course of a single operation. Adaptive automation (AA) is hence proposed to mitigate such issues by adopting transdisciplinary engineering knowledge (i.e., control theory, ergonomics, industrial knowledge, etc.) [7]. AA systems adjust their functions or operations automatically according to their monitoring of the users' needs and mental state [8], [9]. Although many studies suggested that AA has significant effects on the performance of compensatory tracking tasks or air traffic controlling tasks [10], [11], few studies have investigated the impact of AA on the pilots' flight control performance. Additionally, though several existing studies have verified AA's effect on the subjects' performance measured by obstructive methods such as Electroencephalography (EEG) and Functional near-infrared spectroscopy (fNIRS) [3], [12], whether the eye movement will also be impacted by AA remain to be discovered. Therefore, we examine the effect of AA on pilots' both flight control performance and visual attention distribution.

Compared with EEG and fNIRS, eye-tracking is an effective tool to monitor mental state and assess the pilots behaviours since it can capture pilots' visual attention distribution in a nonobstructive and real-time way [13]. Therefore, this study leverages eye movement data with the aircraft controlling data provided by flight simulators to examine the effect of AA on pilots' flight operation performance from both the operational perspective and the psychological perspective. An experiment is conducted where the subjects are required to conduct two comparative flying tasks in the flight simulator wearing an eye tracker. Based on the recorded data and analysis result, two hypotheses are tested: (1) the adaptive automation mode has a positive effect on pilots' flight control performance; (2) the adaptive automation mode has a significant impact on the pilots' visual attention distribution

The study reveals the effects of adaptive automation on pilots' flight control performance from both the operational perspective and the psychological perspective. The major contribution of this study is providing a groundwork to develop practical adaptive automation systems for FMS utilizing eye-tracking technologies thereby mitigating the OOTL phenomenon experienced by pilots. Furthermore, the findings and conclusions can also be extended to other human-automation collaboration scenarios, especially transportation areas such as the autonomous driving [6], [14].

1. Related work

An adaptive automation (AA) system allows the level or mode of automation or the number of automated systems to be modified in real-time [9]. As a result of AA, the human operator and/or machine can change the level of automation by shifting control of specific tasks according to predefined conditions [15]. The AA system is expected to realize a human-automation symbiosis to optimally leverage human skills while also achieving production efficiencies in Industry 4.0 [16]. For example, Bortolini et al. [17] presented an assembly system to reconfigure in real-time, allowing a reduction of the movements during the picking and assembly phases in the manufacturing industry.

Early research studies have examined the effectiveness of AA on system monitoring, tracking, and resource management tasks of the pilot [18], [19]. Prinzel III et al. [20] reported significantly superior performance and lower workload associating AA with psychophysiological self-regulation training in several flight control tasks. A more recent study implemented the concept of AA in the domain of military aviation and concluded a beneficial influence in helicopter flying tasks [21]. Besides, Flumeri et al. developed a system called "Vigilance and Attention Controller" based on EEG and eye-tracking (ET) to evaluate the vigilance level of Air Traffic Controllers (ATCs) and adaptively adjust the automation tasks [22], which have optimized the ATCs working performance.

To study the pilots' flight control performance, researchers have adopted various measurements, such as pitch angle, heading, and airspeed [23]. In the meantime, eye-tracking has been adopted in recent studies as an assistive method to assess pilots' operation performance by analysing their gaze patterns under different conditions [24].

Despite AA has been verified to be beneficial in various aviation tasks, the effect of AA on pilots' aircraft control performance still remains to be undiscovered. Furthermore, though the pilots' gaze patterns have been studied in several different conditions to assess the pilots' performance, the effect of AA on visual attention distribution remains unknown. Therefore, this current study examines the effect of AA on pilots' flight control performance and visual attention distribution.

2. Methods

2.1. Participants

Twenty-six students (22-32 years old, 17 males, 9 females), with normal or corrected-to-normal vision, were recruited from The Hong Kong Polytechnic University (PolyU), The Chinese University of Hong Kong, and the City University of Hong Kong to conduct the experiment. An introduction and practice session is arranged before the formal experiment to make sure all the participants are capable of completing the normal flying process and dealing with the frequent issues that might happen during the simulated flying. The study is ethically approved by the PolyU Institutional Review Board (Reference number: HSEARS20211117002) and Pre-experiment informed consent is obtained from all subjects in written form.

(a) Cessna 172 flight simulator (b) Tobii Pro Glasses 3 (c) Desktop computer

Figure 1. Experiment setting.

2.2. Experiment setting

The experiment platform consists of a Cessna 172 simulator and a Tobii Pro Glasses 3 to capture the subjects' eye movements. Microsoft Flight Simulator is installed in the Cessna 172 simulator to provide the simulated flying environment. Besides, a desktop computer with a 27-inch monitor (1920*1080 pixels) is utilized for conducting monitoring the flight simulation and recording eye-tracking data Fig.1 shows the experiment settings.

2.3. Experiment procedure

There are two flying modes in the experiment, named auto-pilot (AP) mode and semi-auto-pilot (SAP) mode. Both the AP and SAP mode load the same record and start with ongoing cruising under the auto-pilot function, and an engine-shutdown incident is activated after 42 minutes of flight to examine the subjects' aircraft control performance. Under the AP mode, the auto-piloting function is turned on for the whole cruising phase until the pre-set incident happens. The SAP mode is defined following the concept of AA, which is adaptively handover the control back to the human operator to keep the operator in the loop. Under SAP mode, the auto-piloting function is turned off twice during the flight and requires the subjects to take over and manipulate the aircraft manually for two minutes. After each manual flight, the flight switches back to auto-piloting again, until the predesigned incident happens. The two take-over requests of control in SAP mode are preset at 10 minutes and 30 minutes from the beginning of the flight. Before the experiment, the subjects are not aware of when the engine-shutdown incident will happen, as well as whether and when there are take-over requests. The performance of the sudden incident handling is recorded and evaluated to assess whether the periodical handover could mitigate the OOTL effect and improve incident handling capability.

The experiment is a one-way within-subject design as shown in Table 1. Route 2 is the inverse of route 1 to control the irrelevant variables such as weather and flying distance, and reduces the learning effect of subjects getting familiar with the route in the first run. The subjects will switch to another route and another flying mode for their second runs. This increased the confidence level of the result by preventing the possibility that the subjects are more familiar with one of the routes or they enhanced their flying skill in the former mode.

Table 1. Route assignment to experiment groups.

Group	Route 1: Hong Kong to Guangzhou	Route 2: Guangzhou to Hong Kong
Group A (size: 13)	AP mode	SAP mode
Group B (size: 13)	SAP mode	AP mode

The whole experiment lasts for around 2 hours with two simulation flights as shown in Fig. 2. The flow starts with a brief session to introduce the experiment procedure to the subjects, get the signed consent form, and calibrate the eye tracker. After the brief session, the participants were given time for practicing the simulator until both the subjects and the researchers are satisfied with the familiarity. For group A, the simulation flight task of route 1 starts upon the completion of the practice conducted with AP mode. After completing the flight of route 1, the participants have a 10-minute break to reduce the impact of fatigue on the second simulation flight. Next, the second simulation flight is conducted in SAP mode with twice scheduled 2-minute handovers from auto-piloting mode to manual manipulation during the process. Group B takes the adverse sequence of group A during the experiment as shown in Fig. 2.

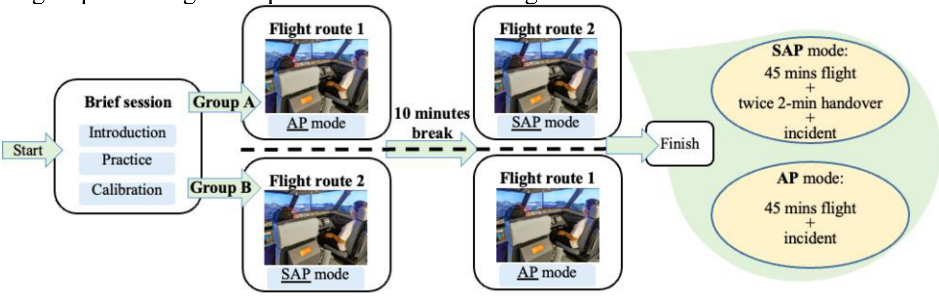

Figure 2. Experiment process.

2.4. Flight control performance

The flight control performance is defined based on the pitch and row angle of the aircraft in the landing phase as shown in Fig.3. After the engine shutdown, the aircraft loses power and the altitude gradually decreases. The task of the subjects is to manipulate the joysticks of the simulator to keep the pitch and row angle as small as possible to keep the aircraft stable in this landing phase.

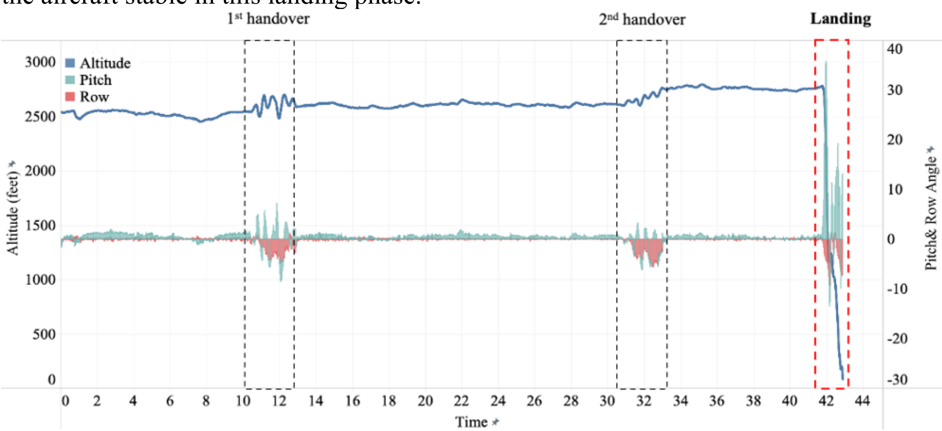

Figure 3. Flight with SAP mode.

Two pairs of indexes are extracted and computed to assess the subjects' flight control performance. The Average Pitch (A_p) and Average Row (A_r) are defined in Equations 1 and 2 to evaluate the overall pitch and row level of the aircraft in the landing phase (t_s: timepoint when the engine shuts down, landing starts; t_l: timepoint when landed). The smaller the A_p and A_r are, the more flat the aircraft is during the landing.

$$A_p = \frac{\sum_s^l |p_i| * \Delta t_i}{t_l - t_s} \tag{1}$$

$$A_r = \frac{\sum_s^l |r_i| * \Delta t_i}{t_l - t_s} \tag{2}$$

$$\Delta t = t_i - t_{i-1}$$

p_i: Pitch value at sampling point i, $-180 < p_i < 180$
r_i: Row value at sampling point i, $-180 < r_i < 180$

The Fluctuation Pitch (F_p) and Fluctuation Row (F_r) are defined in Equations 3 and 4 to evaluate the variance of pitch and row angles in the landing phase. With smaller F_p and F_r, the aircraft is more stable during the landing phase with fewer extreme flips.

$$F_p = \frac{\sum_s^l (p_i - A_p)^2}{l-s} \tag{3}$$

$$F_r = \frac{\sum_s^l (r_i - A_r)^2}{l-s} \tag{4}$$

2.5. Visual attention distribution

To assess the subjects' visual attention distribution, six Areas of Interest (AoIs) were defined as shown in Fig.4. In particular, four indicators on the panel that provide digital information about the current flight state are selected: ① attitude indicator (ATT); ② altimeter (ALT); ③ airspeed indicator (SPD); ④ vertical speed indicator (VSPD). The screen view, which presents the simulated flying scenario and provides the subjects with a direct sense of the aircraft's posture relative to the horizon, is also defined as two AoIs: ⑤ the nose of the aircraft on the screen (Nose); ⑥ the outside window(OTW), which is the remaining part on the screens.

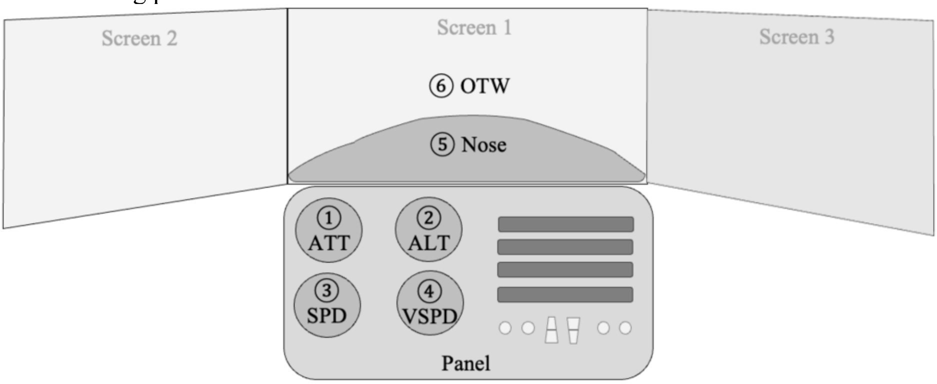

Figure 4. AOI separation on the conceptual cockpit of Cessna 172 simulator.

The total glance count and average glance duration of each AoI are measured to exhibit the subjects' visual attention distribution. A single glance covers from the 1st saccade into the AoI to the last saccade in (leaving) the AoI. (Saccade is ballistic movements of the eyes that abruptly change the point of eye fixations.) The total glance count to an AoI indicates the semantic importance [25] including the effort to refresh and confirm the information [26], [27]. Despite the influence of AoI size, the average glance duration suggests the level of interest towards the AoI [28].

3. Results and discussions

3.1. Flight control performance

All the twenty-six subjects completed the two flight tasks and 52 flight performance data were collected (26 AP, 26 SAP). The results shown in Fig. 5 and Fig. 6 reveal a positive effect of the SAP mode on the flight control performance of the student pilots.

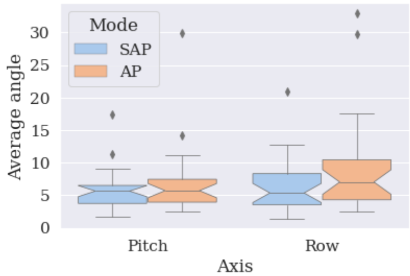

Figure 5. Average Pitch (A_p) and Average Row (A_r).

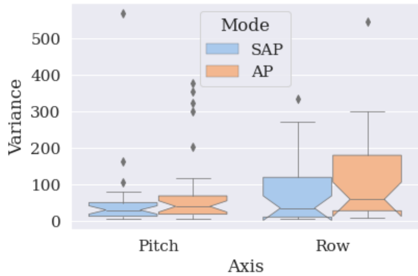

Figure 6. Fluctuation Pitch (F_p) and Fluctuation Row (F_r).

More specifically, a paired t-test is conducted on the four indicators introduced above in order to understand the influence of flying mode on flight control performance. The t-test shows A_p under SAP mode (M = 5.79, SD = 3.26) and AP mode (M = 6.86. SD = 5.44) had no significant difference ($t(25) = -1.32, p = 0.199$). However, the A_r under SAP mode (M = 6.37, SD = 4.22) is significantly smaller than under AP mode (M = 9.21. SD = 7.63) with $t(25) = -2.22$, $p = 0.036$. It suggests the student pilots could keep the aircraft at a more stable attitude on the row axis under the SAP flying mode. Besides, the F_p under SAP mode (M = 58.79, SD = 109.85) is smaller than under AP mode (M = 115.34, SD = 207.87) with a significant difference ($t(25) = -2.36, p = 0.027$). Similarly, significant difference ($t(25) = -2.16, p = 0.041$) is found between the F_r under SAP mode (M = 126.83, SD = 250.21) and AP mode (M = 251.14, SD = 445.43). It suggests the student pilots kept the pitch and row angles more constant making less fluctuation during the landing phase in SAP mode. From the results obtained, the first hypothesis is supported that the adaptive automation mode has a positive effect on pilots' flight control performance.

3.2. Visual attention distribution

After filtering out 10 records from 5 subjects whose eye-tracking rates are too low (below 85%), a total of 42 records from 21 subjects were summarized and analyzed. Table 2 and Table 3 show the t-test results of total glance count and average glance duration, respectively. It is worth to be mentioned that all the data of the cruising phase in the SAP mode have excluded the two manual operations, which means all the data in the cruising phase represents the subjects' behaviours only under the automation control. Correspondingly, the data in the AP mode at the same time have also been excepted to guarantee the same total sampling time for the cruising phases.

Table 2. Total glance count and average glance duration of AoIs.

AoI	Flying Phase	Total glance count (#)			Average glance duration (MS)		Significance
		AP	SAP		AP	SAP	
ALT	Cruising	34.4 (19.7)	72.7 (52.7)	t = -3.56 p < .001*	745.3 (462.9)	760.1 (341.9)	t = -0.17 p = .434
	Landing	6.6 (6.5)	4.5 (5.0)	t = 1.31 p = .102	690.2 (537.3)	425.0 (258.1)	t = 2.47 p = .011*
ATT	Cruising	60.7 (33.9)	139.3 (81.2)	t = -4.96 p < .001*	685.1 (377.0)	820.3 (380.2)	t = -1.74 p = .048*
	Landing	10.8 (8.1)	12.5 (14.4)	t = -0.50 p = .313	741.0 (802.2)	741.7 (733,4)	t = -0.01 p = .498
SPD	Cruising	33.9 (18.3)	39.7 (21.9)	t = -1.19 p = .124	798.6 (415.0)	702.5 (352.4)	t = 2.01 p = .029*
	Landing	2.3 (3.3)	1.3 (1.9)	t = 1.94 p = .034*	292.7 (300.0)	175.2 (224.2)	t = 1.57 p = .066
VSPD	Cruising	10.8 (11.4)	31.3 (44.0)	t = -2.28 p = .017*	625.7 (516.5)	661.7 (419.0)	t = -0.39 p = .351
	Landing	3.8 (6.7)	2.6 (4.7)	t = 1.16 p = .131	232.4 (346.9)	231.5 (342.6)	t = 0.01 p = .50
Nose	Cruising	649.3 (350.2)	630.9 (300.1)	t = 0.31 p = .381	860.7 (452.8)	980.8 (552.3)	t = -1.13 p = .136
	Landing	55.7 (32.0)	53.1 (35.1)	t = 0.29 p = .389	1485.7 (911.5)	1619.6 (1802.1)	t = -0.38 p = .354
OTW	Cruising	1020.3 (517.0)	859.8 (392.0)	t = 2.90 p = .004	1393.2 (814.7)	1510.1 (872.6)	t = -1.06 p = .151
	Landing	52.6 (26.2)	53.4 (38.5)	t = -0.09 p = .464	1221.2 (808.9)	1369.9 (892.8)	t = -0.765 p = .226

From Table 2, no significant difference is found in the landing phase except the total glance count of SPD and the average glance duration of ALT. However, the total glance counts of both AP and SAP modes during the landing phase are too few to make a confident enough conclusion as shown in Table 2. Therefore, a conclusion can be made that the visual attention distribution during the landing phase is similar under the two modes. However, many significant differences can be found in the cruising phase, including the glance count of ATT, VSPD, and OTW, as well as the average glance duration of ATT and SPD. More specifically, the subjects reduced their glance to the outside window and paid more glances and longer glance duration to the attitude indicator under the SAP mode. Possibly this is due to the reduced glances to the outside window (possibly in a daze), which are lower in SAP mode than in AP mode. These results support the second hypothesis that the adaptive automation mode has a significant impact on the pilots' visual attention distribution.

4. Conclusions

In this study, we adopted the theory of psychology, aviation industry knowledge, and analytical methods from engineering to investigate the impact of AA on aircraft control. An SAP flying mode including preset automation-manual handovers is introduced following the concept of AA to keep the pilots in the loop during auto-pilot. The student pilots' flight control performance and visual attention distribution are recorded by the simulator and eye-tracker to examine the effect of SAP mode compared to the AP mode which applies auto-pilot for the whole cruising phase. The pitch and row angles in the landing phase are measured to assess the subjects' flight control performance. The total glance count and average glance duration of six crucial AoIs related to flight control are computed to reflect the subjects' visual attention distribution. The results indicated that AA mode influences visual attention distribution during the cruising phase of the flight and improves flight control performance in the after-incident landing phase.

One limitation of this research is the automation-manual handover time is preset rather than accurately activated when the subject is out of the loop, as there still lacks a precise method to define when and how much a human operator is experiencing an OOTL effect [29]. Future studies will be conducted on revealing the relationship between pilots' visual attention distributions and flight control performance under different flying modes. Furthermore, an AA method based on eye-tracking technologies is expected to be developed and facilitate the implementation of AA systems in the cockpits.

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