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Comparative Analysis of Pilot Workload in Dual-Pilot and Intelligent-Assisted Single-Pilot Operations

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Abstract. With the development of aviation automation and artificial intelligence, Single-Pilot Operations (SPO) have gradually become an important research direction for future civil aviation. Compared with conventional dual-pilot operations, SPO reduces the number of pilots in the cockpit, but the original flight tasks do not disappear. Instead, these tasks need to be redistributed among the single pilot, automated systems, and necessary ground support. Therefore, mitigating pilot workload arising from such task redistribution constitutes a key challenge for the development of SPO. Based on existing studies, this paper compares conventional dual-pilot operations with intelligent-assisted SPO, with particular attention to relatively high-workload phases such as approach and landing. The comparison focuses on three aspects: task distribution and quantity, task difficulty and time pressure, and task sequence and interaction. Through these dimensions, the paper examines how changes in crew configuration and task redistribution affect pilot workload and further discusses the role of intelligent assistance in workload management under SPO. The analysis suggests that the transition from dual-pilot operations to SPO primarily changes the distribution of tasks and workload. Without sufficient assistance, a single pilot may experience greater workload because more tasks can become concentrated on one person. Intelligent assistance can take over some monitoring, information-processing, and support functions, allowing tasks and attentional resources to be distributed more effectively. However, existing evidence remains insufficient to establish that intelligent assistance necessarily reduces the overall workload of SPO below that of conventional dual-pilot operations. Therefore, the development of intelligent-assisted SPO should focus on effective human–automation task allocation rather than simply increasing the level of automation.

Keywords: Single-Pilot Operations, Pilot Workload, Intelligent Pilot Assistance, Task Allocation, Comparative Analysis

1. Introduction

As cockpit automation continues to advance, Single-Pilot Operations (SPO) have received increasing attention as a possible direction for future civil aviation crew configurations. Conventional commercial transport aircraft generally operate with two pilots who share responsibilities such as flight control, navigation, communication, and system management [1]. Moving from dual-pilot operations to SPO does not eliminate these responsibilities. Instead, the

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existing tasks need to be redistributed among the onboard pilot, automated systems, and necessary ground support [1, 2].

This change in task allocation makes pilot workload a central issue in SPO research. Under conventional dual-pilot operations, two pilots can divide tasks, monitor each other, and work together during flight. When the cockpit crew is reduced to a single pilot, certain tasks previously divided between two crew members or executed in parallel tend to concentrate on the sole operator. Simulation research by Bailey et al. found significantly higher workload under SPO than under two-crew operations with current-day flight deck technology. Task shedding may also occur under demanding conditions [3]. Therefore, the development of SPO involves more than merely reducing crew size; it also requires systematic optimization of task redistribution and thorough assessment of its impacts on pilot workload.

Intelligent assistance offers one possible way to address this problem. Previous research has proposed functions such as pilot-state monitoring, environmental and operational monitoring, adaptive alerting, and dynamic task allocation, allowing automated systems to take over some monitoring, information-processing, and support tasks [1]. However, higher automation levels do not necessarily translate to reduced pilot workload. Automation changes the pilot's operational and cognitive roles, while the pilot must still monitor and understand system behavior. Poor human–automation task allocation may even introduce additional cognitive demands [4, 5].

Based on these considerations, this paper does not assume that intelligent-assisted SPO necessarily produces lower workload than dual-pilot operations. Instead, it compares the task allocation and operational processes of the two configurations based on findings from existing literature. Previous studies have used measures such as the NASA Task Load Index (NASA-TLX) and Heart Rate Variability (HRV) to compare pilot workload across different phases of flight. Their results have identified relatively high overall workload during approach and landing, although subjective and objective measurements do not always agree across individual pilots [6]. Therefore, this paper uses approach and landing as representative high-workload conditions and examines the effects of crew configuration on pilot workload from three perspectives: task distribution and quantity, task difficulty and time pressure, and task sequence and interaction. It then considers the role and limitations of intelligent assistance in this redistribution of tasks.

2. Task redistribution from dual-pilot operations to intelligent-assisted SPO

A basic feature of conventional dual-pilot operations is the ability to distribute flight tasks between two flight crew members. Liu et al. noted that in current two-pilot commercial aviation operations, the Pilot Flying (PF) and Pilot Non-Flying (PNF) share four fundamental duties: aviate, navigate, communicate, and manage [1]. The two pilots can execute differentiated tasks while conducting mutual monitoring and coordinating operational actions in response to dynamic mission demands. The importance of the dual-pilot configuration therefore lies not only in the presence of two pilots in the cockpit, but also in its ability to divide tasks and perform some activities in parallel.

These fundamental flight responsibilities remain when operations shift from a two-pilot crew to SPO. The conceptual framework proposed by Bilimoria et al. indicates that the transition toward SPO requires the redistribution of existing crew functions. Some functions previously performed by the second pilot need to be reassigned to the onboard pilot, automated systems, or ground support [2]. Accordingly, SPO should not be merely regarded as a simplistic removal of the second crew member. More importantly, it represents a change in the original task-allocation structure.

Intelligent assistance further contributes to this redistribution. For example, the Cognitive Pilot-Aircraft Interface (CPAI) proposed by Liu et al. includes pilot-state monitoring, environmental and

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operational monitoring, adaptive alerting, and dynamic task allocation. These functions aim to adjust system support according to pilot condition and operational demands [1]. Intelligent assistance, therefore, does not simply replace a particular pilot with a fixed set of automated functions. Instead, it provides a technical basis for dynamically reallocating tasks under different operating conditions.

From this perspective, conventional dual-pilot operations and intelligent-assisted SPO represent two different task-allocation structures. The conventional configuration relies mainly on task sharing, coordination, and mutual monitoring between two pilots. Intelligent-assisted SPO, in contrast, requires tasks to be reorganized among a single pilot, intelligent systems, and necessary ground support [2, 7]. A valid workload comparison between the two configurations must clarify which tasks are transferred to automated systems or ground stations, which remain assigned to the single pilot, and whether the new task allocation induces task concentration during high-demand flight phases.

3. Comparative analysis of pilot workload

Pilot workload does not depend on a single factor. Task quantity, complexity, time pressure, and relationships among different tasks can all influence the cognitive demands placed on a pilot. Existing workload studies have consequently used subjective assessments, flight-performance measures, and physiological indicators to evaluate this complex variable [4, 6]. Comparing only the total number of tasks under dual-pilot operations and SPO would therefore provide an incomplete picture of workload changes. Drawing on task-analysis approaches reported in existing SPO research, this paper compares the two configurations through task distribution and quantity, task difficulty and time pressure, and task sequence and interaction.

3.1. Task distribution and quantity

Under dual-pilot operations, flight tasks can be distributed between two pilots and, to some extent, performed simultaneously. While one pilot is primarily responsible for aircraft control, the other undertakes monitoring, communication, checklist verification, and other supportive flight tasks [1, 3]. This division not only reduces the number of tasks handled by each individual at a given time but also allows the pilots to monitor one another and adjust their task allocation when operational demands suddenly increase.

Under SPO, the original flight tasks still need to be completed, but one pilot has limited time and cognitive resources for handling multiple tasks simultaneously. Bailey et al. observed task shedding under some demanding and abnormal SPO conditions, in which lower-priority tasks could be delayed or temporarily omitted [3]. Li et al., in an experimental comparison involving abnormal and emergency conditions, also found that pilots operating without first-officer assistance showed increased cortical activity during more complex emergencies, together with changes in visual attention distribution [8].

Workload changes during the transition to SPO therefore cannot be evaluated simply by counting the total number of flight tasks. A more important consideration involves how many tasks must be handled by the same pilot at the same time and how activities that could previously be performed in parallel by two pilots are reorganized. One potential function of intelligent assistance involves taking over selected monitoring and information-processing tasks, thereby reducing the concentration of simultaneous demands on the single pilot [1, 9].

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3.2. Task difficulty and time pressure

Task quantity alone cannot fully represent pilot workload. Even when two operational configurations require similar tasks, the complexity of those tasks, whether several demands occur simultaneously, and the time available for completing them can substantially influence workload [3, 4].

During dual-pilot operations, the two pilots can redistribute responsibilities when task demands suddenly increase. For example, one pilot may continue the primary flying task while the other handles monitoring, communication, or abnormal procedures. Under SPO, several demanding tasks occurring within a short period may place greater pressure on the single pilot's available time and cognitive resources. The increased workload in SPO does not necessarily stem from elevated difficulty of individual tasks but from the concentration of multiple concurrent tasks within the same operational time window.

This issue also explains the potential value of adaptive intelligent assistance. Brand and Schulte investigated adaptive support that changes task assistance according to factors such as the task situation, pilot workload, and attention [5]. Zhang et al. also found that the role assigned to automation can influence task-completion performance, with its effects depending on specific workload and task conditions [10]. Importantly, these studies do not all examine civil SPO directly. They are therefore used here to illustrate general mechanisms of adaptive intelligent assistance rather than as direct evidence that such systems have already reduced workload in civil SPO. For intelligent-assisted SPO, the more important questions concern when the system should intervene, which tasks it should perform, and whether this intervention actually reduces task conflicts during periods of high workload.

3.3. Task sequence and interaction

In addition to task quantity and difficulty, the sequence of task execution, dependencies among tasks, and interactions between different participants may also affect workload. In their review of civil SPO research, Puca and Guglieri reported that previous studies have applied task decomposition to approach-and-landing scenarios and used structured task descriptions to examine logical relationships among tasks. Methods such as Operational Event Sequence Diagrams (OESDs) have also been used to represent the timing and sequence of operational activities [7].

This paper does not construct a new OESD or Cognitive Work Analysis (CWA) model. Instead, it draws on the task-analysis principles reflected in previous studies and treats task sequence and interaction as dimensions for comparing dual-pilot operations with intelligent-assisted SPO. This distinction matters because changing the crew configuration affects not only who performs a task but also how different tasks are coordinated.

Under dual-pilot operations, much of this coordination occurs between the two pilots. Standard procedures, verbal communication, and mutual monitoring allow the crew to coordinate task sequences. When operations shift toward intelligent-assisted SPO, some forms of human-to-human cooperation are replaced by interaction between the pilot and automated systems [2, 7]. Intelligent systems can perform selected monitoring and information-processing tasks, but the pilot must still understand the information provided, decide whether to accept system recommendations, and supervise system status and behavior.

Therefore, the reduction of direct operational tasks does not equivalently lower pilots' cognitive demands. Some workload may shift from direct task execution toward automation supervision and decision-making. A review of pilot performance and workload in modern aviation systems noted

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that increasing cockpit automation has reallocated part of the pilot's cognitive resources from direct operation toward supervisory tasks, making human–automation interaction an important consideration in modern cockpit workload [4]. For SPO, the effectiveness of intelligent assistance therefore depends not only on how many tasks the system can perform but also on whether the resulting task sequence and human–automation interaction remain manageable.

4. Role and limitations of intelligent assistance

Based on the preceding comparison, the primary role of intelligent assistance in SPO can be understood as managing and redistributing workload rather than simply reducing its total level. Intelligent systems can perform selected monitoring, information-processing, and support functions, allowing the single pilot to direct limited attentional and cognitive resources toward more important flight and decision-making tasks [1, 7]. Dynamic task allocation and adaptive automation further provide the possibility of changing the level of support according to actual task demands [1, 10, 5].

However, current experimental evidence does not establish that intelligent assistance necessarily produces a significant reduction in overall SPO workload. The HARVIS pilot-in-the-loop experiment on non-stabilized approaches conducted by Duchevet et al. provides a useful example. The study involved seven professional pilots. The mean workload score was 3.35/5 with digital assistant support and 3.41/5 without it, and the difference was not statistically significant [9]. At the same time, participating pilots reported that delegating some monitoring tasks to the digital assistant freed cognitive resources and allowed them to maintain a broader focus on the approach situation [9]. These findings suggest that intelligent assistance may first change how pilots allocate attention and cognitive resources rather than directly reducing total workload.

In other words, workload redistribution does not necessarily equal workload reduction. This represents one of the main observations emerging from the comparison between dual-pilot operations and intelligent-assisted SPO in this paper.

Intelligent assistance may also introduce new workload demands. As automated systems grow increasingly complex, pilots are still required to interpret and supervise system operational behaviors. Existing research has identified potential concerns such as out-of-the-loop effects, reduced situation awareness, and new workload peaks associated with automation under certain conditions [4, 5]. The HARVIS study also found that pilots could reject or ignore recommendations when the digital assistant did not sufficiently explain the reason for an alert, indicating that trust and system explainability can influence the effectiveness of intelligent assistance [9].

Future development of intelligent-assisted SPO should therefore focus not only on adding automation functions but also on improving task allocation and human–automation cooperation [7]. The system needs to perform appropriate tasks at appropriate times while allowing the pilot to understand system status and retain the necessary judgment and control. In the longer term, SPO and intelligent assistance may contribute to research toward higher levels of aviation automation. At the current stage, however, the more immediate challenge involves developing an effective human–automation task-allocation structure that keeps single-pilot workload within manageable limits.

5. Conclusion

This paper compared pilot workload under conventional dual-pilot operations and intelligent-assisted single-pilot operations. The analysis suggests that the main change associated with the transition to SPO does not come from the disappearance of flight tasks. Instead, tasks previously shared between two pilots need to be redistributed. Because two pilots can divide responsibilities,

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perform some tasks in parallel, and monitor each other, removing one cockpit pilot may concentrate certain tasks and increase single-pilot workload when multiple demands occur simultaneously or under greater time pressure.

The comparison across task distribution and quantity, task difficulty and time pressure, and task sequence and interaction indicates that intelligent assistance can perform selected monitoring, information-processing, and support functions, thereby improving the allocation of tasks and attentional resources for the single pilot. However, current evidence remains insufficient to conclude that the overall workload of intelligent-assisted SPO will necessarily fall below that of conventional dual-pilot operations. More precisely, intelligent assistance primarily reshapes workload distribution patterns rather than ensuring a reduction in overall workload levels.

The future development of intelligent-assisted SPO should therefore emphasize effective task allocation and human–automation cooperation rather than simply increasing automation. Future studies could compare dual-pilot operations with different intelligent-assisted SPO configurations under consistent flight phases and operating conditions, using task quantity, task sequence, and both subjective and objective workload measures. Such comparisons could provide a more precise assessment of how different task-allocation strategies affect actual pilot workload.

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