From Flying to Monitoring in the Future Flight Deck: The Differences in Pilot's Perceived Mental Workload

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Abstract. The perceived mental workload of Single Pilot Operations (SPO), as an emerging trend in commercial aviation, has received significant attention. The objective of this study is to investigate the differences in pilots' perceived mental workload between different role assignments and crew configurations. A total of 57 pilots with commercial pilot licenses participated in this study, undertaking three low-visibility approaches as pilot flying (PF) within a crew setting, pilot monitoring (PM) within a crew setting, and PM within a single-pilot setting, respectively. Their perceived mental workloads were evaluated using the National Aeronautics and Space Administration-Task Load Index (NASA-TLX). The results indicated that pilots experienced higher mental workload when performing as PF within the crew setting compared to their role as PM in both the crew and single-pilot settings. As PMs, compared to the crew setting, pilots reported lower levels of effort in the single-pilot setting while perceiving a higher level of physical demand. The significance of this study lies in providing empirical evidence from the perspective of perceived mental workload regarding the feasibility of normal SPO scenarios.

Introduction

From a perspective of human factors and ergonomics engineering, human errors account for the majority of accidents and incidents in complex human-computer interaction systems (Sant' Anna and Hilal, 2021). As such, over the last fifty years, industrial automation systems have been increasingly focused on decreasing the involvement of human operators in order to improve system safety and save on the cost of human resources. In the aviation domain, the number of crew members has decreased from five individuals, comprising two pilots, a flight engineer, a navigator, and a radio operator, to a mere two, consisting of one pilot responsible for flying and another responsible for monitoring, situated in the commercial airline flight deck. This phenomenon of "de-crewing" has continued, with Single Pilot Operations (SPO) exemplifying this trend of having only one pilot present in the cockpit, assisted by advanced onboard automation systems or remote ground operators (Comerford et al., 2013). Expected to save $1.5 billion around the world, this approach has gained significant traction (Castle et al., 2017).

There are three main kinds of SPO design to replace the human copilot: cockpit-centered design (with the assistance of onboard automation systems), air-ground design (with the assistance of remote ground operator), and the integrating design of cockpit and ground (with the assistance of both air and ground). For cockpit-centered design, the automation systems provide the necessary assistance (e.g., navigation, communication, and monitoring) to the single human pilot in human-AI teaming in normal and abnormal conditions (Lim et al., 2017; Dao et al., 2015). The main concerns of this concept are airworthiness certification and automation failure of the onboard systems (Wang et al., 2023; Matessa et al., 2017). For air-ground design, by relocating the function of copilot to the ground, remote operators provide necessary assistance to the single pilot in cockpit (Johnson et al., 2012; Lachter et al., 2014). The concept of distributed crew largely relies on the real-time information transition from flight deck to ground stations (Harris et al., 2015; Stanton et al., 2016). This concept was further developed based on different ground station organization structures (e.g., hybrid ground operator and specialist ground operator, see Bilimoria et al., 2014; Matessa et al., 2017) and varying flight phases (e.g., departure, cruise, and arrival, see Lachter et al., 2017). By integrating the two original concepts of SPO (i.e., cockpit-centered design and air-ground design), seven combined concepts of SPO were proposed to adapt to different situations (Neis et al., 2018). In these cases, the human single pilot, remote ground operator, and advanced automation systems have to share tasks and responsibilities when needed in both normal and abnormal conditions (Matessa et al., 2017).

However, although there are significant benefits to be obtained from automation systems, it brings new risks that should not be overlooked (Anderson, 2014). For example, advanced automation systems have the tendency to transfer human operators from active controllers to passive supervisors, requiring them to perform monitoring tasks for which they may not possess the requisite skills (Bainbridge, 1983). Over time, prolonged periods of acting as a passive supervisor can lead to human operators experiencing mind-wandering (He et al., 2011), resulting in a high mental workload when required to take over immediately in an emergency. In addition, the unique design and features of automated aircraft pose a challenge in human-machine interaction for human pilots who lack specific training. Human operators can become confused by the state of automation, experience difficulties forming an accurate mental model of it, and encounter unexpected interactions with it (Banks et al., 2018; Endsley, 2017). These human-related risks highlight the crucial role of humans play in increasingly advanced systems and human-centered design of SPO (Bainbridge, 1983; Xu et al., 2022).

Mental workload is widely recognized as crucial for the successful implementation of “de-crewing” strategies (Xu et al., 2022). It refers to the comparison between the cognitive demands imposed upon a human operator for task completion and the available cognitive resources at their disposal (Comerford et al., 2013). Extensive research in this domain has identified psychological, behavioral, and physiological approaches as viable means of quantifying mental workload (Young et al., 2015). The National Aeronautics and Space Administration-Task Load Index (NASA-TLX) is a commonly used psychological measure for evaluating mental workload. It is valued for its user-friendly nature and established validity (Zhang et al., 2009), consisting of six aspects: mental demand, physical demand, temporal demand, effort, performance, and frustration.

Typically, in the modern flight deck, two pilots collaborate as a pilot flying (PF) and pilot monitoring (PM) team to accomplish flight tasks. However, in the future, there is a possibility that a single pilot may only undertake monitoring tasks during normal flight scenarios with the assistance of automation/autonomous systems. According to the NASA’s assessment, Single Pilot Operations (SPO) are acceptable due to human pilots’ adaptability in normal scenarios, but they are not acceptable in emergencies due to high task demand and workload (Bailey et al., 2017). Additionally, the scanning behavior of the PF was also affected by the absence of the PM (Faulhaber et al., 2022). Therefore, the objective of this study is to examine the differences in pilots' perceived mental workload across different role assignments and crew configurations in simulated approaches. We designed an approach task for pilots, requiring them to experience three different settings subsequently. Their perceived mental workload was assessed using NASA-TLX scale. Our initial findings are expected to provide valuable insights into the feasibility of normal SPO scenarios.

Method

Participants

A convenience sample of 57 B737 pilots with commercial pilot licenses (all males) from a Chinese airline was recruited to participate in this research. Their ages ranged from 23 to 36 (M = 25.89, SD = 2.61), and their total flight hours ranged from 52 to 4500 (M = 536.11, SD = 904.07). Participants received no financial compensation for their participation in this experiment. This research was conducted in accordance with the Declaration of Helsinki (1973, revised in 1983) and was approved by the ethics committee of the authors' university. After being informed of their rights, all participants gave their written consent.

Apparatus and scenario

This experiment was conducted in collaboration with a Chinese airline, which provided us with a certified D-level B737-800 Full Flight Simulator (FFS) to ensure precision and accuracy (Fig. 1). We designed three low-visibility approaches, specifically configured as Instrument Landing System Category I (ILS CAT I), for each participant to complete within the FFS. The three approaches encompassed three different settings, representing different role assignments and crew configurations: PF within the crew setting (crew-PF), PM within the crew setting (crew-PM), and PM within the single-pilot setting (single-PM). In the two crew settings, participants were required to perform approach as a PF and PM in the first and second settings, respectively, with the assistance of a flight instructor. In the single setting, participants were required to performed approach as a PM with the assistance of the autopilot systems.

Figure 1. Flight deck of B737-800 FFS.

At the commencement of each approach, the aircraft was positioned at an altitude of 1920 ft, with a heading of 359° and airspeed of 148 kt, and approximately 6 nautical miles away from runway 01 of Jinan airport (airport code: ZSJN). According to regulations from the Civil Aviation Administration of China, participants were required to establish visual references at the decision-making altitude for landing under marginally meteorological conditions.

Measures

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) is a widely used questionnaire for evaluating an individual's perceived mental workload (Zhang et al., 2009). It includes six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Participants rated their subjective feelings on a five-point Likert scale from 1 (very low) to 5 (very high) after completing each flight simulated task, instead of the original 7-point scale. Meanwhile, we used raw NASA-TLX ratings, instead of weighted data, for further analysis. These modifications were chosen for its ease of use and understanding, particularly for professional pilots who may be unfamiliar with such scales (e.g., NASA-TLX weighting does not allow equal importance between two or more dimensions in pairwise comparisons, see Virtanen et al., 2022). The average scores of the six dimensions were calculated to determine the overall perceived mental workload scores.

Design and procedure

We employed a full within-subject design for this study, wherein each participant engaged in six nautical miles approach tasks under VFR minimum conditions. This entailed experiencing three different settings: crew-PF, crew-PM, and single-PM. Prior to commencing the tasks, participants were informed that they would be collaborating with an experienced flight instructor firstly. This flight instructor had undergone pre-trained to act as a PM and PF in the first two approaches, ensuring equal cooperation with each participant. The "single-PM" condition refers to a similar scenario where the pilot assumes the role of PM while the approach is flown by onboard automation systems. In this condition, the onboard automation systems are used for most of the approach, but manual control is required after touchdown. A rest period of 10 minutes was scheduled between consecutive tasks to allow participants to recover from any mental fatigue or carry-over effects.

Throughout the experiment, participants followed a specific sequence of steps (Fig. 2). Initially, they read and signed an informed consent form, signifying their participation in the study. Subsequently, participants received instructions regarding the purpose of this research and their specific task. The experienced flight instructor was introduced to the participants, with whom they would work collaboratively to complete the initial two approaches. Finally, participants served as PM, assisted by autopilot systems, monitoring the parameters of the aircraft and executing the final approach. After each approach, participants were required to assess their perceived mental workload using NASA-TLX scale based on their experiences. The entire duration of the experiment was about one hour.

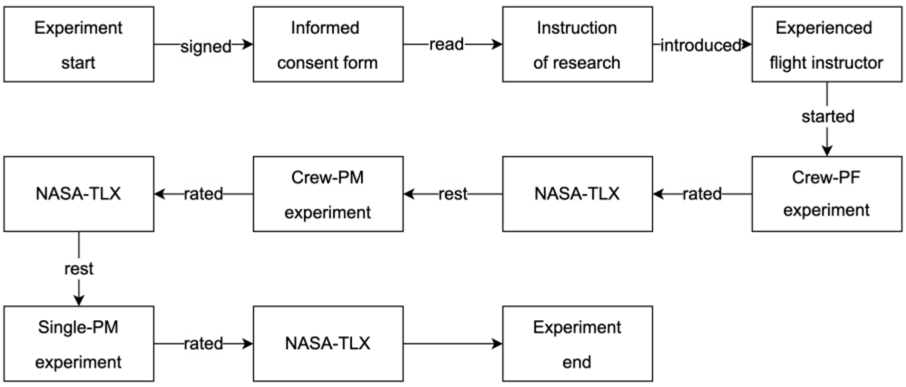

Figure 2. Experimental procedure.

Data analysis

We used SPSS 25.0 (IBM, Armonk, USA) for calculation and analysis. Firstly, we presented the characteristics of our sample, including the mean, median, and interquartile range of the six dimensions of NASA-TLX, as well as the overall NASA-TLX scores in each setting. Secondly, one-way repeated measure ANOVA was performed to examine the differences in pilots' perceived mental workload across different settings. The Shapiro-Wilk's test was used to assess normality assumption violations. Although the initial data did not meet the normality assumption, the normality of the residuals was confirmed. The effect sizes of samples were quantified by partial eta square (η_p^2), and post hoc pairwise comparisons were performed using Bonferroni correction. This correction adjusts the significance level to reduce the likelihood of Type I errors, ensuring the robustness of our findings. Due to the technical issues with the full flight simulator, we were unable to obtain any flight data for further analysis.

Results

The violin plot (Fig. 3) demonstrates the distribution of mental workload metrics across three different settings. Compared to the PM settings (crew and single), most participants rated their physical demand, temporal demand, effort, frustration, and overall NASA-TLX higher in crew-PF setting. Regarding mental demand, the median values in the two crew settings (PF and PM) are same as four, higher than in single-PM with a median value of three. Additionally, the median values of performance in the three settings were three.

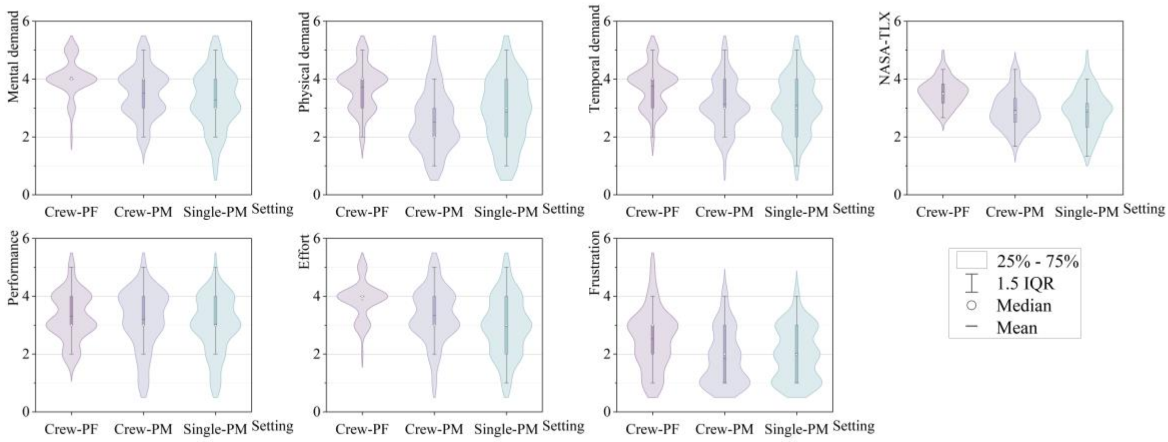

Figure 3. Distribution of Mental Workload Metrics across the Three Settings. IQR = interquartile range.

The bar chart (Fig. 4) shows the differences in mental workload across three different settings. All dependent variables meet the Mauchly's test of sphericity. The results of the one-way repeated measures ANOVA indicated significant differences in participants' perceived mental demand across the three settings ($F_{(2,112)} = 22.77$, $p < 0.001$, $\eta_p^2 = 0.289$). The post hoc pairwise comparison revealed that the perceived mental workload in the crew-PF setting (4.05 ± 0.61) was significantly higher than that in the crew-PM (3.52 ± 0.83) ($p < 0.001$) and single-PM (3.28 ± 0.96) ($p < 0.001$) settings. Similarly, there were significant differences in participants' perceived physical demand ($F_{(2,112)} = 36.18$, $p < 0.001$, $\eta_p^2 = 0.393$), temporal demand ($F_{(2,112)} = 17.52$, $p < 0.001$, $\eta_p^2 = 0.238$), effort ($F_{(2,112)} = 25.70$, $p < 0.001$, $\eta_p^2 = 0.315$), frustration ($F_{(2,112)} = 11.15$, $p < 0.001$, $\eta_p^2 = 0.166$), and overall NASA-TLX ($F_{(2,112)} = 35.37$, $p < 0.001$, $\eta_p^2 = 0.387$) scores across the three settings. The post hoc pairwise comparisons are shown in Fig. 2. There was no significant difference in performance across the three settings.

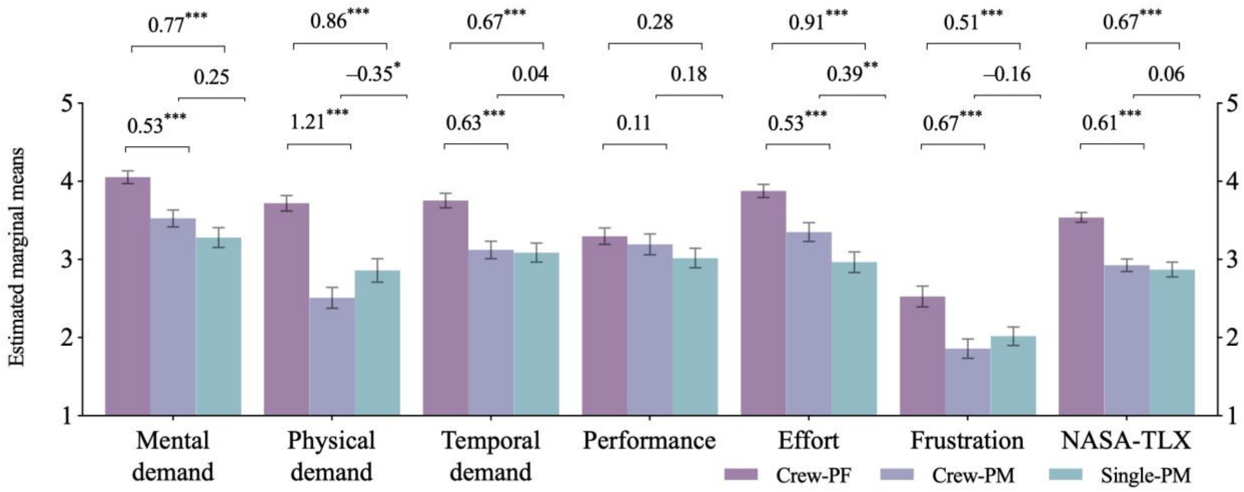

Figure 4. Estimated Marginal Means of Mental Workload Metrics across Three Different Settings. Error Bars: ± S.E. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

Discussion

The aim of this study was to compare the differences in pilots' perceived mental workload across varying crew configurations (crew vs. single-pilot) and role assignments (PF vs. PM) in the context of low-visibility approaches in Level-D FFS. By using the NASA-TLX scale, pilots' perceived mental workload was recorded and evaluated, providing valuable insights into their experience in specific flight scenario.

The responsibility of a PF is to control and maneuver the aircraft, while the responsibility of a PM is to monitor the PF's actions and perform other tasks in flight, such as communication, navigation, and system management. According to the results of one-way repeated measure ANOVA, pilots experienced a higher level of mental workload when performing as the PF within the crew setting, compared to their roles as PM in both the crew and single-pilot settings. And this level of perceived mental workload (3.54/5) was far above average rating of piloting aircraft (47.78/100), reaching the highest level (74/100) in Grier (2015)'s metanalysis. This finding suggests that the operational demand of the PF within a crew setting contributes to a high level of mental workload, which has the potential to result in human errors (Dehais et al., 2017). It is also the need for establishing an appropriate function allocation in mitigating the PF's high mental workload with the assistance of advanced automation systems (Schmid and Stanton, 2020). In addition, the overall ratings of NASA-TLX within the crew-PM (2.93/5) and single-PM (2.87/5) settings were similar with an equal level of monitoring tasks (52.24/100) in Grier (2015)'s metanalysis. This finding aligns with the results from NASA, as they found no influence of non-verbal interaction on crew performance (Lachter et al., 2014).

Interestingly, when serving as PMs, pilots reported lower levels of effort in the single-pilot setting compared to the crew setting. This might be attributed to the absence of cross-checks within the single-pilot setting, such as pilot-to-pilot communication, callouts, and briefings, which are very important for maintaining appropriate arousal and avoiding undesirable states like boredom and distraction. However, despite the lower effort required, pilots perceived a higher level of physical demand in the single-pilot setting. For the single-pilot setting, Faulhaber et al. (2022) demonstrated that the presence of PM contributed to the PF's effective visual behaviors. Our results indicated that the absence of PF may increase the PM's perceived physical demand, which is consistent with pilots' mental model. This finding highlights the need for appropriate support systems and resources in the flight deck to mitigate the perceived physical demands in future single-pilot scenarios (Faulhaber, 2019). For example, the human pilot can be assisted by a virtual pilot to complete a series of tasks such as navigation, communication, and monitoring in the single-pilot setting (Lim et al., 2017). In an emergency, the Emergency Landing Planner (ELP) could also provide the best diversionary airport for the human pilot (Dao et al., 2015). With the assistance of autonomous systems, the role of the single pilot will be transferred from "operator" to "manager" (Harris, 2023).

There are three main limitations that should be noted in this study. Firstly, the sample size was not very representative, which may limit the generalizability of our findings. Future studies with larger and more diverse samples would be beneficial to validate and extend these findings. Secondly, this study focused solely on low-visibility approaches, which are importance but not represent all flight phases. It would be valuable to investigate pilots' perceived mental workload in other flight phases (e.g., takeoff) and specific SPO scenarios (e.g., human-AI interaction or distributed crew collaboration) across varying role assignments and crew configurations. Thirdly, we followed a fixed sequence order for our professional sample, which could have introduced sequence effects such as learning, carry-over, and fatigue. We recommend that future research should consider employing counterbalancing techniques, such as a Latin-square design, to minimize the potential influence of sequence effects.

In conclusion, this study provides empirical evidence regarding the differences in pilots' perceived mental workload across different role assignments and crew configurations in the context of low-visibility approaches. The findings underscore the significance of effective workload management capability and task allocation strategy in optimizing pilot experience and ensuring the feasibility of normal SPO scenarios. Further research in this area is warranted to explore additional factors that may influence pilots' perceived mental workload and to validate the findings in various flight scenarios.

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