International Journal of Industrial Ergonomics 101 (2024) 103588

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Future flight deck design: Developing an innovative touchscreen inceptor combined with the primary flight display

Yifan Wang [a], Wen-Chin Li [a,*], Wojciech Tomasz Korek [b], Graham Braithwaite [c]

[a] Safety and Accident Investigation Centre, SATM, Cranfield, Bedford, MK430AB, United Kingdom
[b] Dynamics, Simulation and Control Group, SATM, Cranfield, Bedford, MK430AB, United Kingdom
[c] Head of Transport Theme, SATM, Cranfield, Bedford, MK430AB, United Kingdom

ARTICLE INFO

Keywords:
Flight deck design
Human-computer interaction
System usability
Touchscreen inceptor
Visual behaviours

ABSTRACT

The touchscreen has the potential to optimize the space usage and efficiency of the flight deck. Currently, touchscreens can combine the input and output functions of different systems. However, it does not yet serve as an inceptor to replace the sidestick or control column for aircraft manoeuvres. This study aims to examine the potential of a touchscreen as a flight inceptor compared with a traditional sidestick and gamepad. This research recruited 72 participants who interacted with three inceptors for both an instrument landing with disturbance and without disturbance using the Future System Simulator. The findings demonstrated that pilot performance, system usability and pilots' situation awareness of touchscreen inceptors were significantly inferior to those of traditional sidesticks and gamepads. Compared to the sidestick and gamepad, the touchscreen provided a poorer situation awareness with the highest supply and demand. In addition, the performance of all inceptors was significantly influenced by disturbance. There is still a long way to go for certification of a touchscreen as an inceptor on the future flight deck. This research showed that even though the touchscreen inceptor scored the lowest on both SUS and SART, the majority of pilots agreed that the touchscreen inceptor provided a better attentional supply in challenging disturbance circumstances, providing proof of concept for its possible inclusion in flight deck design. There is a potential that the emerging touchscreen as an inceptor may develop further along with human-system integration flight deck design.

1. Introduction

The aviation industry strives to develop innovative technologies for improved cost-efficiency and safety in flight operations. Over the past 40 years, the adoption of 'glass cockpits' in commercial aircraft has led to rapid advancements in flight deck evolution, particularly for smaller jet airplanes (Watkins et al., 2018). Touchscreen technology and multi-functional electronic displays have been introduced to save space and integrate information from various systems, replacing conventional displays with buttons and knobs (Harris, 2016). Currently, the functions of the flight deck touchscreen act mostly as an alternative to the original displays and handle some input tasks, which could save the space otherwise needed for a large number of knobs and buttons. However, there has been little research attempting to use the touchscreen for aircraft handling (Li et al., 2022a, b). Despite the significant advancements from the traditional yoke to the current passive sidestick and active sidestick, the core functionality and physical construction of these inceptors have remained unchanged (Al-Lami et al., 2015). With the development of flight deck innovative technology, civil pilots rarely need to control the aircraft throughout its flight. The potential of touchscreen implementation could enhance human-centered flight deck design by mitigating human factors issues and increasing cost-efficiency. Previous research has investigated various aspects of touchscreen usage in flight decks, such as the different digital key sizes on input efficiency and usability (Kim and Kaber, 2014), the effects of Fitts' Law on touchscreen use (Xie et al., 2022), finger actions for click to type, zoom in and out, drag and drop (Sadia et al., 2022), and the effects of supporting multi-touch actions (van Zon et al., 2020). While current research primarily focuses on click-based tasks like navigation displays, flight management systems, electronic flight bags, and checklists, the touchscreen's potential as an inceptor for flight control has not been well explored. Thus, this study aims to investigate the touchscreen's capability as an inceptor, enabling precise aircraft control through high-level human-machine information exchange, similar to the functionality of

---

* Corresponding author. Safety and Accident Investigation Centre, SATM, Cranfield, Bedford, MK430AB, United Kingdom.
E-mail address: wenchin.li@cranfield.ac.uk (W.-C. Li).

https://doi.org/10.1016/j.ergon.2024.103588
Received 11 July 2023; Received in revised form 27 March 2024; Accepted 11 April 2024

sidesticks on current flight decks.

2. Related work

2.1. The evolution of inceptor in the flight deck

Since the Wright brothers' plane made its inaugural flight, the fundamental principles governing aviation controls have not altered substantially; instead, technology to make them simpler was created. The Wright Brothers created and piloted the first aeroplane in 1903. Avro 504 (1914–1922) was one of the earliest aircraft to employ a double-axis column for control; the pilot was seated and the aircraft had rudder pedals but still used a pulley system. In the 1940s, the Avro Lancaster Bomber introduced hydro-mechanical flight controls to adjust flap positions while retaining the concept of inceptors (such as columns/yokes and rudder pedals) (Islam et al., 2008). Between 1945 and 1960, with further advancements in hydro-mechanical controls, larger aircraft such as the Boeing 707 (1958) were made possible, utilizing hydraulic power to control all three control surfaces. The inceptor concept remained unchanged. In 1969, the Boeing 747 became the first aircraft with a hybrid hydro-mechanical system, incorporating a fully powered and functional actuation system. From 1970 to 1994, the Fly-By-Wire (FBW) system was introduced, replacing manual flight controls with an electronic system. This wired electronic system controlled the hydraulic systems. The Mirage 2000 (1978) is believed to be the first aircraft to feature an FBW stick for control. The main distinction from previous architectures was the reduced force required to operate the stick, although this also presented some challenges. The Airbus A320 (1987) became the first airliner with FBW and sidestick controls, which are still in use today. Since 1994, significant research has been conducted on new Flying and Handling Qualities technologies, including the use of fibre optics instead of wires (Koon, 2020), and the integration of touchscreen controls, as seen in the Gulfstream G500 (2018) (Jensen, 2018). The conventional sidestick has been in use for over 30 years, and although aircraft control systems have undergone significant advancements, the basic principle remains the same. Control surfaces manipulate lift and drag in various directions, providing control over the aircraft. However, there has been limited research specifically focused on the sidestick itself. The sidestick's input logic has remained constant throughout its growth. The original sidestick utilised the input logic of pushing forward for a pitch down and pulling back for a pitch up because it directly controlled the rudder surface through force conduction. However, according to the definition of “Input Equals Output" in Organic User Interfaces design, humans may intuitively be more attuned to moving in the direction of the input command (Vertegaal and Poupyrev, 2008).

2.2. Strengths and weaknesses of touchscreen control

Touchscreens revolutionize human-computer interaction in the flight deck by enabling intuitive and direct manipulation and easier hand-eye coordination (Xie et al., 2022). Unlike traditional knobs and buttons, touchscreens eliminate the need for operators to shift attention between displays, reducing cognitive load (van Zon et al., 2020). The technology mimics mechanical components, enhancing human-computer interface design and alleviating pilots' tasks (Korek et al., 2022). Aviation industries, including Airbus and Boeing, recognize the potential of touchscreens and have researched their implementation to improve pilot performance (Boeing, 2016). Touchscreens combine control input and the system's feedback promoting seamless hand-eye coordination (Albinsson and Zhai, 2003; Tang et al., 2023). They enhance efficiency, reduce human errors, require less training, allow for customizable on-screen buttons, and contribute to a streamlined flight deck design (Bhalla and Bhalla, 2010). Further, the use of touchscreen facilitates the integration of multiple systems and the introduction of new technologies, as it offers a high degree of software compatibility that is not available in traditional flight decks, such as replacing traditional checklists, etc (Nagasawa and Li, 2023).

The implementation of touchscreens in the flight deck could increase cost efficiency but also raise HCI concerns that require further investigation (Korek et al., 2022). Issues include potential display clarity due to light and finger grease and affecting visibility (Robinson et al., 2012; Rouwhorst et al., 2017). Interacting with touchscreens involves a speed-accuracy trade-off, particularly when targeting small or closely located elements which might lead to potential mistouches (Dodd et al., 2014). Safety is a critical concern of using touchscreens in the flight deck, as vibrations and turbulence can impact hand-eye coordination and the accuracy of pilots' operational behaviours. Continuous interaction with touchscreens may lead to hand occlusion, which can impact the precision of flight operations (Alapetite et al., 2018). Research has explored techniques such as braced touch and control algorithms to mitigate these negative effects on touchscreen applications (Cockburn et al., 2019). Furthermore, external disturbances like wind gusts can affect pilot performance, demanding further investigation (Coutts et al., 2019). These factors emphasize the importance of carefully addressing touchscreens' limitations in flight deck design. Future research should focus on mitigating display visibility issues, addressing mistouches, improving performance in vibrating conditions, and accounting for external disturbances. By addressing these concerns, touchscreens could be effectively integrated into flight decks, enhancing overall safety and efficiency in flight operations.

2.3. HCI assessments on touchscreen application

Human-centered design has been investigated to provide intuitive human-computer interactions on the flight deck. The flight deck design philosophy offers guidelines to facilitate HCI between pilots and aircraft systems, which was involved in the allocation of functions between pilots and automated systems (Boy, 2020). The touchscreen may be intuitive to use with one simple touch getting immediate visual feedback but implementing it to control an aircraft for ‘aviate, navigate and communicate’ tasks have to follow the regulatory certification processes. The assessments of touchscreen implementation on the flight deck and its impacts on pilots' operational performance have brought out some concerns (Dodd et al., 2014). On a commercial flight deck, the use of touchscreens facilitated miscellaneous information to be displayed with clearer and neater menus on a customizable interface which is consistent with the proximity compatibility principle (PCP) for flight deck design (Wickens and Ward, 2017). PCP is a critical principle for human-centered flight deck design in single pilot operation (SPO) by integrating different sources of information in close spatial vicinity to facilitate operators using one gaze to catch all critical information (Wickens and Carswell, 2016). The use of touchscreens on the flight deck has been steadily increasing; however, their usability may be relentlessly impacted when disturbance conditions occur (Cockburn et al., 2019).

The usability assessment is a simple and effective approach to ensure the successful implementation of touchscreen technology on the future flight deck in the early stages. The usability of touchscreens on the future flight deck can be measured using the system usability scale (SUS), which is a simple and effective tool to assess user's experience with the usability of innovative design (Vlachogianni and Tselios, 2022). Previous research indicated that turbulence had an impact on pilots' subjective assessment of interaction with the flight deck touchscreen, as their workload increased and the usability ratings decreased while turbulence increased (Wynne et al., 2021). However, the objective measures must be construed with prudence and come together with metrics of workload and usability to allow for a thorough consideration of the impact of the touchscreen design related to the pilot's performance, perceived workload, and system usability. Mental workload and situation awareness are frequently viewed as separate but interrelated constructs. If task performance requires cognitive resources for monitoring and comprehension of the dynamic information, human operators' situation awareness may decrease (Braarud, 2021; Vidulich and Tsang, 2014). The most used for assessing a pilot's SA is the Situational Awareness Rating Technique (SART) which consists of three sub-dimensions: demands on attentional resources, supply of attentional resources, and understanding of the situation (Taylor, 2017). SART is a suitable tool to assess a pilot's situation awareness while interacting with a touchscreen on the flight deck. Pilots' SA may have fluctuations while interacting with flight deck touchscreens in different operational environments, as vibration and disturbance have been proven to increase operators' error rate, task completion time, and perceived workload (Coutts et al., 2019).

2.4. Research gap and research questions

The implementation of a touchscreen on the flight deck can reduce weight and maintenance costs while also enabling rapid software/hardware upgrades (Bandur et al., 2021; Watkins and Walter, 2007). Adding touchscreen functionality would have an impact on pilots' monitoring and operational performance, particularly when viewed under high ambient lighting and vibration conditions (Robinson et al., 2012). Touchscreen specifications for flight deck applications are still evolving, and the HCI requirements are not fully established. So far, touchscreens are being used on the flight deck for information displays and flight management on new-generation aircraft such as Boeing 777X and A350XWB. Nevertheless, research into the use of a touchscreen as an inceptor is still an innovative concept and needs further investigation. As a flight inceptor, the touchscreen has the potential to further optimize flight deck design and contribute to the development of an innovative future flight deck. In digital aviation, there are an extremely varied set of innovative devices and applications with a rich range of experiences offered to operators. Gamepads are emerging as a preferred choice for the manual control of unmanned vehicles, but an understanding of their usability characteristics has yet to emerge (Rupp et al., 2015). So far, neither a touchscreen inceptor nor a gamepad inceptor has been used for flight control on the flight deck. As inceptors, touchscreens could be used as a substitute in the future, improving the effectiveness of single-pilot operations (Dodd et al., 2019) and simplifying flight deck layouts. Furthermore, this experiment is conductive to further exploring the potential of touchscreens in flight deck applications. As an exploratory study, it provides more experience and a basis for subsequent research on touchscreens. In the current research, both touchscreen and Xbox gamepad as inceptors were used, with traditional sidestick as a baseline, to explore the best HCI design for the future flight deck, as participants wouldn't have previous experience on both inceptors in the flight simulator. It can eliminate the practice effect on the trials. Based on the above literature review, there are four research questions that need to be addressed, as follows.

RQ1. How is the pilot performance while using a touchscreen as an inceptor in landing scenarios (with non-disturbance vs with disturbance) compared with a gamepad and traditional sidestick?

RQ2. What is the system usability of the touchscreen inceptor in landing scenarios (with non-disturbance vs with disturbance) compared with a gamepad and traditional sidestick?

RQ3. What is the pilots' SA while using the touchscreen inceptor in landing scenarios (with non-disturbance vs with disturbance) compared with a gamepad and traditional sidestick?

RQ4. Would input logic affect pilots' situation awareness?

3. Method

3.1. Participants

There were 72 participants aged from 21 to 63 years old (M = 31.54, SD = 10.27) with flight hours (M = 753.49, SD = 1817.24), including 18 females and 53 males (one participant decided not to share this information). There are nine commercial pilots, 15 general aviation pilots, and all the other participants who have flight experience with the simulator. All participants were volunteered for this experiment without incentive. The research proposal was approved by the Research Ethics Committee before experimenting with data collection. All participants were informed that this research is investigating human-computer interaction (HCI) on the control inputs using touchscreens in the Future Systems Simulator (FSS). Participants had to sign the consent form, which specified the nature of the research objectives and assured their rights to withdraw from the research at any stage. All collected data only be accessed by the research team and stored following the United Kingdom Ethical Code and the Data Protection Act.

3.2. Apparatus and material

3.2.1. Future Systems Simulator (FSS)

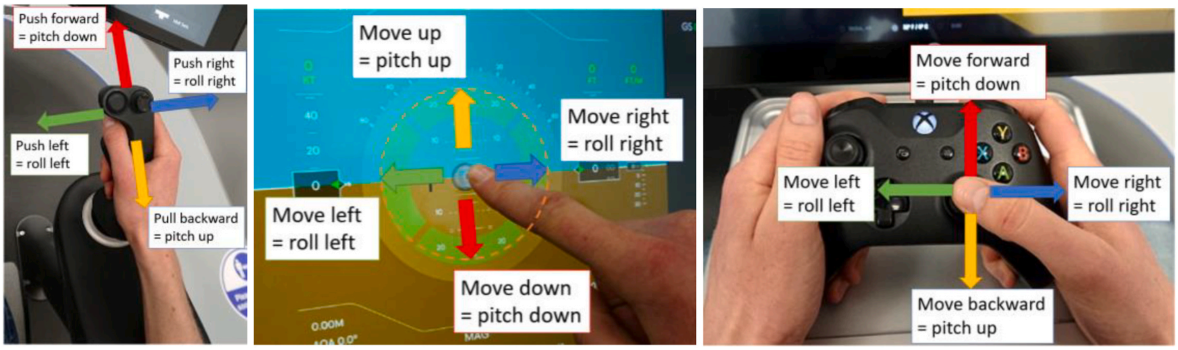
This research was conducted on the engineering flight simulator called FSS, which was developed at Cranfield University in collaboration with Rolls-Royce. FSS provides the flexibility to promptly prototype current and future flight deck configurations. It is a highly reconfigurable flight simulator with repositionable seats, touchscreen displays, sidesticks, and thrust levers (Fig. 1a & b). The Future Systems Simulator provides the ability to quickly model current and future aircraft configurations, as well as design new Human Machine Interfaces to enable pilots to make informed decisions. With reference to the criteria established by the European Aviation Safety Agency (EASA) for commercial flight simulators (European Aviation Safety Agency, 2018), the FSS demonstrates the potential to qualify as a “flight training device" (FTD) at Level 2. The FSS builds supportively on aircraft control and display systems, with the information presented on up to four large reconfigurable touchscreens and two smaller side screens. The HCI design is fully flexible to represent many different aircraft cockpits for maximum usability and intuitive interactions with all aircraft systems and functions (Li et al., 2022a, b). Due to the hardware limitations of the simulator, the disturbance was only simulated as a digital signal, injected into the input of the inceptors. The disturbance signal was created by utilizing Lone's MATLAB function (Lone, 2013), which generated a pre-defined sum-of-sines forcing function. This signal replicated continuous turbulence experienced in an aircraft, distinct from screen vibrations or full simulation motion. Its purpose was to stimulate the participants' controller movement and evaluate their performance relative to the goal or baseline. It remained consistent among participants to enable precise comparisons in subsequent analyses.

3.2.2. Three inceptors for flight deck

This study used three types of inceptors which included traditional sidestick, gamepad, and touchscreen inceptors (Fig. 2a, b & 2c) for flight control to investigate HCI for future flight deck design. The sidestick as the default FSS inceptor, can be classified as a passive displace sidestick, which is directly proportional to the deflection of the control surfaces of aircraft. The sidestick controller in the FSS cockpit was based on an off-the-shelf Thrustmaster HOTAS WARTHOGTM gaming joystick, but the upper part was removed, and a custom-made handle was created by HMI professionals at DCA Design Ltd. to ensure the pilot's comfort and ergonomics. The process was overwatched by actual Gulfstream pilots to ensure real-world representation. For the scenery generation, an off-the-shelf desktop flight simulator called FlightGear (FG) was chosen because of its open-source architecture, vast configuration options, and ease of interfacing with the network through a user datagram protocol (UDP) connection. Additional FG capabilities are used to tailor the test requirements to each simulation scenario. For instance, manipulation of weather conditions can be crucial to replicate scenarios for model and data validation. FG provides various means to either control the weather or to interpret meteorological aerodrome report (METAR) around the

a b

Fig. 1. Future Systems Simulator (FSS) (1a) is a highly reconfigurable modular flight simulator with repositionable seats, displays, sidestick pedestals, thrust levers and touchscreen monitors, which are used as control inputs. The touchscreen monitors can be fully modified to satisfy the needs of the research (1 b).



a b c

Fig. 2. There are three different types of inceptors used in this research: traditional sidestick as a default FSS control input (2a); innovative touchscreen inceptor (2 b); and Xbox gamepad (2c) to investigate the best HCI on future flight deck design.

given airfield.

Control-response (CR) and Control-Display (CD) ratios are very important in the reproducibility of the study. However, their impact on the pilot's performance was not studied in this "proof-of-concept" experiment. The CD ratio for the touchscreen had the size of the attitude indicator area (which has a diameter of 85 mm), and the input was linear based on the finger's position on the display. The touch "knob" centre has a diameter of 17 mm. The CR of each controller was a linear signal, varying from −1 to 1 in both vertical and horizontal channels and being zeroed in idle position. All controllers were returning to idle position when no input was given. The sidestick is a common controller in commercial aircraft for example in the Airbus 320 series. As the active sidestick and passive sidestick have small differences in performance, the passive sidestick is used as the baseline in this research for measuring pilot performance and situation awareness level. The input logic is shown in Fig. 2a.

The touchscreen as an inceptor in this experiment is an integration of the inceptor function into the PFD, which served as the touchscreen equivalent of a physical joystick, enabling circular movements along vertical and horizontal axes within a defined area. Users engaged with the controller through a "tap and drag" technique, providing them with a complete range of movement within the designated area. This interaction approach aligns with Telfer's Touch Control Design concept, categorized as a "casual prodder" method (Telfer, 2023). Participants engaged with the controller by touching the "stick" shown on the screen and moving it in any direction within the circular area corresponding to the size of the attitude indicator. To explore Research Questions, the touchscreen as an inceptor uses the opposite input logic to that of sidestick and gamepad: pitch up when dragging the finger up and pitch down when dragging the finger down (Fig. 2b). The rationale behind the control logic selection of touchscreen interceptor was to simplify the gesture correlation between input and response required for this new technology while promoting a 'eyes out' flight. It is widely adopted in touchscreen technology to have the input of up motion correspond to movement upward, while maintaining finger contact resulting in sustained control input (Asakawa et al., 2017).

The reason for introducing the gamepad in the experiment is the touchscreen was a completely new experiment as an inceptor, it was difficult to control that the participant's experience with the touchscreen could be consistent with their experience with the sidestick. The inclusion of the gamepad was considered a bridge between the two inceptors, with the majority of control through the thumb motion of the participant. There have been studies to suggest that performance on tasks is similar or improved when using touchscreen to gamepad controls for computer gaming (Oshita and Ishikawa, 2012). This study wanted to understand the relationship between users' finger movements and hand gestures for the controllability of the aircraft. The performance between these finger-motion control platforms is vital to understanding how usability can be tailored to future implementation into commercial practice. Therefore, the gamepad, a controller that has also rarely been used as an aircraft inceptor, was introduced as a control; on the other hand, as physical controllers, the gamepad and the sidestick were consistent in their input logic, which helped to compare the effects of different input logics on pilot performance while eliminating differences in experience levels. The participants were asked to hold the gamepad with both hands but only use their right thumb using the right stick to control the aircraft. The input logic is shown in Fig. 2c.

3.2.3. Scenarios on Future Systems Simulator

There were two scenarios used in FSS for this study, landing with disturbance and without disturbance. The only difference is that the pilot needed to compensate for the disturbance to keep the aircraft on the right course using three different inceptors respectively in the disturbance scenario compared with the no disturbance scenario. The aircraft flight dynamics model was a generic business jet based on the Gulfstream G550. The starting position of the aircraft was 5 miles away in a straight line to runway 15 R at Incheon International Airport, Seoul, KR (ICAO: RKSI). The initial speed was 150 knots at an altitude of 1400 ft. Flaps, landing gear, and auto-throttle at a target speed of 120 knots were pre-set and maintained until close to the runway (Fig. 3a & b). Right before the touchdown, the auto-throttle was automatically disengaged, the spoilers were extended, and the brakes were engaged. The weather condition was clear, and no wind effects. This study focused on control surface inceptors.

3.2.4. *Measurement and materials*

The objective pilot performance was measured by the deviation root mean square (RMS) of flight path, which is commonly used for accessing pilot performance (Lone et al., 2012). In addition, there were two measurements, including the system usability scale (SUS) and situation awareness rating technique (SART), used to assess HCI issues in implementing touchscreens for future flight deck design. The SUS is a commonly used standardised questionnaire for evaluating perceived usability. It consists of 10 five-point items with an alternately positive and negative tone (Lewis, 2018). The SUS consists of two dimensions: usability and learnability, with eight questions measuring system usability (questions except question 4 and question 10) and two questions measuring system learnability (question 4 and question 10). The SART is the most widely used subjective situation awareness measurement with 10 seven-point questions (Bolton et al., 2021), which consisted of three dimensions: demand, supply, and understanding, and the SART score can be calculated using the following formula: SART total = (supply − demand) + understanding.

3.3. *Research design*

This study is to investigate HCI in future flight design which involved three different inceptors to perform instrument landing. Participants had to interact with a traditional inceptor (Fig. 4a), touch screen (Fig. 4b), and gamepad (Fig. 4c) during both disturbance and no disturbance conditions in the Future Systems Simulator and provided their feedback on both system usability (SUS) and situation awareness (SART-10D) respectively. The settings for flight deck automation and displays on FSS were the same, the only difference is the control input on the inceptors for participants to perform an instrument landing. All participants undertook the following procedures; (1) complete the demographical data including age, gender, working experience and total flight hours (5 min); (2) watch a briefing video explaining the purpose of the study and FSS layouts (15 min); (3) sit in the simulator to familiarise with three types of inceptors (5–10 min); (4) perform two scenarios randomly presented on instrument landing using three types of inceptors respectively to eliminate practice effects and immediately provided their feedback on rating both SUS and SART-10D after using each inceptor (20–30 min); (5) debriefing and participants feedback on the design of touchscreen applications (5–10 min). It took around 70 min for each participant to complete the experiments.

4. Result

4.1. *Sample characteristics*

Seventy-two participants were invited to conduct two scenarios which consisted of landing with disturbance (LD) and landing non-disturbance (LN) using three inceptors, including sidestick, gamepad and touchscreen on the FSS. The RMS data were collected during each trial and both the system usability scale (SUS) and situation awareness rating technique (SART-10D) were completed by participants at the end of each trial. To explore possible interaction effects of inceptor and scenario, Two-way repeated measure ANOVA was used to analyse the RMS, SUS for system usability involving two sub-dimensions: usability (SUS–U) and learnability (SUS-L), and SART-10D for situation awareness including three sub-dimensions: demand (SART-D), supply (SART-S) and understanding (SART-U). To make the RMS data fit a normal distribution, the data has been log-transformed. After data transformation, the Q-Q plot verifies the normal distribution assumption. According to Mauchly's test, there were RMS and the sub-dimension of SART-U had violated the homogeneity of covariance (RMS: $\chi^2 = 6.46$, $p = 0.04$, $\varepsilon = 0.92$; SART-U: $\chi^2 = 11.66$, $p = 0.003$, $\varepsilon = 0.87$). Therefore, the Huynh-Feldt correction was adopted for RMS and SART-U, the sphericity assumed was applied for the other variables. The post-hoc pairwise comparisons were performed by Bonferroni, and the effect sizes of samples were quantified by partial eta square (η_p^2). The results of descriptive statistics on flight path RMS (M & SD), SUS scores (M & SD) and SART scores (M & SD) are shown in Table 1.

4.2. *Flight path deviation*

Two-way repeated measure ANOVA was conducted to analyse the

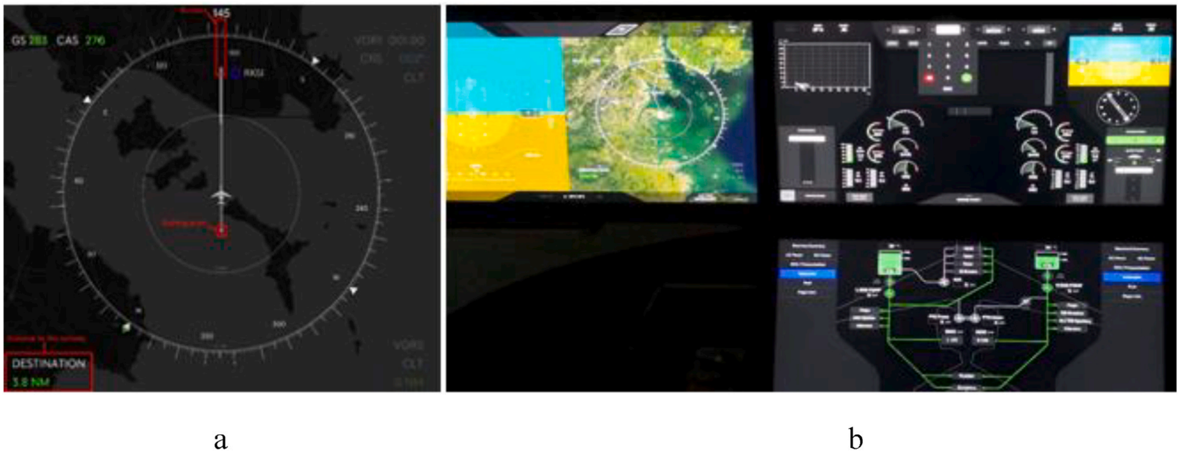


Fig. 3. The Navigation Display (ND) with marked distance to the destination (3.8NM), heading (145), and additional airspeed indication, used in the scenario of ILS landing (3a); a view of example FSS layout setup, which can be seen by a pilot. The setup shows Primary Flight Display, and central displays with Mode Control Panel, crew messaging panel, Vertical Flight Profile, Engine Information, backup instruments, spoilers, landing gear and flaps digital levers and a part of synoptic pages (3 b).

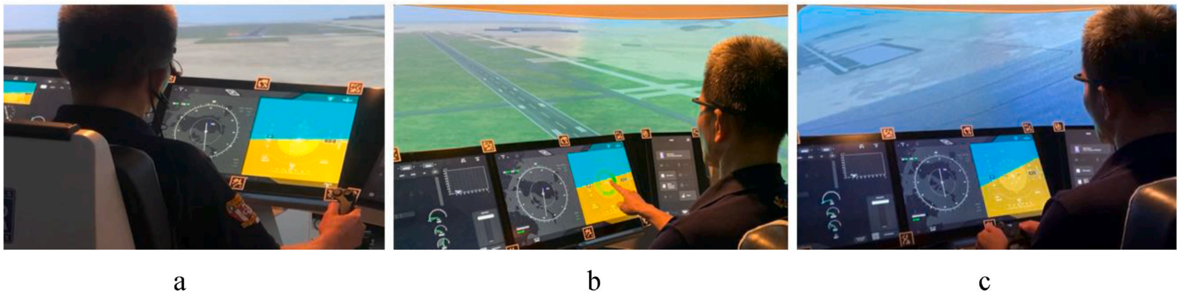


Fig. 4. Participant interacting with three different types of inceptors, traditional sidestick (4a); innovative touchscreen inceptor (4 b); and gamepad (4c), to perform an instrument landing in both with disturbance and without disturbance scenarios randomly on Future Systems Simulator.

Table 1
Description statistics of participants' flight path RMS (after log-transfer), SUS and SART (M & SD) among interacting with three different inceptors in landing with disturbance (LD) and landing with non-disturbance (LN) scenarios. (Unit: RMS in log(m), the scores of SUS and SART are dimensionless).

Dimension	scenarios	sidestick		gamepad		touchscreen	
		M	SD	M	SD	M	SD
RMS	LN	5.07	0.99	5.13	0.91	5.51	0.81
	LD	5.34	0.92	5.41	0.87	5.91	0.80
SUS	LN	70.00	19.28	64.51	21.11	36.70	22.43
	LD	62.74	22.12	58.47	24.22	30.90	21.57
SUS-U	LN	56.53	15.42	50.10	17.50	27.05	19.35
	LD	50.87	17.71	44.90	20.40	22.26	18.23
SUS-L	LN	13.47	5.45	14.41	5.43	9.65	5.80
	LD	11.88	6.19	13.58	6.08	8.65	6.33
SART	LN	23.17	6.57	22.76	6.05	18.75	7.34
	LD	19.17	7.01	19.51	6.78	16.01	7.79
SART-D	LN	10.93	3.85	10.92	4.02	14.32	3.86
	LD	15.53	4.34	14.93	4.78	17.44	4.07
SART-S	LN	18.94	3.75	19.08	3.34	20.10	3.82
	LD	20.35	3.66	20.39	3.43	21.25	4.09
SART-U	LN	15.15	3.43	14.60	3.71	12.97	4.31
	LD	14.35	4.04	14.06	4.16	12.21	4.51

interactions between inceptors (3 levels) and scenarios (2 levels) on flight path deviation. There was no significant interaction between inceptors and scenarios on flight path, F (1.89, 133.80) = 0.91, p = 0.40, $\eta_p^2 = 0.01$. However, there was a significant main effect on three inceptors, F (2.00, 141.68) = 23.25, $p < 0.001$, $\eta_p^2 = 0.25$. Post-hoc Bonferroni comparison revealed that RMS on the touchscreen was significantly higher than sidestick ($p < 0.001$) and gamepad ($p < 0.001$) (Fig. 5). Furthermore, the flight path deviation in LD scenario was significantly higher than in LN scenario, F (1.00, 71.00) = 26.46, $p < 0.001$, $\eta_p^2 = 0.27$.

4.3. *Interaction between inceptors and scenarios on system usability*

Two-way repeated measure ANOVA was conducted to analyse the interactions between inceptors (3 levels) and scenarios (2 levels) on system usability (SUS) total score. There was no significant interaction

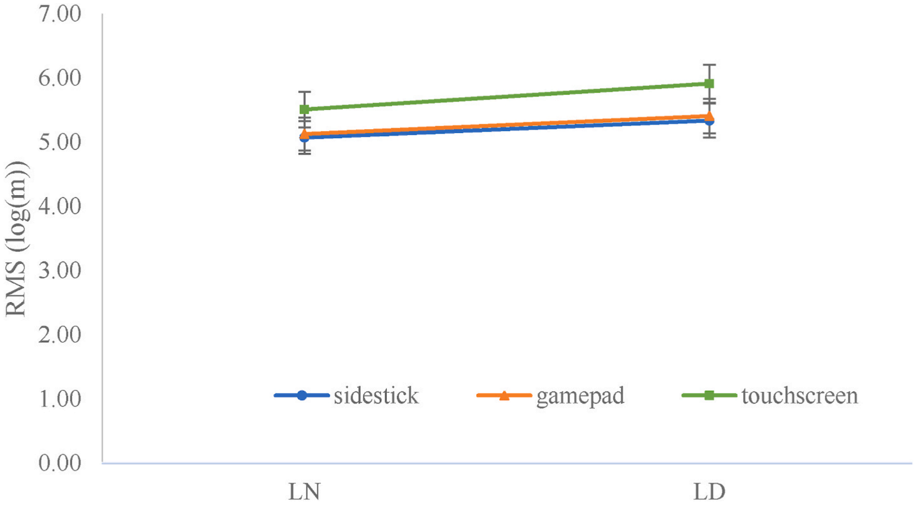


Fig. 5. Participants' flight path deviation (in log(m)) while interacting with three different types of inceptors in landing with disturbance (LD) and landing with non-disturbance (LN) scenarios. Mean and 95% confidence intervals.

between inceptors and scenarios on SUS total score, $F(2, 142) = 0.82$, $p = 0.44$, $\eta_p^2 = 0.01$. However, there was a significant main effect on three inceptors, $F(2, 142) = 56.89$, $p < 0.001$, $\eta_p^2 = 0.45$. Post-hoc Bonferroni comparison revealed that SUS total score on touchscreen was significantly lower than sidestick ($p < 0.001$) and gamepad ($p < 0.001$). Furthermore, SUS total score in LD scenario was significantly lower than in LN ($F(1, 71) = 45.43$, $p < 0.001$, $\eta_p^2 = 0.39$).

There was no significant interaction between inceptors and scenarios on SUS-U, $F(2, 142) = 0.33$, $p = 0.72$, $\eta_p^2 = 0.005$. However, there was a significant main effect on three inceptors, $F(2, 142) = 59.17$, $p < 0.001$, $\eta_p^2 = 0.46$. Post-hoc Bonferroni comparison revealed that SUS-U on the touchscreen was significantly lower than sidestick ($p < 0.001$) and gamepad ($p < 0.001$). The SUS-U on the gamepad was significantly lower than sidestick ($p = 0.03$). Furthermore, there was a significant main effect on two scenarios, $F(1, 71) = 46.73$, $p < 0.001$, $\eta_p^2 = 0.40$. Post-hoc Bonferroni comparison revealed that SUS-U on LD scenario was significantly lower than LN ($p < 0.001$).

There was a significant interaction between inceptors and scenarios on SUS-L, $F(2, 142) = 3.63$, $p = 0.03$, $\eta_p^2 = 0.05$. Simple main effect analysis of three inceptors within two scenarios and the two scenarios within three inceptors are shown as Table 2. Post-hoc Bonferroni comparison revealed that SUS-L score of using touchscreen as inceptor was significantly lower than sidestick ($p < 0.001$) and gamepad ($p < 0.001$) in LN scenario. The SUS-L score for using touchscreen was significantly lower than sidestick ($p < 0.001$) and gamepad ($p < 0.001$) in LD scenario. Moreover, the SUS-L score in LD scenario was significantly lower LN scenario when using sidestick ($p < 0.001$), gamepad ($p = 0.001$) and touchscreen ($p < 0.001$) respectively (Fig. 6).

4.4. *Interaction between inceptors and scenarios on situation awareness*

Two-way repeated measure ANOVA was conducted to analyse the interaction between inceptors and scenarios using SART-10D which consisted of three sub-dimensions, SART-S, SART-U and SART-D. The result showed that there was a significant interaction between inceptors and scenarios on SART total score, $F(2, 142) = 3.31$, $p = 0.04$, $\eta_p^2 = 0.04$. Simple main effect analysis of three inceptors within two scenarios and the two scenarios within three inceptors are shown as Table 3. Post-hoc Bonferroni comparison revealed that the SART score of using touchscreen as inceptor was significantly lower than sidestick ($p < 0.001$) and gamepad ($p < 0.001$) in the LN scenario. The SART score for using touchscreen was significantly lower than sidestick ($p = 0.002$) and gamepad ($p = 0.001$) in the LD scenario. Moreover, the SART score in the LD scenario was significantly lower LN scenario when using sidestick ($p < 0.001$), gamepad ($p < 0.001$) and touchscreen ($p < 0.001$) respectively (Fig. 7).

There was a significant interaction between inceptors and scenarios on SART-D, $F(2, 142) = 19.41$, $p < 0.001$, $\eta_p^2 = 0.22$. Simple main effect analysis of three inceptors within two scenarios and the two scenarios within three inceptors are shown as Table 4. Post-hoc comparison with Bonferroni corrections revealed that SART-D on touchscreen inceptor was significantly higher than on sidestick ($p < 0.001$) and gamepad ($p < 0.001$) in LN scenario; moreover, SART-D on touchscreen inceptor was significantly higher than on sidestick ($p = 0.001$) and gamepad ($p < 0.001$) in LD scenario. Furthermore, the Post-hoc Bonferroni comparison revealed that SART-D in LD was significantly higher than in LN scenario when participants interacted with sidestick ($p < 0.001$), gamepad ($p < 0.001$) and touchscreen ($p < 0.001$).

Table 2
Two-way repeated measure ANOVA on SUS-L.

3 × 2 two-way ANOVA on SUS-L	*df* Effect	*df* Error	F	*p*	η_p^2
Interaction effect “inceptors × scenarios”	2	142	3.63	0.03	0.05
SUS-L simple main effect of scenarios within					
sidestick	1	71	25.26	<0.001	0.26
gamepad	1	71	11.36	<0.01	0.14
touchscreen	1	71	13.98	<0.001	0.16
SUS-L simple main effect of inceptors within					
LN scenario	2	142	22.63	<0.001	0.24
LD scenario	2	142	20.49	<0.001	0.22
Main effect “Inceptors”	2	142	22.21	<0.001	0.24
Main effect “Scenarios”	2	142	26.93	<0.001	0.28

There was no significant interaction between inceptors and scenarios on SART-S, $F(2, 142) = 0.38$, $p = 0.68$, $\eta_p^2 = 0.005$. Furthermore, there was no significant main effect on three inceptors, $F(2, 142) = 2.70$, $p = 0.07$, $\eta_p^2 = 0.04$. However, there was a significant main effect on two scenarios, $F(1, 71) = 26.75$, $p < 0.001$, $\eta_p^2 = 0.28$. Post-hoc Bonferroni comparison revealed that SART-S on LD scenario was significantly higher than LN ($p < 0.001$). There was no significant interaction between inceptors and scenarios on SART-U, $F(1.77, 125.91) = 1.01$, $p = 0.37$, $\eta_p^2 = 0.01$. However, there was a significant main effect on three inceptors, $F(2.00, 142.00) = 10.26$, $p < 0.001$, $\eta_p^2 = 0.13$. Post-hoc Bonferroni comparison revealed that SART-U on the touchscreen was significantly lower than sidestick ($p < 0.001$) and gamepad ($p = 0.002$). Furthermore, there was a significant main effect on two scenarios, $F(1.00, 71.00) = 11.84$, $p = 0.001$, $\eta_p^2 = 0.14$. Post-hoc Bonferroni comparison revealed that SART-U on LD scenario was significantly lower than LN ($p = 0.001$).

5. Discussion

The integration of touchscreens in the flight deck has the potential to replace physical control knobs, buttons, and switches, with Airbus, Boeing, and Gulfstream already developing touchscreen controls (Watkins et al., 2018). However, there are varying opinions regarding the advantages and drawbacks of touchscreen applications in flight operations, including system usability, perceived workload, cost-efficiency, space utilization, and HCI flight deck design (Khoshnewiszadeh and Pool, 2021; Lin and Lee, 2022; Xie et al., 2022). While most touchscreen research has focused on HCI tasks such as checklists, navigation, and flight management, the present study aims to investigate the usability and pilots' situation awareness (SA) when using touchscreens as flight inceptors compared to traditional sidesticks and gamepads in scenarios with and without disturbances. The objective is to enhance the theoretical understanding of how inceptor controllers on the flight deck impact the user experience, with a focus on measuring the user's perception of usability and situation awareness while interacting with these flight control systems.

5.1. *The impact of inceptor and scenario on pilot performance*

In this study, the pilots' performance was evaluated based on flight path deviation RMS, where a lower score indicates better performance. The results from section 4.2 indicate that there was no interaction between the inceptor and scenario on pilot performance. However, both the inceptors and scenarios had a significant impact on pilot performance. Overall, the touchscreen performed the worst among the three inceptors, while turbulence had a significant effect on pilot performance. Sudden changes in airflow can cause the aircraft to pitch, roll, or yaw, requiring constant adjustments from the pilot to maintain control. In this study, turbulence had a significant impact on the use of both the gamepad and touchscreen as inceptors, indicating that incorporating the inceptor into the touchscreen does not mitigate the effects of turbulence on flight control. Future flight deck inceptor designs will need additional software support to address the impact of turbulence. Among the three inceptors, the sidestick performed the best with the lowest RMS score, indicating that it was the most suitable option as a mature controller. The gamepad had a slightly higher RMS score than the sidestick, while the touchscreen had a significantly higher RMS score than both the sidestick and the gamepad. Despite participants having comparable levels of experience with gamepads and touchscreens, the touchscreen's

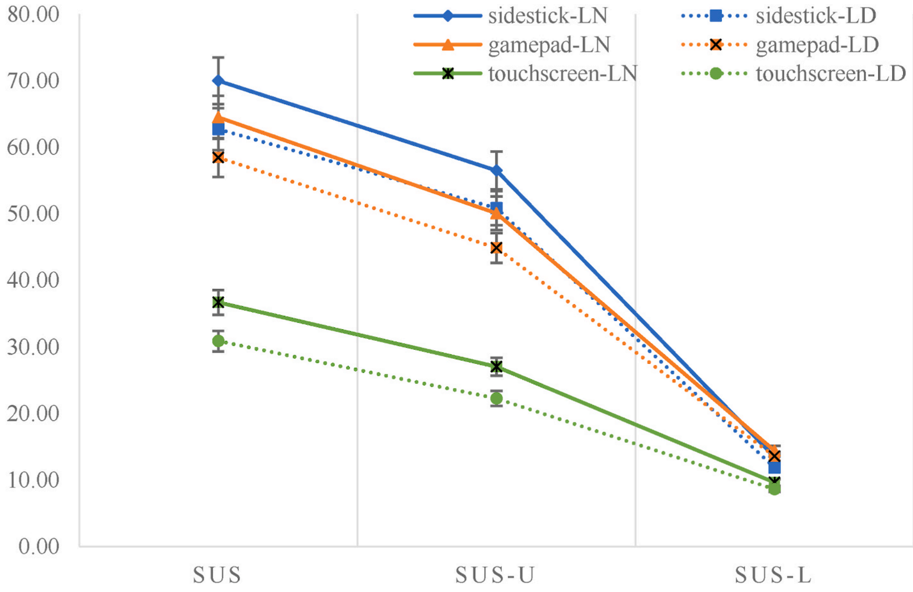


Fig. 6. Participants' rating on SUS including both sub-dimensions of Usability (SUS–U) and Learnability (SUS-L) while interacting with three different types of inceptors in landing with disturbance (LD) and landing with non-disturbance (LN) scenarios. Mean and 95% confidence intervals. (All scores are dimensionless).

Table 3
Two-way repeated measure ANOVA on SART.

3 × 2 two-way ANOVA on SART	*df* Effect	*df* Error	F	*p*	η_p^2
Interaction effect "inceptors × scenarios"	2	142	3.31	0.04	0.04
SART simple main effect of scenarios within					
sidestick	1	71	42.25	<0.001	0.37
gamepad	1	71	30.55	<0.001	0.30
touchscreen	1	71	28.99	<0.001	0.29
SART simple main effect of inceptors within					
Landing with non-disturbance	2	142	13.69	<0.001	0.16
Landing with disturbance	2	142	7.69	<0.01	0.10
Main effect "Inceptors"	2	142	11.05	< 0.001	0.14
Main effect "Scenarios"	1	71	45.03	<0.001	0.39

Table 4
Two-way repeated measure ANOVA on SART-D.

3 × 2 two-way ANOVA on SART-D	*df* Effect	*df* Error	F	*p*	η_p^2
Interaction effect "inceptors × scenarios"	2	142	8.46	<0.001	0.11
SART-D simple main effect of scenarios within					
sidestick	1	71	136.19	<0.001	0.66
gamepad	1	71	101.06	<0.001	0.59
touchscreen	1	71	69.16	<0.001	0.49
SART-D simple main effect of inceptors within					
Landing with non-disturbance	2	142	26.40	<0.001	0.27
Landing with disturbance	2	142	10.80	<0.001	0.13
Main effect "Inceptors"	2	142	19.41	<0.001	0.21
Main effect "Scenarios"	1	71	140.88	<0.001	0.66

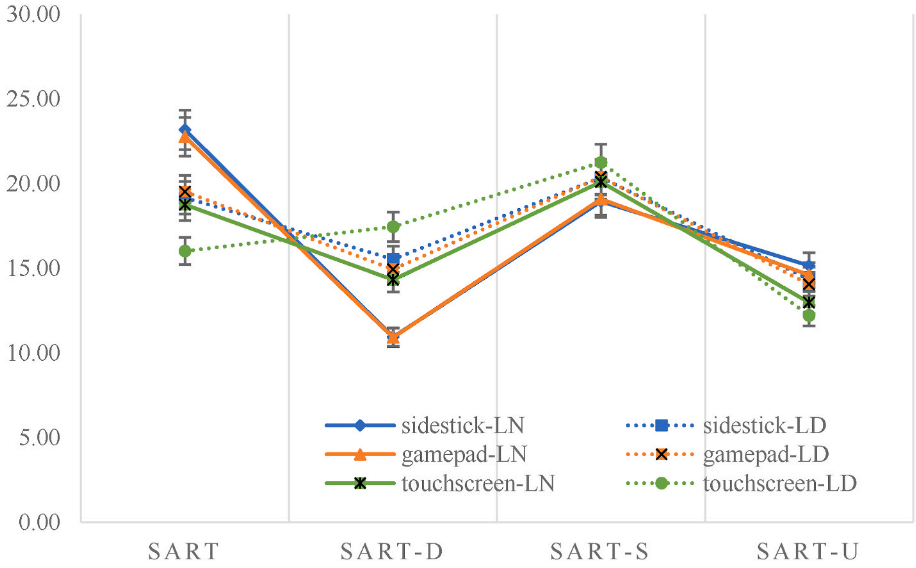


Fig. 7. Participants' rating on SART including three sub-dimensions on Demand (SART-D), Supply (SART-S) and Understanding (SART-U) while interacting with three different types of inceptors in landing with disturbance (LD) and landing with non-disturbance (LN) scenarios. Mean and 95% confidence intervals. (All scores are dimensionless).

performance was significantly lower. The use of touchscreens as inceptors has clear disadvantages at this stage, the accuracy of touchscreen operations is affected when it is used under the influence of disturbance. Furthermore, the lack of physical feedback is a drawback that clearly distinguishes the touchscreen from the other two inceptors. The integration of the inceptor into the Primary Flight Display (PFD) is an experimental concept that requires further refinement and testing.

5.2. Turbulence affecting system usability of inceptors on flight control

In this study, the System Usability Scale (SUS) was used to assess the system usability of the touchscreen as an inceptor compared to the sidestick and gamepad. SUS consists of two dimensions: usability (SUS–U) and learnability (SUS-L) (Lewis and Sauro, 2009). The results showed that there was no significant interaction between inceptors and scenarios for the SUS total score. However, both inceptors and scenarios had a significant main effect on system usability and learnability. Turbulence had a significant impact on the usability and learnability of the system, consistent with previous studies (Wynne et al., 2021). The touchscreen scored significantly lower than the sidestick and gamepad on the SUS total score, as well as on the sub-dimensions of usability and learnability (Fig. 6). Additionally, the disturbance had negative effects on pilots' interaction with all three inceptors when handling the aircraft. The low SUS score of the touchscreen may be attributed to its poor handling quality, which is closely related to system usability. Furthermore, using the touchscreen inceptor with their index fingers caused physical fatigue for pilots, as the touchscreen lacked support for their arms (Figs. 2b & 4b). This finding aligns with previous research indicating that prolonged manipulation of a touchscreen with raised arms can induce fatigue and result in lower usability ratings (Dodd et al., 2014). There were several research about improve the stability when using touchscreen by providing hand support or elbow support, which could be benefit in touchscreen inceptor design (Cockburn et al., 2019; Shin and Zhu, 2011). While there are numerous studies evaluating the usability of touchscreens and gamepads in various domains, there is limited literature on how the design of a touchscreen inceptor can impact pilots' performance and HCI issues on the flight deck.

System learnability encompassed learning how to manipulate the aircraft using innovative inceptors (touchscreen and gamepad) and following the flight path on the navigation display for instrument landing (Fig. 3a & b). The learnability of the touchscreen was significantly lower than the other two inceptors, possibly due to its lack of physical feedback (Wynne et al., 2021). Participants found it challenging to quickly acquire muscle memory and adapt to the innovative design concept of the overlapped touchscreen inceptor with the Primary Flight Display (PFD) (Fig. 2b). In contrast, even though participants were unfamiliar with the gamepad, they were able to adapt quickly, as both the sidestick and gamepad are physical point-supported joysticks with distinct manoeuvring bounds.

5.3. Interacted with different inceptors affected pilots' SA

Touchscreens offer the potential to reduce cognitive workload and enhance situational awareness by providing an intuitive approach to interaction and the flexibility to display task-related information (van Zon et al., 2020). Ensuring increased situational awareness is an important characteristic of system design for operational safety and collaboration (Li et al., 2022a, b). The results revealed a significant interaction between inceptors and scenarios in the SART-total score. The primary reason for the interaction is that the gamepad performs better than the sidestick in LD situations while the gamepad had lower SART score than sidestick in LN scenario. This is likely due to the fact that manipulating the gamepad only involves using the fingers, whereas using the sidestick requires the entire wrist, therefore the accuracy is likely to be higher when manipulating the gamepad, which also suffers less from the effects of disturbance. The main effect on inceptors showed that the touchscreen had the lowest SART-total score, followed by the sidestick and gamepad in both disturbance and non-disturbance scenarios. This finding suggests that using the touchscreen as an inceptor may lead to poor visual scan patterns among pilots, increased head-down time, limited processing of other flight deck information, and potential hazards in flight operations. Interestingly, in the three sub-dimensions of SART, pilots rated the touchscreen the lowest in understanding but the highest in both supply and demand compared to the other two inceptors (Fig. 7). When the touchscreen is used as an inceptor for aircraft manipulation during landing, the demand on pilots' attentional resources (SART-D) and the supply of attentional resources (SART-S) are higher compared to the other inceptors. This may be due to the innovative functions of the touch-control overlapped with the PFD, providing critical information such as airspeed, altitude, heading, and glideslope for instrument landing to pilots. Touchscreens can integrate information inputs and output consequences in the same visual area, facilitating zero displacements of the user's hand action and eye gaze, which explained why pilots rated the touchscreen inceptors highest in SART-S (Tang et al., 2023). However, the increased information supply may also require higher cognitive demands and attentional resources to process the substantial amount of critical flight control information.

The SART-D showed a significant interaction in the two-way repeated measures (Table 4). The reason for this is that the sidestick is affected by disturbance more than the gamepad, making the participant's SA's demand elevated, which is the same as the SART score interaction. The highly integrated capacity of the touchscreen is one reason why this study and previous studies aimed to use it to optimize information integration, increase situational awareness, and reduce cognitive load on the flight deck. The demand for the touchscreen was significantly higher than that for the sidestick and gamepad. This high demand may be due to participants' unfamiliarity with the design principle of the superimposed touchscreen inceptor in the centre of the PFD for aircraft manoeuvring (Figs. 2b & 4b). When using the unfamiliar touchscreen inceptors, participants had to invest significant effort to ensure manipulation accuracy (Dodd et al., 2014; Wynne et al., 2021). The results indicate that the touchscreen had the lowest understanding score ($p < 0.001$), which may be attributed by differences in the input logic since the main difference of touchscreen apart from sidestick and gamepad is the input logic.

The sidestick and gamepad share the same input logic, where pushing the joystick/gamepad forward causes the aircraft to pitch down (Fig. 2a & c). However, the touchscreen inceptor follows a different input logic, requiring the pilot's fingertip to pitch up to manoeuvre the aircraft upwards (Fig. 2b). This contrasting input logic between the touchscreen and the sidestick/gamepad, particularly for experienced pilots accustomed to the sidestick, may lead to confusion and misuse of the touchscreen inceptor. However, the inverted vertical profile of the touchscreen aligns with the concept of "Input Equals Output" in Organic User Interfaces design, as defined by Vertegaal and Poupyrev (2008). Based on participants' feedback, especially those with little or no flying experience, some suggested modifying the input logic to improve understanding and facilitate easier adaptation for new users. By addressing this aspect, it would help newcomers become familiar with this type of controller.

5.4. Subjective feedback on interacting with touchscreen inceptor

Although touchscreens offer significant advantages, there are concerns on using a touchscreen as a control inceptor from experienced pilots based on this research. The HCI issues include potential display clarity problems due to light and fingers affecting the visual scan of the critical information (Rouwhorst et al., 2017). Participants demonstrated a wide range of opinions regarding the use of touchscreens as inceptors. Some experienced commercial pilots expressed their reservations about the implementation of touchscreens as an inceptor for flight control. The negative feedback of participants could be summarised as:

"touchscreens lack amplitude feedback and are less intuitive", "more demanding", "not for primary control" and "might get tiring". However, there are also participants who expressed a positive viewpoint regarding the potential use of touchscreens as inceptors for flight control. What's more, those younger participants with less flight experience were more positive about using the touchscreen inceptor. The young generation of pilots expressed that a touchscreen inceptor could be incorporated into the flight deck in the future, but pilots would need considerable training to familiarise themselves with the controllability of the aircraft. This indicates that, despite the current drawbacks of a touchscreen inceptor, it still has some potential applications for technological growth. Most participants conveyed that touchscreen inceptors are not suitable to integrate with the Primary Flight Display on the current flight deck and touchscreens could be more appropriate for other simple tasks in flight operations. The summaries of participants' feedback are shown in Table 5.

5.5. Limitation

This research has several limitations that must be made clear about the data collection and analysis process. Firstly, the practise effects may have an impact on the assessment of both system usability and their situation awareness while pilots interacted with different inceptors on the flight deck (Barendregt et al., 2006). And the touchscreen input logic is set up opposite of sidestick and gamepad, which may further affect pilot performance. Secondly, the measurement method used in this experiment is not comprehensive and only includes flight path deviation RMS as an objective evaluation criterion (Krejtz et al., 2018; Lobo et al., 2016). Future studies shall evaluate the HCI design of touchscreen as an inceptor using objective approaches such as eye tracking for pilots' attention distribution, and biofeedback for stress index and perceived workload. Third, the effect of flight experience on the evaluation of inceptors was not explored in this research, as participants have different flight experiences from general aviation to commercial airline pilots. The diversities of participants' experiences may have impacted subjective assessment and objective performance since commercial pilots may be accustomed to traditional sidestick inceptors (Socha et al., 2020). This phenomenon aligned with the mere-exposure effect (familiarity principle), human operators rated things they were familiar with higher than non-familiar ones (Serenko and Bontis, 2011). As it was seen participants of lower experience had higher positivity towards this control inceptor; future interest in touchscreen inceptors could be considered between the performance variation of flight experiences on various tasks to validate the touchscreen inceptor and remove the mere-exposure effect.

Table 5
Summaries on participants' feedback when using touchscreen as inceptor compared with sidestick and gamepad.

positive feedback	negative feedback
I embrace the touchscreen inceptor, and it is feasible, yet further works needs to explore more psychological factors.	Using the touch screen makes it difficult to see the information on the screen and there is no physical sense of zero.
I think the idea is good. I liked that to control the aircraft the inputs were direct (move up = pitch up).	The stick cannot be captured immediately (slide required) there is unwillingness to let go of the stick.
It has potential but specific training and certificates are needed.	I am still quite skeptic about the accuracy and precision it can bring, especially during turbulence.
Touchscreen was very innovative technology for aircraft. It can be improved in future.	For the touch screen I was having to watch the screen which meant that I was often over controlling the aircraft as I couldn't also concentrate on the cockpit view.
I think touchscreen certainly has use, with its ease of use and low threshold of training needed.	It might get tiring to hold your hand out on the screen for a long period of time.

6. Conclusion

Modern aircraft can be supplemented with flight automation systems which reduce pilot control inputs to ensure operational safety and efficiency. This study reported on three inceptor designs and evaluated HCI on both usability and pilot's situation awareness in both disturbance and non-disturbance scenarios. Currently, touchscreen is gradually replacing the traditional display with knobs/switches/buttons and aims to improve the efficiency of human-computer interaction. The benefits of touchscreen displays could improve flight deck ergonomics and the pilot's hand-eye coordination, reduce mechanical complexity and the through-life cost, and mitigate pilots' task loads. However, touchscreens used as inceptors face both technical and design challenges. The lack of physical feedback, fatigue induced by continuous operations, and their impact on a pilot's situation awareness all have noticeable negative effects on their use as inceptors. To efficiently interact with the flight control system, the design of future flight deck automation and inceptor for pilot's control inputs have to consider a pilot-in-the-loop perspective which is consistent with the principle of the human-centered flight deck. This experiment represents just an initial attempt at utilizing touchscreens as inceptors and serves as an exploration of their potential applications. Although the findings of this research showed that the overall touchscreen inceptor is not ready yet for flight decks due to low performance, the findings revealed traditional sidestick is still the preferred inceptor in terms of both system usability and maintaining situational awareness on the flight deck. Interestingly, the gamepad also was rated similarly on both usability and situation awareness measurements, though both the gamepad and touchscreen have never been implemented as a control inceptor on the flight deck. It may be attributed to new generation pilots being more comfortable with the new input logic due to their gaming experiences either on a gamepad or touchscreen on mobile devices.

Future work

Based on the conclusions drawn from this experiment, the use of touchscreens as inceptors results in a significant performance decline under disturbance conditions, and prolonged operation leads to physical fatigue among pilots. Therefore, it may be prudent to consider using touchscreens in scenarios only with short durations and minimal disturbance environments. In addition to this, it is essential to explore the applicability of haptic feedback technology for tasks that require continuous operation, such as inceptor usage. Furthermore, the potential benefits of providing additional elbow support or hand support should be investigated as a potential solution to address issues related to pilots' physical fatigue on their fingers. These considerations will refine the applications of touchscreens as inceptors and maximise their usability in various contexts in the future flight deck. It's crucial to consider human-centric design by changing the positions of the touchscreen inceptor integrated with the other flight deck displays and exploring its potential applications in dynamic operational scenarios. Future research should reduce pilots' 'head down' time by focusing on the control of the touchscreen inceptor and giving them visual confirmation to promote SA while scanning the operational environment. The combination of these technologies would help mature the operational concept of touchscreen and become viable interactive control of the aircraft and its systems.

CRediT authorship contribution statement

Yifan Wang: Writing – original draft, Software, Formal analysis, Data curation. **Wen-Chin Li:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation, Conceptualization. **Wojciech Tomasz Korek:** Writing – review & editing, Software, Resources, Formal analysis, Data curation. **Graham Braithwaite:** Writing – review & editing, Supervision, Resources, Project administration, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research is co-financed by the European Union through the European Social Fund (grant number POWR.03.02.00–00-I029). The authors would like to thank the PINES project Team in Cranfield. Especially Mudassir Lone, for his generous support during the project's development, and particularly Peter Beecroft from Rolls-Royce for supporting the research to be carried out in the Future Systems Simulator.

Appendix

System Usability Scale						
I think that I would like to use this system frequently.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I found the system unnecessarily complex.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I thought the system was easy to use.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I think that I would need the support of a technical person to be able to use this system.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I found the various functions in this system were well integrated.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I thought there was too much inconsistency in this system.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I would imagine that most people would learn to use this system very quickly.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I found the system very cumbersome to use.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I felt very confident using the system.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
I needed to learn a lot of things before I could get going with this system.						
Strongly disagree				Strongly agree		
○	○	○	○	○		
Situation Awareness Rating Technique						
Demand						
instability of situation						
very low						very high
○	○	○	○	○	○	○
Variability of situation						
very low						very high
○	○	○	○	○	○	○
Complexity of situation						
very low						very high
○	○	○	○	○	○	○
Supply						
Arousal						
very low						very high
○	○	○	○	○	○	○
Spare mental Capacity						
very low						very high
○	○	○	○	○	○	○
Concentration						
very low						very high
○	○	○	○	○	○	○
Division of Attention						
very low						very high
○	○	○	○	○	○	○
Understanding						
Information Quantity						
very low						very high

(*continued on next page*)

(*continued*)

Situation Awareness Rating Technique						
○	○	○	○	○	○	○
Information Quality						
very low						very high
○	○	○	○	○	○	○
Familiarity						
very low						very high
○	○	○	○	○	○	○

References

Alapetite, A., Møllenbach, E., Stockmarr, A., Minakata, K., 2018. A rollercoaster to model touch interactions during turbulence. Advances in Human-Computer Interaction 2018. https://doi.org/10.1155/2018/2698635.

Albinsson, P.A., Zhai, S., 2003. High precision touch screen interaction. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems 105–112. https://doi.org/10.1145/642611.642631.

Al-Lami, H., Aslam, A., Quigley, T., Lewis, J., Mercer, R., Shukla, P., 2015. The Evolution of Flight Control Systems Technology.

Asakawa, D.S., Dennerlein, J.T., Jindrich, D.L., 2017. Index finger and thumb kinematics and performance measurements for common touchscreen gestures. Appl. Ergon. 58, 176–181. https://doi.org/10.1016/j.apergo.2016.06.004.

Bandur, V., Selim, G., Pantelic, V., Lawford, M., 2021. Making the Case for Centralized Automotive E/E architectures. IEEE Trans. Veh. Technol. 70 (2), 1230–1245. https://doi.org/10.1109/TVT.2021.3054934.

Barendregt, W., Bekker, M.M., Bouwhuis, D.G., Baauw, E., 2006. Identifying usability and fun problems in a computer game during first use and after some practice. Int. J. Hum. Comput. Stud. 64 (9), 830–846. https://doi.org/10.1016/J.IJHCS.2006.03.004.

Bhalla, Mudit R., Bhalla, Anand V., 2010. Comparative study of various touchscreen technologies. Int. J. Comput. Appl. 6 (8), 975–8887.

Boeing, 2016. Boeing: touchscreens come to 777X flight deck. https://www.boeing.com/features/2016/07/777x-touchscreen-07-16.page.

Bolton, M., Biltekoff, E., Humphrey, L., 2021. The level of measurement of subjective situation awareness and its dimensions in the situation awareness rating technique (SART). IEEE Transactions on Human-Machine Systems 1–8. https://doi.org/10.1109/THMS.2021.3121960.

Boy, G.A., 2020. Aerospace human systems integration. A Framework of Human Systems Engineering: Applications and Case Studies 113–128. https://doi.org/10.1002/9781119698821.CH7.

Braarud, P.Ø., 2021. Investigating the validity of subjective workload rating (NASA TLX) and subjective situation awareness rating (SART) for cognitively complex human–machine work. Int. J. Ind. Ergon. 86 (May) https://doi.org/10.1016/j.ergon.2021.103233.

Cockburn, A., Masson, D., Gutwin, C., Palanque, P., Goguey, A., Yung, M., Gris, C., Trask, C., 2019. Design and evaluation of braced touch for touchscreen input stabilisation. Int. J. Hum. Comput. Stud. 122 (February 2018), 21–37. https://doi.org/10.1016/j.ijhcs.2018.08.005.

Coutts, L.v., Plant, K.L., Smith, M., Bolton, L., Parnell, K.J., Arnold, J., Stanton, N.A., 2019. Future technology on the flight deck: assessing the use of touchscreens in vibration environments. Ergonomics 62 (2), 286–304. https://doi.org/10.1080/00140139.2018.1552013.

Dodd, S., Lancaster, J., Demers, B., Boswell, S., 2019. Multi- touch touch screens on the flight deck: the impact of display location, display Inclination Angle and gesture type on pilot performance. In: AIAA/IEEE Digital Avionics Systems Conference - Proceedings, 2019-September. https://doi.org/10.1109/DASC43569.2019.9081723.

Dodd, S., Lancaster, J., Miranda, A., Grothe, S., De Mers, B., Rogers, B., 2014. Touch screens on the flight deck: the impact of touch target size, spacing, touch technology and turbulence on pilot performance. Ergonomics 6–10. https://doi.org/10.1177/1541931214581002.

European Aviation Safety Agency. (2018). Certification Specifications for Aeroplane Flight Simulation Training Devices 'CS-FSTD(A).' 2, 154. https://www.easa.europa.eu/sites/default/files/dfu/CS-FSTD%28A%29-Issue2.pdf.

Harris, D., 2016. Human performance on the flight deck. Human Performance on the Flight Deck. https://doi.org/10.1201/9781315252988.

Islam, R., Www, W., Capt, G., Garg, A., Linda, R.I., Chowdhury, T., 2008. Evolution of aircraft flight control system and fly-by-light flight control system. International Journal of Emerging Technology and Advanced Engineering 9001 (12). https://www.researchgate.net/publication/328773327.

Jensen, A., 2018. Honeywell Technologies Take to the Skies in Gulfstream's Newest Certified Aircraft. https://aerospace.honeywell.com/us/en/about-us/press-release/2018/07/honeywell-technologies-take-to-the-skies-in-gulfstreams.

Khoshnewiszadeh, A., Pool, D.M., 2021. Mitigation of Biodynamic Feedthrough for touchscreens on the flight deck. Int. J. Hum. Comput. Interact. 37 (7), 680–692. https://doi.org/10.1080/10447318.2021.1890490.

Kim, S.H., Kaber, D.B., 2014. Examining the effects of conformal terrain features in advanced head-up displays on flight performance and pilot situation awareness. Hum. Factors Ergon. Manuf. 24 (4), 386–402. https://doi.org/10.1002/hfm.20501.

Koon, J., 2020. How Fiber Optics Will Propel Future Avionics. https://interactive.aviationtoday.com/how-fiber-optics-will-propel-future-avionics/.

Korek, W.T., Li, W.C., Lu, L., Lone, M., 2022. Investigating pilots' operational Behaviours while interacting with different types of inceptors. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 13307 LNAI 314–325. https://doi.org/10.1007/978-3-031-06086-1_24/COVER.

Krejtz, K., Duchowski, A.T., Niedzielska, A., Biele, C., Krejtz, I., 2018. Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze. PLoS One 13 (9), e0203629. https://doi.org/10.1371/JOURNAL.PONE.0203629.

Lewis, J.R., 2018. The system usability scale: past, present, and future. Int. J. Hum. Comput. Interact. 34 (7), 577–590. https://doi.org/10.1080/10447318.2018.1455307.

Lewis, J.R., Sauro, J., 2009. The factor structure of the system usability scale. *Lecture Notes in computer Science (including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 5619 LNCS 94–103. https://doi.org/10.1007/978-3-642-02806-9_12.

Li, W.C., Liang, Y.H., Korek, W.T., Lin, J.J.H., 2022a. Assessments on human-computer interaction using touchscreen as control inputs in flight operations. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 13307 LNAI 326–338. https://doi.org/10.1007/978-3-031-06086-1_25/COVER.

Li, W.C., Wang, Y., Korek, W.T., 2022b. To be or not to be? Assessment on using touchscreen as inceptor in flight operation. Transport. Res. Procedia 66 (C), 117–124. https://doi.org/10.1016/J.TRPRO.2022.12.013.

Lin, C.J., Lee, Y.H., 2022. Most acceptable and least capable target sizes for zoom-and-click tasks on mobile touchscreens- implications for user performance and applications to interface design. Int. J. Ind. Ergon. 87 https://doi.org/10.1016/j.ergon.2021.103251.

Lobo, J.L., Ser, J. Del, De Simone, F., Presta, R., Collina, S., Moravek, Z., 2016. Cognitive workload classification using eye-tracking and EEG data. Proceedings of the International Conference on Human-Computer Interaction in Aerospace, HCI-Aero 2016. https://doi.org/10.1145/2950112.2964585.

Lone, M.M., 2013. Pilot Modelling for Airframe Loads Analysis. Cranfield University. https://dspace.lib.cranfield.ac.uk/handle/1826/10388.

Lone, M.M., Ruseno, N., Cooke, A.K., 2012. Towards understanding effects of non-linear flight control system elements on inexperienced pilots. Aeronaut. J. 116 (1185), 1201–1206. https://doi.org/10.1017/S0001924000007569.

Nagasawa, T., Li, W.C., 2023. The application of a human-centred design integrated touchscreen display with automated electronic checklist in the flight deck. Lect. Notes Comput. Sci. 14018 LNAI, 135–149. https://doi.org/10.1007/978-3-031-35389-5_10/COVER.

Oshita, M., Ishikawa, H., 2012. Gamepad vs. touchscreen: a comparison of action selection interfaces in computer games. Proceedings - WASA 2012: Workshop at SIGGRAPH Asia 2012 1 (212), 27–31. https://doi.org/10.1145/2425296.2425301.

Robinson, T., Grabski, G., Yugawa, K., Jeffers, J., Green, J., Humphrey, S., 2012. Touchscreen display Enhancements for flight deck applications. SAE International Journal of Aerospace 5 (1), 151–156. https://doi.org/10.4271/2012-01-2116.

Rouwhorst, W., Verhoeven, R., Suijkerbuijk, M., Bos, T., Maij, A., Vermaat, M., Arents, R., 2017. Use of touch screen display applications for aircraft flight control. AIAA/IEEE Digital Avionics Systems Conference - Proceedings, 2017-September. https://doi.org/10.1109/DASC.2017.8102060.

Rupp, M.A., Oppold, P., McConnell, D.S., 2015. Evaluating input device usability as a function of task difficulty in a tracking task. Ergonomics 58 (5), 722–735. https://doi.org/10.1080/00140139.2014.988755.

Sadia, B., Sadic, A., Ayyildiz, M., Basdogan, C., 2022. Exploration strategies for tactile graphics displayed by electrovibration on a touchscreen. Int. J. Hum. Comput. Stud. 160, 102760 https://doi.org/10.1016/J.IJHCS.2021.102760.

Serenko, A., Bontis, N., 2011. What's familiar is excellent: the impact of exposure effect on perceived journal quality. Journal of Informetrics 5 (1), 219–223. https://doi.org/10.1016/j.joi.2010.07.005.

Shin, G., Zhu, X., 2011. User discomfort, work posture and muscle activity while using a touchscreen in a desktop PC setting. Ergonomics 54 (8), 733–744. https://doi.org/10.1080/00140139.2011.592604.

Socha, V., Socha, L., Hanakova, L., Valenta, V., Kusmirek, S., Lalis, A., 2020. Pilots' performance and workload assessment: Transition from Analogue to glass-cockpit. Appl. Sci. 10 (15), 5211. https://doi.org/10.3390/APP10155211.

Tang, J., Weiss, H., Stirling, L., 2023. A comparison of sensorimotor assessment accuracy between augmented reality and touchscreen environments. https://doi.org/10.1177/21695067231192547.

Taylor, R.M., 2017. Situational awareness rating technique (SART): the development of a tool for aircrew systems design. Situational Awareness 111–127. https://doi.org/10.4324/9781315087924-8/SITUATIONAL-AWARENESS-RATING-TECHNIQUE-SART-DEVELOPMENT-TOOL-AIRCREW-SYSTEMS-DESIGN-TAYLOR.

Telfer, A., 2023. Touch control design: Ways of Playing on mobile — mobile free to Play. https://mobilefreetoplay.com/control-mechanics/.

van Zon, N.C.M., Borst, C., Pool, D.M., van Paassen, M.M., 2020. Touchscreens for aircraft navigation tasks: Comparing accuracy and Throughput of three flight deck interfaces using Fitts' law. Hum. Factors 62 (6), 897–908. https://doi.org/10.1177/0018720819862146.

Vertegaal, R., Poupyrev, I., 2008. Organic user interfaces. Commun. ACM 51 (6), 26–30. https://doi.org/10.1145/1349026.1349033.

Vidulich, M.A., Tsang, P.S., 2014. The Confluence of situation awareness and Mental workload for adaptable human–machine systems. J. Cogn. Eng. Decis. Mak. 9 (1), 95–97. https://doi.org/10.1177/1555343414554805.

Vlachogianni, P., Tselios, N., 2022. Perceived usability evaluation of educational technology using the System Usability Scale (SUS): a systematic review. J. Res. Technol. Educ. 54 (3), 392–409. https://doi.org/10.1080/15391523.2020.1867938.

Watkins, C.B., Nilson, C., Taylor, S., Medin, K.B., Kuljanin, I., Nguyen, H.B., 2018. Development of touchscreen displays for the gulfstream G500 and G600 Symmetry^{TM} flight deck. AIAA/IEEE Digital Avionics Systems Conference - Proceedings, 2018-September. https://doi.org/10.1109/DASC.2018.8569532.

Watkins, C.B., Walter, R., 2007. Transitioning from federated avionics architectures to integrated modular Avionics. AIAA/IEEE Digital Avionics Systems Conference - Proceedings. https://doi.org/10.1109/DASC.2007.4391842.

Wickens, C.D., Carswell, C.M., 2016. The proximity compatibility principle: its Psychological Foundation and Relevance to display design. Hum. Factors 37 (3), 473–494. https://doi.org/10.1518/001872095779049408.

Wickens, C.D., Ward, J.Viera, 2017. Cockpit displays of Traffic and weather information: effects of 3D perspective versus 2D Coplanar Rendering and Database integration. International Journal of Aerospace Psychology 27 (1–2), 44–56. https://doi.org/10.1080/10508414.2017.1366270.

Wynne, R.A., Parnell, K.J., Smith, M.A., Plant, K.L., Stanton, N.A., 2021. Can't touch this: Hammer time on touchscreen task performance Variability under simulated turbulent flight conditions. Int. J. Hum. Comput. Interact. 37 (7), 666–679. https://doi.org/10.1080/10447318.2021.1890492/SUPPL_FILE/HIHC_A_1890492_SM1106.ZIP.

Xie, Y., Zhou, R., Qu, J., 2022. Fitts' law on the flight deck: evaluating touchscreens for aircraft tasks in actual flight scenarios. Ergonomics 1–18. https://doi.org/10.1080/00140139.2022.2097318.

Future flight deck design: developing an innovative touchscreen inceptor combined with the primary flight display

Wang, Yifan

2024-04-27

Wang Y, Li WC, Korek WT, Braithwaite G. (2024) Future flight deck design: developing an innovative touchscreen inceptor combined with the primary flight display. International Journal of Industrial Ergonomics, Volume 101, May 2024, Article number 103588

https://doi.org/10.1016/j.ergon.2024.103588