

Pilots' Perceived Workload and Flight Performance while Interacting with Touchscreen Inceptor during Instrument Landings

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Abstract—In this study, to dig into the further potential application of the touchscreen in flight operation, an integrated touchscreen system as the aircraft control inceptor was innovatively proposed. The touchscreen inceptor is integrated into the middle of the primary flight display allowing pilots to control the aircraft's movement horizontally (roll) and vertically (pitch) with their fingers. Fifty-six participants (23 pilots and 33 non-pilots) joined the Future Systems Simulator trail to perform instrument landings using the touchscreen and sidestick in conditions without and with simulated turbulence in vertical and horizontal channels. The heart rate variability reflecting the perceived workload was measured using the Inner Balance device. The flight data related to the flight path, touchdown location, and landing load were collected and calculated as the performance score. The three-way analysis of variance was applied to compare the perceived workload and flight performance between touchscreen and sidestick controllers in different disturbance conditions among pilots and nonpilots. The data analysis results indicated that in the scenario of landing with the disturbance, participants' heart rate variability was improved while interacting with the touchscreen inceptor compared to the sidestick. The flight performance of nonpilots while performing landing tasks with sidestick was significantly lower than pilots. Nevertheless, no significant difference in flight performance was found between nonpilots and pilots when using the touchscreen inceptor. The empirical study indicated that the touchscreen could provide a more intuitive interaction of a 'point-where-you-want-to-go' control technique without the additional input device of sidestick to reduce the mental workload and cognitive stress. Furthermore, there is an evident decrease in performance score with the touchscreen inceptor compared to traditional sidestick due to the unfamiliarity of the touchscreen interactive mode in the prolonged aircraft control process. However, it is notable that nonpilots showed an equal level of flight performance with pilots in landing tasks with touchscreen control, revealing a quick-adapt interactive mode of touchscreen inceptor for novices to perform flight operations. Therefore, the training duration can be remarkably shortened for next-generation pilots, and the cost-efficiency can be improved as well.

Keywords—*future flight deck, touchscreen, aircraft control, heart rate variability, flight performance*

I. INTRODUCTION

Applying touchscreen technology in human-computer interaction was initially proposed over 50 years ago and developed for commercial production by 1983 [1]. Nowadays, touchscreen interfaces have been implemented into day-to-day life, offering human factors and ergonomics benefits to improve user experience and operational performance [2, 3]. Touchscreen technology has significant appeal from the human-centric design perspective to integrate display and input functions in a graphical interface and allow intuitive interaction with users' fingers [4]. In the aviation industry, an integrated touchscreen system allowing data input and information access for commercial aviation on A350 aircraft was certified by EASA in 2019 [5]. This system is a milestone for the evolution of future flight deck design. Previous research demonstrated the effectiveness and advantage of touchscreen input systems in aircraft manipulation and flight operation to decrease task completion time and increase user interface satisfaction [6]. Furthermore, the integrated touchscreen display in the modern flight deck is easily configurable to achieve a human-centred design of interface and functionality without physical input devices change to improve cost-efficiency for airlines and aircraft manufacturers [7]. These considerable benefits motivated increasing involvement and exploration of touchscreen interfaces in the avionics industry for future flight deck design and next-generation flight operations. However, there are still challenges facing the large-scale implementation of touchscreen technology in flight operations. The lack of haptic force feedback in the touchscreen-based system can be detrimental to human-computer interaction efficiency. Without clear system feedback, operators have to devote additional visual attention to the interactive panel, which can negatively impact attention allocation and situation awareness in multi-task operations [8]. Furthermore, from the perspective of human-machine interface (HMI) design, the location of touchscreen interfaces could influence system usability and task performance [9]. Therefore, the human-centric design optimisation in the HMI can be a potential solution to cope with the challenges of the touchscreen implementation in the future flight deck.

The manual control of the aircraft flight path management is one of the eight core pilot competencies

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defined by the International Civil Aviation Organization (ICAO) [10]. Flight path monitoring and controlling require pilots to have excellent cognitive information processing and hand-eye coordination capacities to ensure the successful execution of fine motor skills in control input and appropriate reaction to changing environments and situations [11]. Furthermore, the perceived workload is also a critical factor in influencing manual flight control performance and operational safety [12, 13]. Especially in the innovative system development and implementation process, operators' task performance and perceived workload should be given full consideration for validation purposes. Heart Rate Variability (HRV) is composed of the variations in the interval between successive heartbeats, known as the heartbeat interval (IBIs). The oscillations of healthy hearts enable the cardiovascular system to adapt to any challenges for homeostasis quickly. More than an index of healthy heart function, the HRV state can also reflect the integrative system of the brain for adaptive regulation and provide psychophysiological information related to cognitive capacity in a complex environment [14]. HRV parameters are closely associated with the functions of the cardiovascular system and automatic nervous system for the cognitive process [15]. A previous study has noted that pilots' HRV state is a sensitive measure for detecting gradual changes in task workload and mental effort in flight operations [16]. HRV state is also sensitive to varying task demands and complexity, thus, is closely associated with pilots' decision-making, situation awareness, and flight performance [17, 18]. In the current study, to dig into the further potential application of the touchscreen in flight operation, an integrated touchscreen system as the aircraft control inceptor was innovatively proposed. The performance of manual flight control and perceived workload were collected through flight data analysis and HRV measurement to investigate the applicability of the touchscreen technology as the flight control inceptor.

II. METHODOLOGY

A. Future System Simulator (FSS)

The Cranfield University/Rolls-Royce Future System Simulator (FSS) features a highly reconfigurable and modular futuristic cockpit to explore the human-machine interface of the alternative inceptor in next-generation flight operations. The aircraft model used in the FSS represents the in-service Gulfstream G550 aircraft configuration with a six-touchscreen panel of flight deck displays (Fig. 1a). The innovative touchscreen inceptor is integrated into the middle of the primary flight display (PFD), allowing pilots to control the aircraft's movement horizontally and vertically with their fingers (Fig. 1b). To investigate the applicability of the touchscreen as an alternative aircraft control inceptor, the traditional sidestick controller is also equipped in the FSS as the baseline operational mode (Fig. 1c). The scenarios in the simulated flight trials are landing tasks from 5 miles away to runway 15R at Incheon International Airport. The aircraft speed is 150 knots, the altitude is 1400 ft, and the heading is 90 degrees. Two flight scenario variants are also applied: without disturbance and with disturbance in both vertical and horizontal channels.



Fig. 1. Cranfield University/Rolls-Royce FSS (1a) with the touchscreen inceptor integrated into the middle of the primary flight display (1b) and traditional sidestick controller as the baseline operational mode (1c)

B. Participants

Fifty-six participants, including 12 females, 43 males, and one preferred not to say, joined the simulated flight trials to perform landing tasks with traditional sidestick and innovative touchscreen inceptors based on FSS. Their age ranged from 21 to 63 years old ($M = 31.95$, $SD = 10.82$). Participants were categorised into the 'nonpilot' group without flight experience (33 participants, 58.93%) and the 'pilot' group, who held a certificated license or were attending flying school (23 participants, 41.07%). The flight experience of participants in the pilot group is between 80 and 9,000 hours ($M = 2596.52$, $SD = 2994.01$). As the flight data and HRV parameters were collected from human subjects, the research proposal was submitted to the Cranfield University Research Ethics System for ethical approval. Participants had the right to terminate the experiment at any time and to withdraw their provided data at any moment, even after the data collection. The dataset will be stored anonymously and confidentially. Only authorised researchers can access and analyse the data for research purposes.

C. Data Collection

In this study, an experienced pilot with 7100 flight hours was invited to perform a landing operation as the baseline to compare with other participants' flight performance in the FSS trials. The flight score was ranging from 0 (worst performance) to 100 (best performance). Since the flight trials focus on participants' flight path control performance, the deflection from the baseline flight path was weighted with 75% as the most important aspect of the flight performance score. The remaining 25% of attributes consisted of the touchdown distance error outside the acceptable/desirable margin and maximum downward gravitational force (G-force) upon touchdown. Participants' flight performance score for landing tasks is calculated as follows:

$$FS = 100 - PP_{RMS} \times 75 - (PP_{AccTD} + PP_{DesTD}) \times 5 - PP_G \times 15 \quad (1)$$

Where:

FS: flight score for the landing operational performance;

PP : penalty points, subtracted from 100 in order to calculate the flight score;

PP_{RMS} : the normalised value of root-mean-square error from baseline landing's flight path;

PP_{AccTD} : the normalised value of the distance outside the acceptable margin of the baseline landing' touchdown location (up to 1,000 meters);

PP_{DesTD} : the normalised value of the distance outside the desirable margin of the baseline landing' touchdown location (up to 500 meters);

PP_G : the normalised value of the difference in maximum downward G-force compared to the baseline landing.

The Inner Balance device was applied to measure and collect participants' HRV state during the simulated flight trials. The Inner Balance device is equipped with an ear-attached photoplethysmographic (PPG) sensor for biomarker measurements of the HRV data (Fig. 2a). The HRV parameters can be further calculated and exported using the Kubios software (Fig. 2b). In the current study, the time-domain HRV parameter of the heart inter-beat (R-R) intervals (mean RR) was involved in data analysis to investigate participants' cognitive workload using different control input inceptors under the nondisturbance and disturbance flight scenarios.

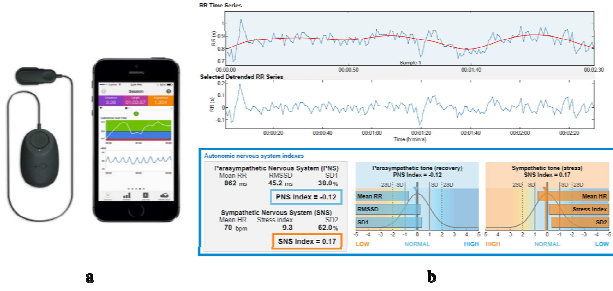


Fig. 2. The HRV state data measured using the Inner Balance device (2a) and processed via the Kubios software (2b)

D. Research Design

Before the FSS flight trials began, participants were informed of the experiment procedures and signed the consent form allowing their HRV parameters and flight data to be collected and analysed. Participants were subsequently asked to use innovative touchscreen and traditional sidestick as flight control inceptors to perform landing tasks under conditions without disturbance and with disturbance. The procedures were as follows: (1) sign the consent form to approve the data collection (five minutes); (2) complete the briefing video regarding the research aim and experimental apparatus, including FSS, sidestick/touchscreen inceptors, and HRV measurements device (10 minutes) (3) provide the demographic information, including age, gender, qualifications, and total flight hours (five minutes); (4) seat in the FSS to practice sidestick and touchscreen operation (10 minutes); (5) perform landing tasks in nondisturbance and disturbance scenarios using the sidestick and the touchscreen inceptors (10 minutes); (6) provide feedback on the usability of sidestick and touchscreen inceptors. The flight data and HRV parameters will be further analysed by three-way ANOVA using SPSS 28.0.0.0 software.

III. RESULTS

A. Sample Characteristics

Fifty-six HRV state and flight performance scores were measured and collected when the participants performed the landing tasks using traditional sidestick and innovative touchscreen inceptors under conditions without and with disturbance. To investigate the influence of 'control inceptor' (sidestick vs touchscreen), 'flight scenario' (nondisturbance vs disturbance), and 'flight experience' (nonpilot vs pilot) on flight performance and perceived workload, three-way ANOVA was applied to analyse the flight performance score and HRV data of mean RR. The sample effect sizes were quantified by partial eta square (η^2). The descriptive statistics are shown in Table I.

TABLE I. MEANS (M) AND STANDARD DEVIATIONS (SD) OF FLIGHT SCORE AND MEAN RR DURING THE FSS SIMULATED FLIGHT TRIALS

	Control inceptor	Flight scenario	Flight experience	N	M (SD)
Flight score	Sidestick	Nondisturbance	Nonpilot	33	69.01 (22.37)
			Pilot	23	86.11 (13.37)
		Disturbance	Nonpilot	33	59.93 (20.28)
			Pilot	23	80.81 (14.83)
	Touchscreen	Nondisturbance	Nonpilot	33	58.85 (22.86)
			Pilot	23	65.58 (12.82)
		Disturbance	Nonpilot	33	48.30 (24.70)
			Pilot	23	60.64 (14.29)
Mean RR (ms)	Sidestick	Nondisturbance	Nonpilot	33	756.63 (91.80)
			Pilot	23	730.94 (158.03)
		Disturbance	Nonpilot	33	743.62 (92.59)
			Pilot	23	724.53 (149.87)
	Touchscreen	Nondisturbance	Nonpilot	33	763.24 (106.14)
			Pilot	23	725.63 (139.84)
		Disturbance	Nonpilot	33	764.53 (96.74)
			Pilot	23	736.58 (139.67)

B. Interaction Effects between Control Inceptor, Flight Scenario, and Flight Experience

Based on the data analysis results, no significant three-way interaction effect on flight score among the 'control inceptor', 'flight scenario', and 'flight experience' was found, $F = 0.08$, $p = .782$. There is a significant two-way interaction effect on flight score between the 'control inceptor' and 'flight experience', $F = 5.19$, $p = .027$, $\eta^2 = 0.088$. The simple main effect analysis showed that pilots' flight score while performing landing tasks using the sidestick is significantly higher than nonpilots, $F(1, 54) = 18.08$, $p < .001$, $\eta^2 = 0.25$. Furthermore, there are significant main effects on the flight score of 'control inceptor', $F(1, 54) = 56.65$, $p < .001$, $\eta^2 = 0.51$; 'flight scenario', $F(1, 54)$

= 16.37, $p < .001$, $\eta^2 = 0.23$; and ‘flight experience’, $F(1, 54) = 11.53$, $p = .001$, $\eta^2 = 0.18$.

There is no significant three-way interaction effect on mean RR among the ‘control inceptor’, ‘flight scenario’, and ‘flight experience’, $F = 0.08$, $p = .773$. A significant two-way interaction of mean RR between ‘control inceptor’ and ‘flight scenario’ was found, $F(1, 54) = 9.05$, $p = .004$, $\eta^2 = 0.14$. The simple effect analysis indicated that in disturbance scenarios, participants’ mean RR was higher while interacting with the touchscreen inceptor compared to the sidestick, $F(1, 54) = 6.74$, $p = .012$, $\eta^2 = 0.11$. Moreover, the disturbance scenario significantly decreased participants’ mean RR during landing tasks using the sidestick inceptor, $F(1, 54) = 5.99$, $p = .018$, $\eta^2 = 0.10$. However, no significant main effect on mean RR was found for ‘control inceptor’, $F = 1.56$, $p = .217$; ‘flight scenario’, $F = 0.41$, $p = .523$; and ‘flight experience’, $F = 0.76$, $p = .387$. The detailed three-way ANOVA results are shown in Table II.

TABLE II. THREE-WAY ANOVA INTERACTION EFFECTS ON FLIGHT SCORE AND MEAN RR

2 × 2 × 2 three-way ANOVA		df Effect	df Error	F	p	η^2
Flight score	Main effect ‘control inceptor’	1	54	56.65	<.001**	.51
	Main effect ‘flight scenario’	1	54	16.37	<.001**	.23
	Main effect ‘flight experience’	1	54	11.53	.001**	.18
	Two-way interaction ‘control inceptor × Flight scenario’	1	54	0.03	.868	.00
	Two-way interaction ‘control inceptor × flight experience’	1	54	5.19	.027*	.09
	Simple main effect ‘control inceptor’ within					
	Nonpilot	1	54	16.77	<.001**	.24
	Pilot	1	54	40.78	<.001**	.43
	Simple main effect ‘flight experience’ within					
	Sidestick	1	54	18.08	<.001**	.25
	Touchscreen	1	54	3.79	.057	.07
	Two-way interaction ‘flight scenario × flight experience’	1	54	1.62	.209	.03
	Three-way interaction ‘control inceptor × flight scenario × flight experience’	1	54	0.08	.782	.00
	Mean RR (ms)					
Mean RR (ms)	Main effect ‘control inceptor’	1	54	1.56	.217	.03
	Main effect ‘flight scenario’	1	54	0.41	.523	.01
	Main effect ‘flight experience’	1	54	0.76	.387	.01
	Two-way	1	54	9.05	.004**	.14

2 × 2 × 2 three-way ANOVA		df Effect	df Error	F	p	η^2
	interaction ‘control inceptor × flight scenario’					
	Simple main effect ‘control inceptor’ within					
	Nondisturbance	1	54	0.01	.937	.00
	Disturbance	1	54	6.74	.012*	.11
	Simple main effect ‘flight scenario’ within					
	Sidestick	1	54	5.99	.018*	.10
	Touchscreen	1	54	2.73	.104	.05
	Two-way interaction ‘control inceptor × flight experience’	1	54	0.57	.452	.01
	Two-way interaction ‘flight scenario × flight experience’	1	54	2.12	.151	.04
	Three-way interaction ‘control inceptor × flight scenario × flight experience’	1	54	0.08	.773	0.00

a. *, $p < .05$

b. **, $p < .01$

IV. DISCUSSION

Although there is a decrease in flight performance while using the touchscreen to control the aircraft movements for landing scenarios compared to the sidestick, the two-way interaction on flight performance between ‘control inceptor’ and ‘flight experience’, as well as the two-way interaction in HRV state between ‘control inceptor’ and ‘flight scenario’ revealed the potential of applying touchscreen inceptor in next-generation flight operations to improve the cost-efficiency of manual flight training and reduce pilots’ cognitive workload in complex flight scenarios.

A. Touchscreen Inceptor Boosting Next-generation Flight Training

The two-way interaction effect on flight performance between the ‘control inceptor’ and ‘flight experience’ demonstrated the experience influences on pilots’ and nonpilots’ operational performance showing different patterns on sidestick and touchscreen inceptors. The simple main effect analysis indicated that pilots’ flight performance ($M = 83.46$, $SD = 14.22$) is significantly higher than nonpilots ($M = 64.47$, $SD = 21.67$) when performing the landing tasks using the traditional sidestick (Fig. 3). However, with the touchscreen inceptor, no significant difference in flight performance between pilots ($M = 63.11$, $SD = 13.65$) and nonpilots ($M = 53.57$, $SD = 24.21$) during the landing tasks (Fig. 3). Previous research indicated in the traditional flight deck with the control wheel or sidestick as the main control inceptors, pilots’ manual handling performance is closely associated with their recent flight experience: lack of manual flight experience would lead to skill fade of significant deviations in the flight path or airspeed for undesirable flight performance [19]. Aircraft

movement control requires high levels of manual dexterity and hand-eye coordination [11]. These abilities are gained and improved via substantial training and practical exercise with a steep learning curve. However, in the current study, the application of the touchscreen inceptor virtually eliminated the experience influence on flight performance, which can be attributed to the widespread touchscreen technology in everyday life. The touchscreen control inceptor can provide pilot trainees with a more intuitive human-system interaction mode to control aircraft movements, which can improve training effectiveness and cognitive performance [20].

Nevertheless, there is indeed a significant decrease in flight performance with the touchscreen inceptor compared to traditional sidestick (table I and Fig. 3), which can be due to the unfamiliarity of the touchscreen interactive mode in the prolonged aircraft control process. The adoption of the sidestick as aircraft control input can date to 1957 when the National Advisory Committee for Aeronautics (NACA) modified a T-33 aircraft with a sidestick controller [21]. Although the touchscreen is ubiquitous in day-to-day life, it is still unconversant in aircraft control. Especially for experienced pilots, the unfamiliar operational experience will bring more dissatisfaction and bias regarding the usage of the touchscreen inceptor. Such bias can be concluded as a negative emotional response to influence their operational performance and engagement [22]. Therefore, the implementation of the innovative touchscreen inceptor in the flight deck requires careful consideration from a human-centric perspective to meet the needs of flight operations and user experience. The touchscreen inceptor can improve the cost-efficiency of flight training; however, pilots switching from the traditional sidestick or control wheel to an innovative touchscreen inceptor for manual operations, as well as the recertification process, will be primary concerns. Furthermore, from the human-centric design principle, it is necessary to apply haptic force feedback in touchscreen inceptor operations to improve human-computer interaction and operational performance [23].

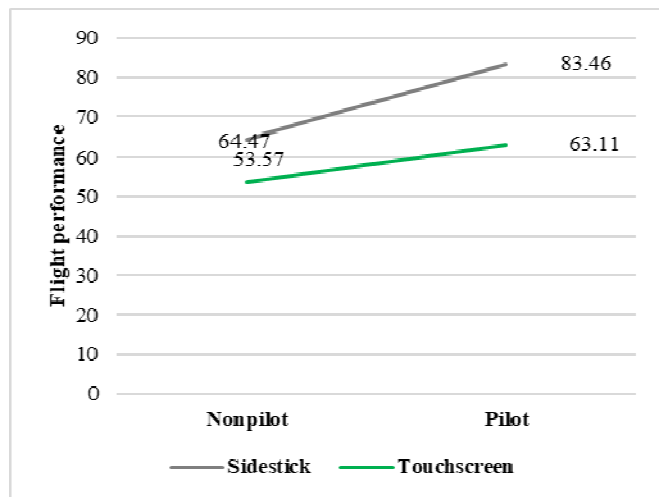


Fig. 3. Two-way interaction effects on flight performance between control inceptor and flight experience

B. Touchscreen Inceptor Moderating Perceived Workload

The decreased mean RR was proved to be closely associated with the mental workload [24]. The two-way interaction effects on mean RR between ‘flight scenario’ and

‘control inceptor’ demonstrated the applicability of the touchscreen inceptor in the complex disturbance scenario to moderate participants’ mental workload. In the disturbance scenario, participants’ mean RR when performing landing tasks using the touchscreen inceptor ($M = 753.05$, $SD = 115.93$) is significantly higher than traditional sidestick ($M = 735.78$, $SD = 118.58$); nevertheless, no significant difference in mean RR between nondisturbance and disturbance scenarios was found in sidestick operations (Fig. 4). These findings indicated the touchscreen control inceptor in landing operation could cause less mental workload and cognitive stress compared with the traditional sidestick in disturbance scenarios. The touchscreen inceptor enables a multitouch gesture of dragging the sensor overlaid on the PFD to control the aircraft attitude of pitch and roll (Fig. 1b). Through this interactive mode, manual flight operations can be performed in a more intuitive way of a “point-where-you-want-to-go” control technique without the additional input device of sidestick. Furthermore, based on the proximity compatibility principle (PCP), the task-relevant information should be rendered close together in perceptual space [25]. In the current research, the centre of the PFD is overlaid with the touchscreen controller. The movements of the control sensor can provide additional information about aircraft attitude without frequent checking and monitoring of navigation display and out-of-window view during flight operation. Therefore, through the reallocation of attention resources, this human-centred design based on PCP can effectively decrease participants’ mental workload and improve cognitive performance [26]. Previous research confirmed the advantage of the touchscreen controller in information supply to facilitate situation awareness during flight operation compared to the traditional sidestick [27].

In landing scenarios, pilots’ overall task loads are mainly from two sources: mental cognitive process and physical activity demand [28]. In the current flight trials, participants need to continuously make force input on the sidestick controller to control the attitude of the aircraft in the landing operation, leading to a higher physical workload and control activity compared to touchscreen operation (Fig. 4). Performing landing tasks with disturbance from both horizontal and vertical channels is a typical “pilot-induced oscillations” scenario, which required higher physical demand and mental workload [29]. Robinson and Brewer indicated that in cognitive tasks, the touchscreen operational mode has benefits on cognitive performance and task workload, including both mental and physical aspects [2]. Furthermore, in flight operation, the tablet touchscreen-based human-machine interface (HMI) can significantly decrease pilots’ workload and improve user interface satisfaction in runway change and rerouting to alternate tasks [30]. Therefore, the application of the touchscreen control inceptor can effectively moderate pilots’ perceived workload from both mental and physical aspects in complex flight scenarios that require frequent and long-term manual operations.

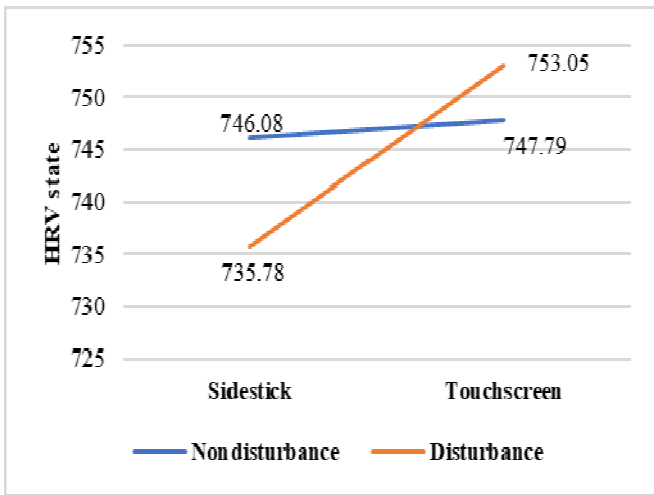


Fig. 4. Two-way interaction effects on HRV state between flight scenario and control inceptor

V. CONCLUSION AND FUTURE WORK

This empirical study revealed the potential of applying an innovative touchscreen system as the flight control inceptor in future flight deck design. The touchscreen inceptor can provide a more intuitive interaction with a ‘point-where-you-want-to-go’ control technique to reduce the perceived workload and cognitive stress during complex flight operational scenarios. It is also notable that nonpilots show an equal level of flight performance to pilots in manually controlling aircraft movements using the touchscreen inceptor. This finding revealed that the application of the touchscreen inceptor could provide a quick-adapt interactive mode for novices to perform manual flight operations. Therefore, the training duration can be remarkably shortened, and the cost-efficiency can be improved in next-generation flight operations. However, there is an evident decrease in flight performance while using the innovative touchscreen inceptor due to the unfamiliarity of the touchscreen interactive mode in the prolonged aircraft control process. Although the touchscreen is ubiquitous in day-to-day life, it is still unconversant in aircraft control, especially for experienced pilots. Therefore, the implementation of the innovative touchscreen inceptor in the future flight deck still requires careful consideration from a human-centric perspective to meet the needs of flight operations and user experience. Pilots switching from the traditional sidestick to an innovative touchscreen inceptor for manual flight path control will be primary concerns. Furthermore, the human-centric design of touchscreen interfaces should be optimised in future studies. Appropriate feedback in touchscreen interfaces should be developed and applied to improve human-computer interaction and operational performance.

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