



Jingyi Zhang

Improving Human Performance in Flight Operations Using
Augmented Reality and Quick Coherence Technique

School of Aerospace, Transport and Manufacturing
Transport Systems

PhD

Academic Year: 2020 - 2023

Supervisor: Dr Wen-Chin Li

Associate Supervisor: Professor Graham Braithwaite

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This thesis is submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

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Abstract

Human errors continuously play a major role in the root cause of air accidents, which brings up the need for effective improvements in pilots' human performance during flight operations. This research addresses two main challenges of pilots' interface to improve the non-technical performance in flight operations from a system human factors perspective.

The first part is related to the human-computer interaction considerations in modern flight decks. An innovative augmented reality (AR) interactive checklist is developed. This AR application blends the virtual holographic checklist and augmented guiding cues within the flight deck and allows multiple input modes of gesture and voice. Compared to the traditional paper-based pre-landing checklist, the voice-command AR can improve cognitive information processing during landing operations. The voice input modality of AR provides a more intuitive and flexible interface to improve human-computer interaction effectiveness. It is also well-applicable in multitasking flight scenarios compared to the gesture-command interaction.

In the second part, the interface between pilots and the societal environment is investigated. The quick coherence technique (QCT) training is applied to address the negative impacts on pilots' psychological health and cognitive performance during the COVID-19 pandemic. The QCT is based on paced breathing exercises and heart rate variability biofeedback. Pilots practise the five-minute QCT not only in day-to-day life but also during flight operations as a controlled rest strategy. The two-month QCT training effectively increases well-being and decreases perceived stress. Practising QCT in the flight deck improves pilots' stress resilience and cognitive functions, subsequently improving human performance and aviation safety.

This research can provide promising solutions to improve human performance and aviation safety. Furthermore, the AR and QCT applications have further practical implications for enhancing pilots' non-technical skills in real operational

scenarios. Also, the safety concerns of single pilot operations related to human capacity can be effectively addressed.

Keywords:

human factors; non-technical skills; human-computer interaction; cognitive information processing; psychological well-being; stress resilience

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Table of Contents

Academic Integrity Declaration	i
Abstract	ii
Acknowledgements	iv
Table of Contents	v
List of Publications	ix
Journal articles	ix
Conference papers	x
List of Figures	xii
List of Tables	xv
List of Abbreviations	xvi
1 Introduction	1
1.1 Research background	1
1.2 Aims and objectives	4
1.3 Thesis structure	5
1.4 Reference	7
2 Literature review	9
2.1 Cognitive information processing in flight operations	11
2.2 Mental workload and psychological stress in flight operations	16
2.3 Augmented reality applications in aviation	19
2.4 Psychophysiological resilience intervention	20
2.5 Reference	22
3 The influences of the augmented reality application on cognitive information processing in flight operations	32
3.1 Introduction	32
3.2 Related work	33
3.2.1 Benefits of applied augmented reality in industries	33
3.2.2 Cognitive process in human-computer interaction	34
3.2.3 Evaluation of cognitive demands on augmented reality applications	35
3.2.4 Implication and hypotheses	36
3.3 Method	38
3.3.1 Participants	38
3.3.2 Apparatus	38
3.3.3 Augmented reality checklist development	40
3.3.4 Research design	41
3.3.5 Statistical analysis	43
3.4 Results	44
3.4.1 Sample characteristics	44
3.4.2 Augmented reality application impacts perceived workload	45
3.4.3 Augmented reality application impacts situation awareness	46

3.5 Discussion	47
3.5.1 Voice-command augmented reality checklist reduces perceived workload.....	47
3.5.2 The interactive mode of augmented reality influences situation awareness.....	50
3.5.3 Considerations of augmented reality applications in the future flight deck	52
3.5.4 Limitations and future work	53
3.6 Conclusion	54
3.7 References	55
4 The impacts of input modality of the AR application on system usability and user interface experience during flight operations	63
4.1 Introduction	63
4.2 Related work.....	64
4.2.1 Multimodal augmented reality technology improves human performance	64
4.2.2 Human-centred flight deck design.....	66
4.2.3 Input modalities in human-computer interaction.....	68
4.2.4 Motivation and hypotheses.....	69
4.3 Method.....	71
4.3.1 Participants	71
4.3.2 Apparatus.....	71
4.3.3 Research design	74
4.3.4 Statistical analysis.....	75
4.4 Results.....	75
4.4.1 Sample characteristics	75
4.4.2 Augmented reality interactive modes impacts system usability	76
4.4.3 Augmented reality interactive modes impacts user interface satisfaction	76
4.4.4 Correlation between gesture-command and voice-command augmented reality interactions	78
4.5 Discussion	79
4.5.1 The control input modality of augmented reality influences system usability	80
4.5.2 Emotional effectiveness impacts user interface satisfaction.....	82
4.5.3 Applicability of voice-command augmented reality in flight operations	83
4.5.4 Limitations and future work	85
4.6 Conclusion	86
4.7 References	87
5 Quick coherence technique training effects on pilots' psychological well-being and stress management	98

5.1 Introduction	98
5.2 Related works	99
5.2.1 Pilots' psychological states affect aviation safety	99
5.2.2 Biofeedback technique improves mental health	101
5.2.3 Self-regulation enhances well-being.....	102
5.2.4 Motivations	104
5.3 Method.....	105
5.3.1 Participants	105
5.3.2 Apparatus and materials	105
5.3.3 Training syllabus	107
5.3.4 Research procedures	107
5.4 Results.....	108
5.4.1 Sample characteristics	108
5.4.2 Quick coherence technique improves psychophysiological coherence	110
5.4.3 Quick coherence technique training effects on well-being and perceived stress	111
5.4.4 Correlation between practice sessions and perceived stress	112
5.5 Discussion	114
5.5.1 Quick coherence technique biofeedback training increases pilots' psychophysiological health.....	114
5.5.2 Habitually practising quick coherence technique enhances training effect on stress management.....	116
5.5.3 Limitations and future work	119
5.6 Conclusions	120
5.7 References	120
6 Quick coherence technique practice effects on pilots' psychological resilience and cognitive associated biomarkers in flight operations	131
6.1 Introduction	131
6.2 Related works	133
6.2.1 COVID-19 pandemic influences psychological health and cognitive function.....	133
6.2.2 Heart rate variability biofeedback paced breathing training improves stress resilience	135
6.2.3 Heart rate variability reflects cognitive performance and psychological resilience	137
6.2.4 Hypotheses development.....	138
6.3 Method.....	139
6.3.1 Participants	139
6.3.2 Quick coherence technique.....	140
6.3.3 Procedures.....	140
6.3.4 Measures	141

6.3.5 Statistical analysis	143
6.4 Results	143
6.4.1 Sample characteristics	143
6.4.2 Quick coherence technique practice effects on psychophysiological indicators in day-to-day life and flight operations....	145
6.4.3 Quick coherence technique practice effects on heart rate variability in day-to-day life and flight operations	146
6.5 Discussion	149
6.5.1 Quick coherence technique training supports commercial pilots' stress management.....	150
6.5.2 Quick coherence technique practice promotes the sympathetic- controlled stress resilience process	151
6.5.3 The controversy of LF/HF regarding stress response and resilience intervention.....	152
6.5.4 Quick coherence technique improves stress resilience and cognitive associated biomarkers in flight operations	153
6.5.5 Practical and theoretical implications	154
6.5.6 Limitations and future work	155
6.6 Conclusion	156
6.7 References	156
7 General discussion	169
7.1 Overview	169
7.2 Human-computer interaction considerations related to advanced technology implemented	170
7.3 Psychophysiological approach to improving human performance and aviation safety	172
7.4 Improving pilots' non-technical performance in flight operational context	173
7.5 Enhancing cognitive capacity to support single pilot operations	176
7.6 Reference	178
8 Conclusion and future work	185
8.1 Conclusion	185
8.2 Limitations and future work	186
8.3 Reference	188
Appendix A Ethical approval letters	189
Appendix B One-way repeated measures ANOVA results of NASA TLX and SART-10D scores	191
Appendix C T-test and Pearson Correlation Analysis results of System Usability Scale and Questionnaire for User Interface Satisfaction scores ..	196

List of Publications

Journal articles

Zhang, J., Li, W-C., Court, S., D. Sevilian, & Braithwaite, G. (2023, under review). Applying interactive augmented reality in flight operations: assessment of system usability and user interface satisfaction. *International Journal of Industrial Ergonomics*.

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Zou, P., Li, W-C., & Zhang, J. (2021). Implementation Digital Tower for Apron Control on a Large-Scale of International Airport. In International Conference on Human-Computer Interaction (pp. 151-159). Springer, Cham. https://doi.org/10.1007/978-3-030-77932-0_13

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List of Figures

Figure 1-1 Basic structure of non-technical skills (adapted from <i>Development of the NOTECHS System for Assessing Pilots' CRM Skills</i> , by R. Flin et al., 2003, p. 101)	2
Figure 2-1 The evolution of the human-computer interaction framework from the SHELL model (2-1a, adapted from <i>Human Performance and Limitations in Aviation</i> , by R. D. Campbell & M. Bagshaw, 2002, p. 4) to the Five Ms model (2-1b, adapted from <i>Human Performance on the Flight Deck</i> , by D. Harris, 2016, p. 8)	11
Figure 2-2 The four-dimensional multiple resource model describing the cognitive information processing (2-2a, adapted from <i>Engineering Psychology and Human Performance</i> , by C. D. Wickens et al., 2021, p. 4) and the structure of multimodal resource components in the complex system (2-2b, adapted from <i>Multiple resources and performance prediction</i> , by C. D. Wickens, 2002, p. 163)	13
Figure 2-3 Situation awareness model in the dynamics decision-making process (adapted from <i>Toward A Theory of Situation Awareness in Dynamic Systems</i> , by M. R. Endsley, 1995, p. 35).....	15
Figure 2-4 Definitions of workload and performance illustrated in the control paradigm (adapted from <i>Definitions, Models and Measures of Human Workload</i> by T. B. Sheridan & R. W. Simpson In N. Moray (eds) <i>Mental Workload: Its Theory and Measurement</i> , 1979, p. 221).....	17
Figure 3-1 The cockpit display systems on the flight simulator on the scenario of instrument landing (3-1a); participant wears the head-mounted display Augmented Reality device (HoloLens) during the experiment (3-1b)	39
Figure 3-2 Participant wears a HoloLens device using gesture-command in the flight simulator (3-2a); participant's point of view in the flight deck while interacting with virtual SOPs on pre-landing checklist by gesture command, the virtual checklist (red) is the currently SOP item, the crosshair (white) centred shows participant's visual attention, the guiding arrows (yellow) indicate the next SOP action to operate Landing-Gear down (3-2b)	41
Figure 3-3 The visual cue design of application on HoloLens for instrument landing, the yellow guiding arrows directing to the position for next action, the yellow text indicating the current SOP (3-3a); HoloLens view of QR code and alignment with a square with a cross in blue colour indicate registration calibration completed in the flight deck (3-3b); visual cues of guiding position for confirmation the execution of checklist in red colour (3-3c)	43
Figure 3-4 The differences of perceived workload by NASA-TLX total scores and six dimensions among three interactive modes on performing ILS pre-landing checklists	46

Figure 3-5 The differences in participants' situation awareness on SART-10D to three interactive modes on performing ILS pre-landing checklists.....	47
Figure 3-6 Participant's point-of-view on wearing HoloLens conducting ILS checklists by gesture-command (3-6a); both gesture-command and voice-command checklists including moving flaps lever to 30-degree (3-6b); moving landing gear DOWN and check green light (3-6c); moving speedbrakes to ARM position (3-6d); and switching landing light ON (3-6e)	50
Figure 4-1 The flight deck display systems of a flight simulator for the experiment of instrument landing (4-1a); the participant wearing a HoloLens (shown in the top left-hand inset) and the perspective while operating the Landing Gear DOWN command following UI instruction (4-1b)	72
Figure 4-2 The opaque SOP menus that use different colours to indicate the status of operations, green indicating executed, red for the current operational step, and grey for standby (4-2a); visual cues of guiding arrows and position indicator (4-2b); 'Air-tap' gesture used for AR interactive mode using yellow arrows for directing pilot's attention to check Landing Light On (4-2c); pilot conducting gesture-command wearing HoloLens while performing 'Speedbrakes On' (4-2d).	73
Figure 4-3 The differences in usability, learnability and SUS scores between AR gesture-command and AR voice-command modes in flight operations based on paired sample t-tests	76
Figure 4-4 The differences in QUIS dimensions between AR gesture-command and AR voice-command in flight operations based on paired t-tests	77
Figure 4-5 The negative correlation of SUS total scores (4-5a) and positive correlation of QUIS scores (4-5b) between AR gesture-command and AR voice-command modes.....	79
Figure 4-6 The augmented visualisation cues to guide pilots in executing required actions to perform instrument landing procedures consisted of the following actions: move the Flap to 30 Degree (4-6a); put the landing gear down (4-6b); move speed brakes to ARM (4-6c); switch landing light on (4-6d)	85
Figure 5-1 The Inner Balance device is a state-of-the-art, ultra-low Bluetooth device with 125 hertz sample rate measuring HRV parameters to optimize accurate HRV and QCT training	106
Figure 5-2 The interaction effect of self-regulated practising QCT and flight duty on pilots' psychophysiological coherence	110
Figure 5-3 The differences in AWSA and PSS scores among three different stages of QCT pre-training, post-training, and two-month self-regulated practising	112
Figure 5-4 The significant negative correlation between PSS score after two-month QCT practice and practice session (5-4a) and nonsignificant association between AWSA score and practice session (5-4b).....	113

Figure 6-1 Comparisons of respiration rate (6-1a) and stress index (6-1b) between baseline measure and QCT practice in day-to-day life and flight operations.....	146
Figure 6-2 Comparisons of HRV time-domain (SDNN, 6-2a & RMSSD, 6-2b) and frequency-time (log-transformed VLF power, 6-2c & LF/HF, 6-2d) parameters between baseline measure and QCT practice in day-to-day life and flight operations.....	149
Figure 7-1 The evolution of crew numbers on the flight deck	177

List of Tables

Table 3-1 The ranking of three checklist modes on perceived workload and situation awareness by NASA-TLX and SART-10D	49
Table 5-1 Means (M) and standard deviations (SD) of pilot's AWSA and PSS scores among three stages of QCT training	109
Table 5-2 Means (M) and standard deviations (SD) of recorded sessions (N) of all participated pilots' psychophysiological state between baseline and practising QCT while off-duty (day-to-day life) and on-duty (flight operations) for two-month practice	109
Table 5-3 Two-way ANOVA interactions, simple main effects, and main effects on pilots' psychophysiological coherence between practising QCT and flight duty.....	111
Table 5-4 Summaries on pilots' experiences shared while practising QCT both on controlled reset in the flight deck and day-to-day life.....	116
Table 6-1 Means (M) and standard deviations (SD) of commercial pilots' psychophysiological indicators and HRV parameters of baseline measures and QCT practices in day-to-day life and flight operation	144
Table 6-2 Two-way ANOVA results on pilots' psychophysiological indicators between practising QCT and flight duty	146
Table 6-3 Two-way ANOVA results on commercial pilots' HRV parameters between practising QCT and flight duty	148
Table 7-1 Main categories and key elements of pilots' non-technical skills in flight operations.....	174

List of Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
APP	Application
AR	Augmented Reality
AI	Artificial Intelligence
ANOVA	Analysis of Variance
ANS	Autonomic Nervous System
APU	Auxiliary Power Unit
AWSA	Ardell Wellness Self-Assessment
CAA	Civil Aviation Authority
CFIT	Controlled Flights into Terrain
CLT	Central Limit Theorem
CRM	Crew Resource Management
EASA	European Union Aviation Safety Agency
EBT	Evidence-Based Training
FAA	Federal Aviation Administration
FOV	Field of View
GDPR	General Data Protection Regulation
GUI	Graphical User Interface
HUD	Head-Up Display
IATA	International Air Transport Association
IBI	Inter-Beat Interval
ICAO	International Civil Aviation Organization
LOSA	Line Operations Safety Audit
LF/HF	Low-Frequency to High-Frequency Power
IMU	Inertial Measurement Unit
ILS	Instrumented Landing System
HCI	Human-Computer Interaction
HD	High-Definition
HMD	Head-Mounted Display
HRV	Heart Rate Variability
M	Mean

MTTR	Mean Time to Repair
MRTK	Microsoft Mixed Reality Toolkit
NASA	National Aeronautics and Space Administration
NASA-TLX	NASA Task Load Index
NASDAC	National Aviation Safety Data Analysis Centre
NM	Nautical Miles
NTSB	National Transportation Safety Board
PCP	Proximity Compatibility Principle
PF	Pilot-Flying
PFD	Primary Flight Display
PM	Pilot-Monitoring
PNS	Parasympathetic Nervous System
PPE	Personal Protective Equipment
PSS	Perceived Stress Scale
PTSD	Post-Traumatic Stress Disorder
QCT	Quick Coherence Technique
Q-Q plot	Quantile-Quantile plot
QUIS	Questionnaire for User Interface Satisfaction
RMSSD	Root Mean Square of The Successive Differences
RSA	Respiratory Sinus Arrhythmia
SARS	Severe Acute Respiratory Syndrome
SART	Situation Awareness Rating Technique
SD	Standard Deviation
SDK	Software Development Kit
SDNN	Normal-to-Normal RR Intervals
SNS	Sympathetic Nervous System
SOP	Standard Operating Procedure
SPO	Single Pilot Operations
SUS	System Usability Scale
UI	User Interface
VFR	Visual Flight Rules
VLF	Very Low Frequency
VR	Virtual Reality

WHO World Health Organization

1 Introduction

1.1 Research background

The emergence of human factors in aviation can be traced back to the early 1940s when investigating the design inadequacies in the flight deck to reduce human error and improve operational safety and performance (Chapanis, 1999). With the improvements in the system reliability and structural integrity of aircraft, human error becomes the primary risk to aviation safety, especially regarding pilots' non-technical performance (Harris, 2016). This alteration acts as a catalyst in the process of human factors discipline development. The human factors perspective has been applied pervasively throughout all aspects of flight deck design and flight operations, particularly emphasising the optimisation of flight crew interfaces to improve non-technical performance in aviation. The critical individual aspects of pilots' non-technical skills, the cognitive skills, include situation awareness and decision-making (Figure 1-1), which have been shown to contribute to flight safety as fundamental components (Flin et al., 2003). The flight deck is a critical computer interface in which pilots perform flight tasks through effective human-computer interaction with the onboard avionic systems. In the modern flight deck, the advanced flight management system integrated numerous sophisticated information and functions. However, the information presentation and control input are limited to the small screens of the control and display unit and the flight deck displays (primary flight display, navigation display, Engine indicating and crew alerting system, etc.). Searching for task-relevant data and maintaining situation awareness for constant information perception require higher cognitive efforts and mental workload, posing potential risks to operational safety. Therefore, the advanced interface between pilots and flight deck should be investigated to improve human-computer interaction and human performance in flight operations. In the current thesis, an innovative interactive checklist based on augmented reality (AR) technology is developed and applied in landing operations. AR is a rapidly emerging technology that allows augmented visualisation of textual and graphical information overlaid with the operational environment and intuitive multimodal interaction of gesture and voice control

(Azuma, 1997). However, from the human factors perspective, technological advancement always comes along with human-computer interaction considerations. Hence, pilots' cognitive information processing while interacting with the AR checklist, as well as the system usability and user interface experience of different interactive modes of the AR system, are investigated.

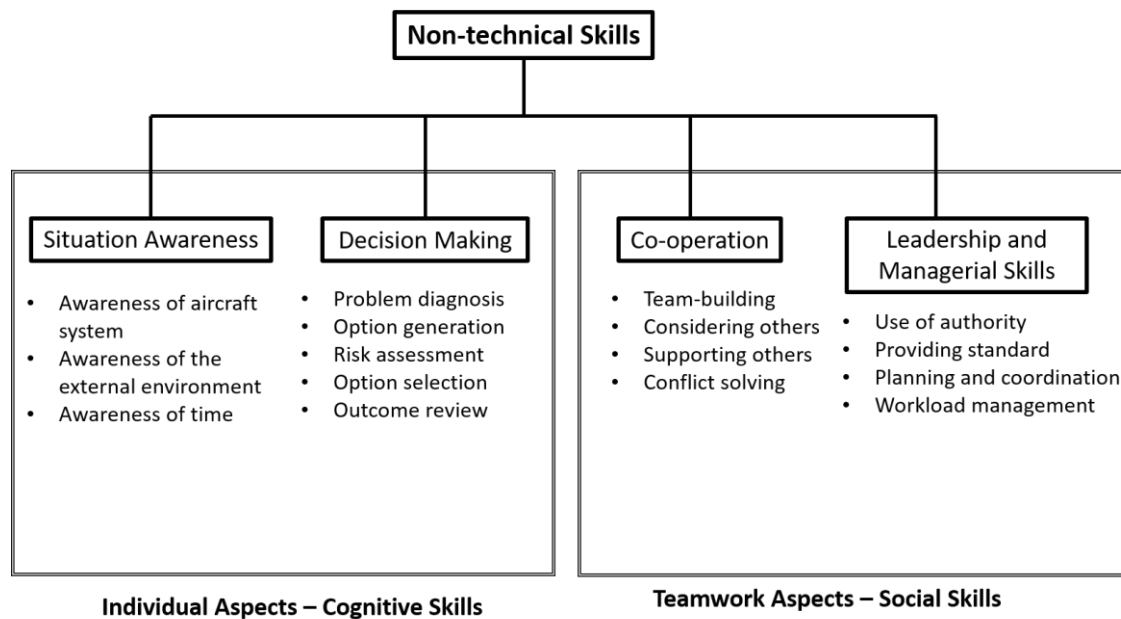


Figure 1-1 Basic structure of non-technical skills (adapted from *Development of the NOTECHS System for Assessing Pilots' CRM Skills*, by R. Flin et al., 2003, p. 101)

Human performance in flight operations is not only associated with human-computer interaction issues caused by the unavailability and inapplicability of advanced technology but also with dramatic social changes external to the aircraft, which can negatively impact pilots' psychological health and cognitive functions. Social pressure is a critical psychological factor influencing pilots' cognitive information processing and decision-making, especially in emergency scenarios (Hunter et al., 2003). The COVID-19 pandemic has been posing sustaining threats across typical daily social life and the entire global aviation industry since 2019. Pilots' internal reactions in this exceptional context under more pressure than usual may manifest as loss of appetite, increased alcohol intake, the use of psychoactive substances, not being able to concentrate, and not being able to sleep (CAA, 2020). These maladaptive stressors caused by the

COVID-19 pandemic led to psychological/physical health decline, cognitive function detriment, and even pilot aircraft-assisted suicide (Vuorio & Bor, 2020). Furthermore, the limited access to the flight deck will decrease pilots' professional proficiency in performing routine flight tasks. Due to prolonged furlough during the pandemic, the lack of recency in practising operational procedures and operating automation systems resulted in pilots suffering from skill fades, directly undermining human performance and operation safety. These compound risks suggest that effective interventions and support programmes are urgently needed to improve pilots' psychological well-being and cognitive functions to ensure aviation safety in the post-pandemic era. Therefore, this thesis developed a training programme based on the quick coherence technique (QCT) and implemented it in an international airline to cope with the negative influence of the COVID-19 pandemic. QCT aims to improve individuals' stress management and cognitive performance through a five-minute paced breathing exercise with real-time heart rate variability (HRV) biofeedback (HeartMath, 2016). Psychophysiological coherence refers to the harmony of the heart, brain, and body related to autonomic nervous system (ANS) balance and cognitive activities. HRV, as an easily measured biomarker of individuals' ANS activities, can reflect cognitive functions and psychological resilience (Thayer & Lane, 2009; Lau et al., 2021). QCT has been proven to be an effective intervention to address accumulated workload and chronic stress, as well as improve psychophysiological well-being and operational performance (e.g. Burke, 2017; Li et al., 2023). By understanding the full implications of QCT, the aviation industry can move forward by creating an effective support programme to improve pilots' psychological/physical well-being, stress resilience, and cognitive performance. The QCT training is not only beneficial to cope with the pandemic-related psychological issues, but also able to be applied as a supplemental strategy of crew resource management training in normal operation scenarios after pandemic to improve non-technical performance and operational safety.

1.2 Aims and objectives

Currently, there are two main challenges to human performance and operational safety in the aviation industry: (1) the long-standing human-computer interaction considerations, which matter in both conventional flight deck design and advanced technology applications; (2) pilots' cognitive and psychological capacities undermined by the enormous shock of COVID-19 pandemic, which still threatens aviation safety in the post-pandemic context. This research aims to investigate effective improvements to pilots' cognitive performance and operational safety by (1) using AR technology to improve human-computer interaction and by (2) implementing QCT training to improve commercial pilots' psychological resilience to the negative impacts of the pandemic. This study consists of four individual objectives as follows:

Objective 1: Compare perceived workload and situation awareness while performing landing tasks with the traditional paper-based checklist and the AR interactive checklists to evaluate the feasibility and effectiveness of applying AR technology in flight operations.

Objective 2: Investigate the system usability and user interface experience of different input modalities of AR (gesture-command vs. voice-command) to identify the appropriate interactive mode and improve human-computer interaction effectiveness in flight operations.

Objective 3: Assess commercial pilots' psychological well-being and perceived stress during the QCT training programme (short-term training course and long-term regular practice) to examine the training effectiveness.

Objective 4: Investigate the HRV fluctuation (time-domain and frequency-domain parameters) while practising the five-minute QCT in daily life and flight operations to identify the influences of QCT practice on pilots' ANS activities, psychological resilience, and cognitive functions.

1.3 Thesis structure

This thesis adopts a paper-format structure based on four journal articles (two published and two under peer review). It is comprised of eight chapters, and the structure can be summarised as follows:

Chapter 1 presents an introduction of the research background/motivation, aim and objectives, and an overview of the thesis structure.

Chapter 2 provides a comprehensive literature review from the system human factors perspective. It includes a critical review of the theoretical framework models for the human performance of non-technical aspects in flight operations, the feasibility of introducing AR applications in flight operations, and the rationale for applying resilience intervention in the context of post-pandemic.

Chapter 3 addresses individual objective one on the application of the AR interactive checklist in landing scenarios. Compared to the traditional paper-based checklist, the voice-command AR can improve cognitive information processing in terms of situation awareness and perceived workload during landing scenarios. The potential of applying AR support systems in flight operations is confirmed to be feasible. The work presented in this chapter has been published in a journal article: *Li, W-C., Zhang, J., Court, S., Kearney, P., & Braithwaite, G. (2022). The influence of augmented reality interaction design on Pilot's perceived workload and situation awareness. International Journal of Industrial Ergonomics, 92, 103382. <https://doi.org/10.1016/j.ergon.2022.103382>.* The author's contributions include data curation, formal analysis, methodology, visualisation, and writing (original draft and review & editing).

Chapter 4 further investigates the human-computer interaction effectiveness of different input modalities of AR as per individual objective two. Through the evaluation and comparison of the system usability and user interface experience between gesture-command and voice-command interactive modes, the applicability and limitations of multimodal AR have been identified for optimising human-computer interaction in flight operations. This study has been submitted for publication in a journal article: *Zhang, J., Li, W-C., Court, S., D. Sevillian, &*

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Chapter 5 corresponds with individual objective three, applying the QCT training programme as an effective stress intervention to improve commercial pilots' psychological well-being, stress management, and psychophysiological coherence. This chapter focuses more on the long-term training effects and emphasises the importance of forming regular QCT practice as habitual behaviour to enhance stress resilience. The outcome of this study has been published as a journal article: *Li, W-C., Zhang, J., Braithwaite, G., & Kearney, P. (2022). Quick coherence technique facilitating commercial pilots' psychophysiological resilience to the impact of COVID-19. Ergonomics, 1-14. <https://doi.org/10.1080/00140139.2022.2139416>.* The author's contributions include data curation, formal analysis, methodology, investigation, visualisation, and writing (original draft and review & editing).

Chapter 6 further analyses the influence of QCT on pilots' psychophysiological indicators, including respiration rate, stress index, and HRV parameters, to examine the short-term QCT practice effects in daily life and flight operations. The HRV fluctuation shows significant improvements in commercial pilots' psychological resilience and cognitive functions through five-minute QCT practice. The findings suggest the potential of developing QCT as an effective control rest strategy in long-haul flights to recharge pilots' psychological and cognitive resources. This work has been submitted for publication as a journal article: *Zhang, J., Li, W-C., Braithwaite, G., & Blundell, J. (2023, under review). Practice effects of a breathing technique on pilots' psychological resilience and cognitive associated biomarkers in flight operations. Stress.* The author's contributions include conceptualisation, data curation, formal analysis, methodology, investigation, visualisation, and writing (original draft and review & editing).

Chapter 7 is an in-depth discussion of the research findings. In this thesis, two main challenges to aviation safety and operational performance are addressed from the system human factors perspective. Further implementations of AR and QCT to enhance pilots' non-technical skills and support single pilot operations are also described.

Chapter 8 concludes all the findings presented in this thesis. Future work for addressing the current research limitations, advancing the AR system development, generalising QCT training in various operational scenarios, etc., are also proposed.

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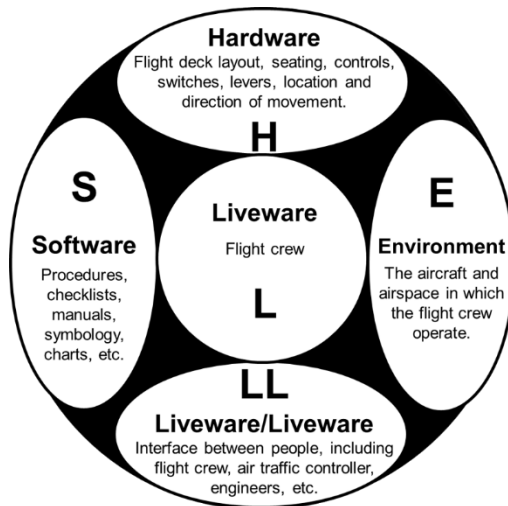
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2 Literature review

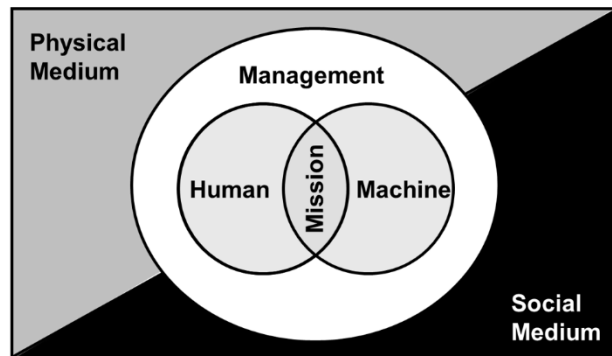
With the developments of material science and engineering techniques in the mid-1960s, improved capabilities and performance of aircraft effectively reduced operational risks (Higton, 2005). Subsequently, however, human errors as the prominent contributing factor began to surface in numerous high-performance aircraft accidents in the 1970s (Reason, 2017). From the 1960s to the 1990s, the estimated contribution of human factors issues with transporting accidents increased from 20 per cent to 80 per cent (Hollnagel, 1993). It is evident that with increasing technical reliability, human errors of the flight deck crew have become the major factors that enormously influence aviation safety until today. The International Air Transport Association (IATA) safety report revealed that pilots' human errors are the main contributing factors in over 70 per cent of accidents in 2022, including standard procedures non-compliance, manual handling errors, inadequate management decisions, lack of monitoring and crossing checking, etc. (IATA, 2023). This statistical report indicated that various factors influence pilots' human performance during the complex human-computer interaction and cognitive processing in flight operations. Besides the adequate knowledge of technical aspects such as aircraft engines, instruments, meteorology, and navigation, non-technical skills are playing an increasingly important role in different dimensions of pilots' performance and competency to impact aviation safety. Therefore, to improve pilots' cognitive and social skills of non-technical performance as flight deck managers of highly automated aircraft systems, crew resource management (CRM) training was widely applied. However, beyond the classroom/simulator-based CRM training, practical solutions in the flight deck are still in pressing need to improve pilots' cognitive processing and psychological capacity based on human factors perspective and human-centred principle.

Aviation is regarded as a socio-technical 'system of systems' consisting of intricate interactions between humans and technology in the operational environment (Harries, 2016; Harris & Stanton, 2010). Edwards (1972) proposed the SHELL model to expound the interfaces between multiple system components (Software, Hardware, Environment, and Liveware) in flight

operations (Figure 2-1a). Harris and Smith (1997) developed the Five Ms model (huMan, Mission, Machine, Management, and Physical/Societal Medium) to extend the human-computer interaction model in the flight deck with considerations of the societal environment from the integrated human factors perspective (Figure 2-1b). From the system human factor perspective, there are currently two major challenges in human performance and aviation safety: (1) the ineffective and inefficient interaction between pilots and implemented technology; (2) the psychological issues and cognitive detriments on pilots caused by the COVID-19 pandemic. In the modern flight deck, the wide-range application of automated electronic systems significantly reduced the traditionally manual tasks in flight operations. Pilots are primarily responsible for monitoring and managing various complex aircraft systems, which place additional cognitive processing demands on flight crews (Rehmann, 1995). This is attributed to the lack of human-centred design in developing and implementing innovative flight deck technologies, which focused more on component functionality and technical performance than pilots' usage and operability (Foyle et al., 2005). Furthermore, the aviation industry has a long history of being influenced by sudden societal changes, such as global pandemics, terror attacks, and financial recession. The most prominent hazard caused by these social changes is pilots' psychosocial stress, which can deteriorate operational performance and aviation safety, even leading to pilot aircraft-assisted suicide (Vuorio & Bor, 2020).



2-1a



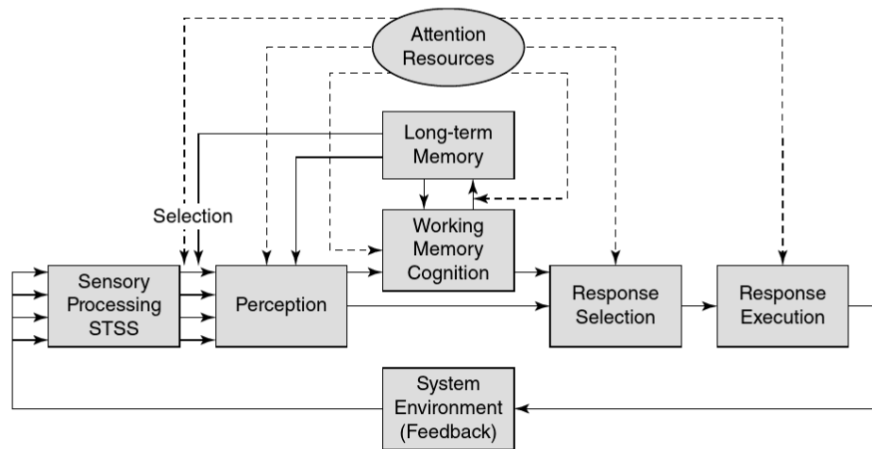
2-1b

Figure 2-1 The evolution of the human-computer interaction framework from the SHELL model (2-1a, adapted from *Human Performance and Limitations in Aviation*, by R. D. Campbell & M. Bagshaw, 2002, p. 4) to the Five Ms model (2-1b, adapted from *Human Performance on the Flight Deck*, by D. Harris, 2016, p. 8)

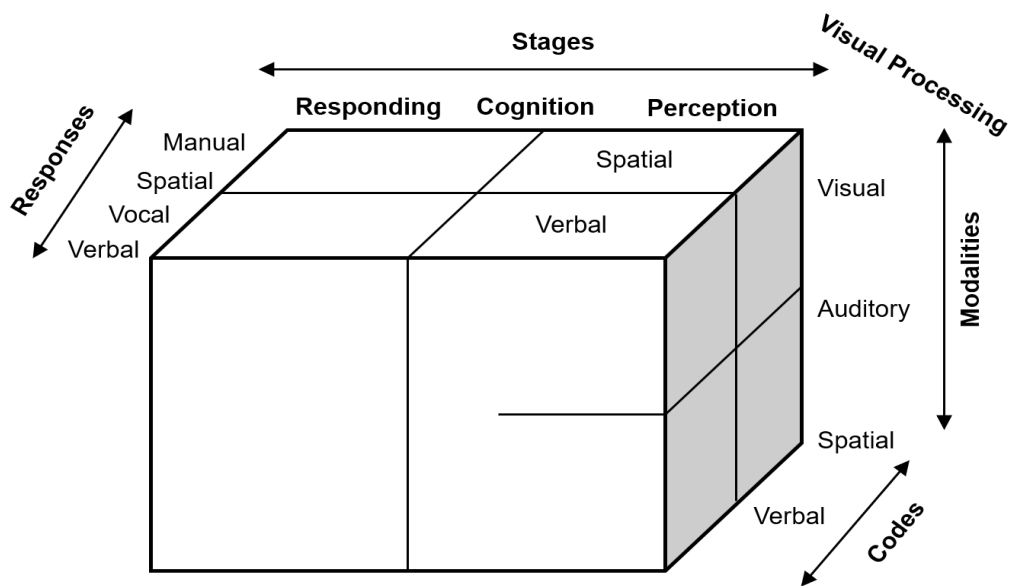
2.1 Cognitive information processing in flight operations

Pilots' cognitive information processing is a key structure in flight operations, including multiple domains of perception, memory, logical reasoning, and learning (Huttunen et al., 2011). Wickens et al. (2021) developed a framework for investigating the typically cognitive/psychological processing series while pilots interact with the complex systems in the flight deck (Figure 2-2). This model demonstrated the four-dimensional cognitive processing (sensory, perception, response selection, and execution) in a multitasking environment with multiple pools of resources and emphasised the vital influence of attention, memory, and feedback throughout various stages. Also, Wickens (2002) highlighted the advantages of applying multimodal resource components from various sensory channels in multi-task scenarios to improve time-sharing efficiency and operational performance. The flight deck is a multi-task environment in which pilots receive task-relevant information from several senses, including visual, tactile, auditory, etc. However, among the large array of sensory information in dynamic flight scenarios, only a small amount can be perceived depending on pilots' cognitive capacity of situation awareness and attention resources. Based

on professional knowledge and continuously perceived information, pilots make decisions to perform flight tasks with high frequency. During flight operations, pilots mostly perform routine tasks, such as initiating checklists and following procedures, which are barely considered decision-making (Vidulich et al., 2010). However, procedure non-compliance issues, both intentionally and unintentionally, still comprise a considerable proportion of air accidents and incidents, which are closely associated with inadequate situation awareness and cognitive processing failures under high-workload scenarios (IATA, 2023).



2-2a



2-2b

Figure 2-2 The four-dimensional multiple resource model describing the cognitive information processing (2-2a, adapted from *Engineering Psychology and Human Performance*, by C. D. Wickens et al., 2021, p. 4) and the structure of multimodal resource components in the complex system (2-2b, adapted from *Multiple resources and performance prediction*, by C. D. Wickens, 2002, p. 163)

Endsley (1995) defined situation awareness in the dynamic decision-making process with a three-level model (Figure 2-3) as 'level 1: the perception of the elements in the environment within a volume of time and space; level 2: the comprehension of their meaning; and level 3: the projection of their status in the near future (pp. 36-37)'. There are closely hierarchical interrelationships among situation awareness, decision-making, and cognitive information process: situation awareness is a key factor in influencing decision-making, and decision-making is a pivotal subdimension under cognitive information processing (Stanton et al., 2001; Zsombok, 1997). Furthermore, when pilots are equipped with sufficient technical and operational capacities, good situation awareness can effectively reduce the possibility of poor flight performance in flight operations (Endsley, 1990). Jones and Endsley (1996) noted that 77.4 per cent of situation awareness errors committed by the flight crew in 143 incidents could be attributed to inefficiency and failure in perceiving needed information (level 1), and 21.1 per cent related to level-2 situation awareness. Level-1 situation awareness is the fundamental and critical process for pilots to perceive the status, attributes, and dynamics of all the relevant elements in operational scenarios via multiple sensory detection. Level-2 and level-3 situation awareness require advanced cognitive information processing to timely and effectively integrate, interpret, retain, and anticipate operation-relevant information derived from level-1 situation awareness (Endsley & Garland, 2000). The significance of level-1 situation awareness is readily apparent.

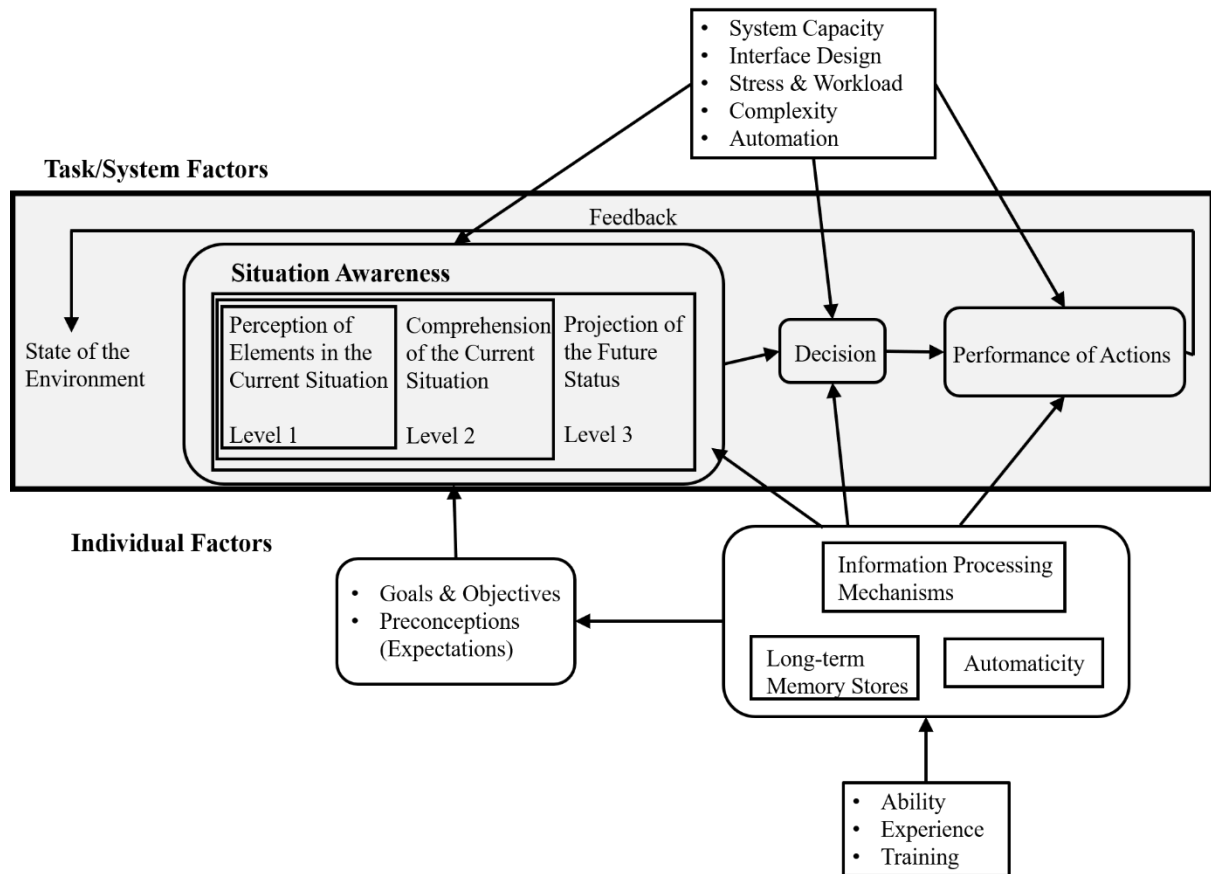


Figure 2-3 Situation awareness model in the dynamics decision-making process (adapted from *Toward A Theory of Situation Awareness in Dynamic Systems*, by M. R. Endsley, 1995, p. 35)

Enhancing pilots' situation awareness requires the human-centred design of display interfaces to support pilots in perceiving and comprehending the critical task-relevant information from huge volumes of data in flight scenarios (Endsley & Garland, 2000b). Fitts and Jones (1947) noted that many accidents resulted from design-induced errors, such as misreading altitude displays, which required the more appropriate human-centred redesign of information presentation equipment. European Union Aviation Safety Agency (EASA, 2021) also emphasised the 'clear and unambiguous presentation of information', requiring the design of display equipment must enable the flight crew to achieve the intended function in an intuitive, consistent, and compatible manner in flight operations, to provide better performance, increase safety, and decreased workload. With the ever-expanding capacity and function of aircraft systems,

deriving desired information and achieving proper situation assessment and decision-making from the huge amount of data and components is a challenge. The effects of system complexity can be alleviated via the user-centred design of the human-machine interface with straightforward, salient, and integrated information presentation to support attention allocation and develop situation awareness in flight operations (Martins, 2016; Endsley, 2012). Furthermore, the intuitive interaction design, which allows the unconscious application of prior knowledge and previous experience, can enhance pilots' capacities of cognitive processing and situation perception, leading to improved decision-making and operational performance (Cellier et al., 1997; Vidulich et al., 2010).

2.2 Mental workload and psychological stress in flight operations

Along with situation awareness, mental workload is the other fundamental topic throughout all aspects of human factors practice in aviation operations, which is regarded as a determinant factor of flight performance and aviation safety (Kantowitz & Casper, 2009). Federal Aviation Administration (FAA, 1993) established Federal Aviation Regulation 25 to specify the workload assessment as a mandatory certification requirement for flight deck design regarding the minimum flight crew. Mental workload occurs when the cognitive system experiences a high load, which is frequently in the modern flight deck with decreased crew members and complex aircraft systems (Harris, 2016). Sheridan and Simpson (1979) developed a model to define pilots' task-relevant mental workload in operational scenarios, depicting the close association between mental workload and cognitive information processing (Figure 2-4). This model also noted that flight tasks require the interconnected implementation of sensory, cognitive, and motor elements, which were limited by pilots' capacity for mental efforts and cognitive resources, thus limiting flight performance (Sheridan & Simpson, 1979). Furthermore, one significant characteristic of flight operations is that pilots frequently perform multiple tasks. For example, during approach and landing scenarios, pilots must perform the pre-landing checklist concurrent with constantly monitoring flight paths, controlling aircraft movements, and

communicating with the tower. The simultaneous primary task, secondary task(s), and potential unexpected emergencies require cognitive ‘spare capacity’, which is related to dramatically increased cognitive efforts and mental workload (Rudner & Lunner, 2014). Wickens (2002, 2008) also noted that based on the multiple resource theory (Figure 2-2), in a multitasking scenario, due to task interference and resource overlap, the sensory channel modalities (unimodal or multimodal) and operators’ limited cognitive resources would influence attention allocation and time-sharing efficiency, leading to mental overload and performance breakdown.

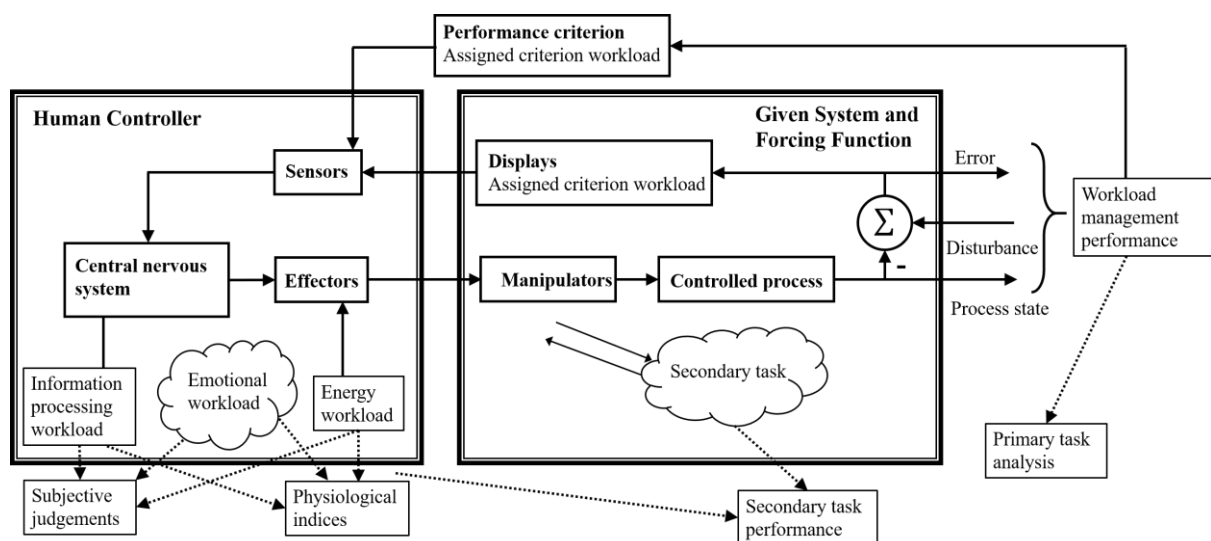


Figure 2-4 Definitions of workload and performance illustrated in the control paradigm (adapted from *Definitions, Models and Measures of Human Workload* by T. B. Sheridan & R. W. Simpson In N. Moray (eds) *Mental Workload: Its Theory and Measurement*, 1979, p. 221)

The increasing level of automation in the flight deck provides several valuable benefits in providing predictable and programmable systems, freeing pilots from most routine psychomotor tasks to reduce physical workload, etc (Kantowitz & Campbell, 1996). However, in the initial generation of the automated flight deck, automation failed to mitigate the overall workload in flight operations as expected. Tenney et al. (1995) suggested that during the taxi, approach, and landing scenarios, pilots’ mental workload in the automated glass flight deck is even higher than in the conventional flight deck. Previous research noted that the

increase in cognitive/mental workload could be caused by the mixed blessing reduction of manual task load, which would further decrease the involvement and resistance to distraction of flight crew in flight operations (Wiener, 1989). Furthermore, automation altered the nature of flight task requirements to emphasise pilots' cognitive information processing and decision-making, leading to increased cognitive efforts and mental workload (Harris, 2016). Endsley and Kaber (1999) indicated that an appropriate level of automation (batch processing support) could minimise pilots' overall workload in flight operations but with the compromises of situation awareness (level-2 and level-3) and manual performance during automation failures. These empirical findings demonstrated the importance of considering pilots' mental workload, as well as the cognitive demands from the system human factors perspective, before implementing any innovative support equipment or systems in the flight deck.

Stress is defined as the physiological and psychological reactions when perceived work-related demands exceed an individual's available resources, which may impact human performance with both short-term and long-term consequences to threaten aviation safety (Martinussen & Hunter, 2010). Prolonged and accumulated stress can negatively affect pilots' cognitive information processing and flight performance (Staal, 2004; Wickens et al., 2017). Albuquerque and Fonseca (2016) identified three categories of stressors that pilots were exposed to. (1) Physical/psychological stressors refer to the specific flight task demands in flight operations, such as the psychomotor efforts to control aircraft movements, uncomfortable flight deck environments, unexpected emergencies, etc. (2) Job-related stressors are related to the organisational and occupational natures of being a pilot, including irregular working hours, role ambiguity and conflict, career development uncertainty, and flight deck hierarchy (Colligan & Higgins, 2006). (3) Personal stressors are related to the challenges of daily life events outside the flight deck, which are also closely associated with pilots' operational performance in the flight deck (Harris, 2016). Personal stressors are currently attracting increasing attention and concerns during the context of the post-pandemic. Recent studies illustrated the significant negative impacts on aviation personnel's psychological health, job motivation, and task

performance caused by the COVID-19 pandemic (Cahill et al., 2021; Kim et al., 2022). Civil Aviation Authority (CAA) also noted that the COVID-19 pandemic posed additional stressors to undermine pilots' psychological well-being and professional skills (decision-making, fatigue/stress management, communication, resistance to distraction, etc.), as well as emphasised the urgent need for effective intervention to improve pilots' psychological resilience and cognitive performance (CAA, 2023).

2.3 Augmented reality applications in aviation

The effectiveness of human-machine integration is a primary consideration in flight deck design to improve human performance and minimise mental workload. With air incidents and accidents constantly related to human-computer interaction errors, as well as the pressing necessity to develop single pilot operations, it offers a window for the feasible applications of advanced pilot support systems based on augmented reality (AR). AR supplements reality by rendering three-dimensional (3D) content superimposed over the real world and allowing users to remain conscious of changes within the surrounding environment (Azuma, 1997). In fact, AR has a long history of being applied to the flight deck in the form of the head-up display (HUD) to support navigation and guidance from the mid-twentieth century (Nicholl, 2014; Safi & Chung, 2023). The HUD, as a non-wearable AR device, integrated the primary flight display with the out-of-window view in a single visual scene to reduce pilots' head-down time, thus improving situation awareness and flight control performance (Kim & Kaber, 2014). However, the fixed non-wearable HUD is limited in the field of view, merely allowing pilots access to the flight information in front of the flight deck window. Therefore, the head-mounted display was developed and proved to be viable practically in the military flight deck since the 1980s (Arthur et al., 2017). The head-mounted display is regarded as a wearable AR device that can provide augmented flight information in pilots' lines of sight across a 360-degree field of view to support demanding manoeuvre and fight scenarios in military flight tasks.

The increasing popularisation of AR technologies in the aviation industry has led to the development and application of various supportive AR interactive systems

in next-generation flight operations for enhancing human-computer interaction and operational performance. Boeing applied an AR support system to streamline the process of wiring installation on the 767 and 747 aircraft production lines with remarkably decreased error rate and task completion time (Boeing, 2018). Performing the aircraft auxiliary power unit (APU) maintenance task with an AR glass revealed significantly faster task time and notably more fluency with ease in component locations and procedurally 'flowed' through the designated checklist items smoothly (Borgen et al., 2021). For the future flight deck design, BAE Systems announced the concept of developing an AR-based flight deck for next-generation flight operations, which would provide pilots with interactive and configurable displays with haptic feedback to improve pilots' situation awareness and user experience, as well as reduce perceived workload (Osborne, 2018). Bell Helicopters also launched a project to develop an advanced flight control system integrating artificial intelligence (AI) and AR, with manual override physical controls and augmented visualisation of flight parameters (Petrescu et al., 2017). However, the wearable AR support system within the flight deck is still far from the threshold of wide-range practical application. Further research and development are needed to gain the momentum of acceptance. Furthermore, the AR interface design must follow the human-centred perspective, such as encompassing salient visual cues to facilitate pilots' attention allocation and cognitive information processing in specific phases of flight (Li et al., 2019).

2.4 Psychophysiological resilience intervention

Pilots' psychological issues persist as an insidious threat to aviation safety due to the impairment of the pilot's cognitive functions and task performance (Marin et al., 2011). Especially since the Germanwings accident in 2015, airline pilots' mental health and psychological states have been brought to the forefront (BEA, 2016). International Civil Aviation Organization (ICAO, 2016) issued a working paper to convene a task force to analyse recent aviation accidents in which a mental health condition was cited as a 'causal factor'. Moreover, the Federal Aviation Administration (FAA, 2021) has included the consideration of psychological conditions and mental health in the medical certification of

commercial pilots. Commercial airlines have focused on pilots' mental health by managing crew fatigue and alertness (Cahill et al., 2021). Furthermore, the mnemonic-type startle and surprise procedures have been proposed to help pilots cope with in-flight startle and surprise, as well as improve decision-making performance (Landman et al., 2020). However, psychological issues and well-being detriments related to chronic and accumulated stress are not properly addressed within existing airline safety management systems due to pilots' concerns about losing their medical certification and jobs (Vuorio & Bor, 2020). The recent context of the COVID pandemic adds to this challenge by posing additional stressors and accumulated mental workload, which may lead to pilots experiencing burnout and serious mental issues, thus threatening aviation safety even after the pandemic crisis has passed (Demerouti et al., 2019; Miani et al., 2021). Therefore, effective intervention programmes to improve pilots' psychological well-being and stress resilience are in urgent need to cope with the negative impacts of the COVID-19 pandemic and improve aviation safety.

Resilience refers to the ability to cope with traumatic events and return to baseline status through psychophysiological processing for self-protection from the potential negative effects of stressors (Robertson et al., 2015). Previous research demonstrated that a high level of psychological resilience has significant long-standing mediation benefits on cognitive information processing (Yang et al., 2021). The paced breathing exercise with heart rate variability (HRV) biofeedback has become a promising intervention tool for an effective alternative psychotherapy treatment to improve stress resilience and psychological well-being (Steffen et al., 2021). The biofeedback of HRV can provide individuals with a greater awareness of psychological status and cognitive functions based on the close association between HRV and autonomic nervous system (ANS) balance (Thayer & Lane, 2009). HRV indicates the oscillations in the interval between consecutive heartbeats (RR intervals) that result mainly from the dynamic interaction between the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS) functions (Malik, 1996). On the other hand, the paced breathing exercise, typically requiring individuals to breathe in a slow frequency of around six to ten cycles per minute, has been proven to significantly

improve psychological resilience and cognitive information processing via the moderation of baroreflex and cardiovascular system capacities (Gevirtz, 2013). Therefore, a resilience training programme based on paced breathing and HRV biofeedback, which is titled the quick coherence technique (QCT), has been widely applied throughout various scenarios of daily life and occupational operations to improve psychological well-being, stress resilience, and cognitive performance (Edwards et al., 2022; McCraty, 2017). The effective improvements in air traffic controllers' fatigue management and HRV state through a five-minute QCT practice indicated a huge potential for developing QCT as a resilience intervention tool and pilot peer support programme to address the negative influences of the pandemic (Li et al., 2023).

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3 The influences of the augmented reality application on cognitive information processing in flight operations

3.1 Introduction

The increasing sensory information in the flight deck may result in a cognitive burden to the pilots and lower their situation awareness. The highly automated cockpit has evolved to encapsulate a plethora of human-computer interaction (HCI) issues. However, such evolution raises questions related to the efficiency of interactions with automated systems on the flight deck (Dorneich et al., 2016). Emerging head-mounted augmented reality (AR) technologies can display rich textual and graphical imagery overlaid upon the operational environment and permit intuitive interaction through gestural and voice modes (Gardony et al., 2018). The development of pilot support systems, such as information automation and augmented visualisation in the flight deck, should be considered from a human factors perspective regarding pilots' cognitive information processing in the initial stage of future flight deck design (Dorneich et al., 2017). HCI research on the impact of AR on the user's perception and cognition has gained importance in recent years due to the advancing technology (Spicer et al., 2017). AR renders three-dimensional (3D) content superimposed over the real world by allowing the user to remain conscious of changes within the surrounding environment to maintain situation awareness. This contrasts with immersive virtual reality (VR), which removes the user from the surrounding environment, thus reducing situational awareness and inducing spatial disorientation (Knibbe et al., 2018). Human perception is constructed in real-time by integrating different sensory modalities, which consist of vision, auditory, haptics and somatosensory. The multisensory integration mechanism is critical to perception, cognition, and adaptive behaviours. The most common feedback on HCI interface design is visual and auditory during interaction with technology (Obrist et al., 2016). Current AR applications have a potential impact on operator performance and perceived workload in safety-critical systems (Stanton et al., 2016) in different ways. Hence,

the application of innovative AR technology in the flight deck requires further investigation for validation and certification purposes.

3.2 Related work

3.2.1 Benefits of applied augmented reality in industries

AR aims to alter the operator's perception of reality and provide support to users through integrated digital content and enhanced perception of the real world. These characteristics have increased researchers' interest in exploring the system usability, monitoring performance and cognitive loads related to AR applications (Beitzel et al., 2016). Moreover, with the development of visual technology, the display resolution of AR devices continues to improve, making AR devices far more relevant to real-world applications (Aromaa et al., 2020). AR has been applied in many fields to benefit the cognitive process, increasing task performance, speeding up the completion time and decreasing the cost of the operation process (Carmigniani et al., 2011). Furthermore, AR technology could support pilots by making meaningful connections between virtual representations of the standard operating procedures (SOP) and specific levers and gauges in the physical environment (Cecilia & Marti, 2005). The use of augmented visualization on head-up displays (HUD) has extended from military aviation to become prevalent in civil aviation on aircraft such as the Boeing 787 and Airbus 350 (Yeh et al., 2003). Virgin Atlantic has implemented a similar AR application to train flight crew members (Virgin, 2018).

Flight operations require real-time information to be perceived, analysed, and filtered for pilots to make in-flight decisions under time pressure. Pilots have to process large amounts of information, resulting in a high mental workload (Dorneich et al., 2016). Compared to traditional displays, AR technology provides additional task-relevant information through the virtual display within the limited operational environment. Through the 3D spatial mapping technique, immersive AR can synchronise the virtual information with its corresponding real object in the operational environment, which can benefit operators' information processing and human-computer interaction. Previous research also demonstrated that the augmented visualisation of immersive AR allows operators to update their

cognitive information processing and enhance situation awareness on a momentary basis in safety-critical scenarios (Grabowski et al., 2018). The most prevalent AR device is the Microsoft HoloLens, with wide applications in the aerospace, manufacturing, automobile, medical, and entertainment industries (Carey, 2018). Various empirical studies have demonstrated the successful applications of HoloLens AR devices in aircraft manufacturing and maintenance to improve operational performance and efficiency (e.g. Boeing, 2018; Borgen et al., 2021). It is also predicted that the use of the AR device will reduce the training time for flight operation per trainee by approximately 75% compared to traditional methods of classroom instruction and practical application (MacPhedran, 2018).

3.2.2 Cognitive process in human-computer interaction

It is often observed that there are sequential multitasking activities confronting pilots (Wickens et al., 2003). This sequential multitasking in flight operations includes how the pilot scans the aircraft instrument panel and may serve different sub-tasks, such as the control of heading, altitude, or the display of navigational hazards. The cognitive process of task switching described requires a high level of situation awareness to make appropriate decisions in safety-critical and dynamic systems. AR has been shown to support information processing since the virtual objects do not require any continuous interaction and could instead provide augmented support to enhance the operator's situation awareness (Aromaa et al., 2020). Situation awareness was described by Endsley (1988) as 'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future'. The dynamic cues provided by augmented visualization on AR devices could lessen pilots' cognitive loads by following visual cues that facilitate attention distribution and situation awareness on the flight deck (Li et al., 2020).

AR devices can allow the operator to attain multiple methods of interaction, including gesture-command and voice-command. AR devices can mitigate the problems by projecting visual feedback on the interface and auditory feedback through device speakers, hence improving operators' situation awareness performance and decision-making (Rowen et al., 2019). The application of AR in

flight deck Head-up displays (HUDs) provides operational benefits on situation awareness and workload for the flight crew (Kramer et al., 2009). The interface designs relating to the effectiveness of HCI could also affect the level of physical demand, mental demand and lack of comfort while performing safety-critical tasks due to the burdensome weight of the head-mounted display (Kim et al., 2019). Alternatively, AR could reduce the cognitive workload by integrating multiple sources of information (Neumann & Majoros, 1998). The AR technology developed based on the Microsoft Mixed Reality Toolkit (MRTK) can provide a highly supported operational environment that replaces traditional instructions and procedural descriptions with multimedia data and flexible interaction paradigms (Microsoft, 2022). Operators not only complete tasks more efficiently but also reduce the mental workload to comprehend the presented information, thus improving operational efficiency and task performance (Chu & Ko, 2021). It has been demonstrated that the use of AR has helped engineers reduce the cognitive workload on comprehension time and their overall efficiency in maintenance tasks (Yang et al., 2019).

3.2.3 Evaluation of cognitive demands on augmented reality applications

The correct assessment of AR applications linked to pilots' workload and situation awareness is of critical importance in safety and human factors in aviation. The NASA task load index (NASA-TLX) and situation awareness rating technique (SART) are popular subjective measurements of cognitive demands which measure operators' perceived workload and situation awareness on the completion of a task (Taylor, 1990; Hart & Staveland, 1998; Endsley et al., 1998). Workload is normally self-evaluated and reflects an individual perception of a multidimensional concept, covering mental and physical effort, frustration, or time constraints that go beyond the objective task difficulty and demands (Fernandes & Braarud, 2015). The evaluation of cognitive workload often leads to variations in multiple dimensions, and disentangling each respective impact remains complex. However, an intensive cognitive activity may yield a high level of workload without eliciting a high level of stress, and thus, a high level of stress might occur even when the workload is low (Hidalgo-Muñoz et al., 2018). There

are three main methods to measure cognitive workload: subjective surveys, performance metrics and assessing physiological response. Each method has its strengths and weaknesses when applied to real-world situations (Hart & Staveland, 1988).

Pilots' cognitive process in the flight deck is both environment- and subject-dependent. It changes amongst different operational stages, the complexity of tasks and the design of automated systems. Pilots' perception, comprehension, and projection of dynamic information on the flight deck reflect the requirement of three-level situation awareness in the current operational environment and tasks (Endsley, 1995). Measures of situation awareness provide an index of how well operators can integrate information in a complex environment where data may strive for their attention. Several techniques for situation awareness measurement have been developed. One of the most used and tested widely is the Situation Awareness Rating Technique (SART, Taylor, 1990). SART is a simplistic post-trial subjective assessment that was originally developed for assessing pilots' situation awareness based on their performance of the current task. The ratings are then combined into three dimensions: (1) demands on attentional resources, (2) supply of attentional resources, and (3) understanding of the situation. SART scores have been found to be correlated with operator performance in evaluations of cockpit designs and subjective measures of workload (Selcon & Taylor, 1990).

3.2.4 Implication and hypotheses

The implementation of AR on the flight deck introduced new HCI paradigms by blending augmented visual stimulus and objectives with the operating environment. The design principles of AR must be consistent with human cognitive information processing, which is the key element in ensuring innovative technology can be used by human operators. The AR checklist developed in this research has holographic interactive menus, voice-command vs. gesture-command, and spatial overlay. The use of AR gesture-commands has been compared with voice-commands since both interactive modes are available with the first-generation HoloLens. The direction indicators of guiding arrows and

spatial highlights have been added to facilitate the pilots' situation awareness. This study has been motivated by previous research on AR applications for flight deck design and single pilot operations (Tran et al., 2018; Comerford and Johnson, 2007; Hilton, 2012). The rationale is that well-designed AR interaction modes can improve pilots' situation awareness and reduce perceived workload. Pilots' cognitive aspects, when correlated to the properties of an AR device, could influence decision-making performance with offloaded information processing by means of supplemented visual cues (Fiore & Wiltshire, 2016). Therefore, in the current study, the visual interface of AR checklists was designed following the proximity compatibility principle (PCP), to integrate different sources of information in close spatial vicinity to facilitate operators using one gaze to catch all critical information (Wickens & Carswell, 1995). Furthermore, based on 3D mapping, the AR interactive checklists also provide visual cues guiding pilots' attention to the task-relevant equipment and synchronise the relevant information superimposing the equipment in the flight deck. The objectives of this research were to evaluate the cognitive demands and situation awareness while using different AR interactive modes during instrumented landing system (ILS) scenarios. The operation with the traditional paper-based checklist was used as the baseline for comparison with AR gesture-command and voice-command interactions. In order to ensure that all participants have a same-level familiarity with the AR interface, tutorial briefing and test practice of the HoloLens device and the ILS operations were conducted before the commencement of the simulated flight trial. This research identified the following two hypotheses regarding the pilots' perceived workload and situation awareness while interacting with AR control modes:

H₁: There are significant differences in pilots' perceived workload using different AR interactive modes on ILS landing

H₂: There are significant differences in pilots' situation awareness while using different AR interactive modes on ILS landing

3.3 Method

3.3.1 Participants

There were 34 participants, including six females (17.65%) and 28 males (82.35%), aged between 21 and 55 years old ($M = 29.79, SD = 9.85$) attending this trial. All participants were current practitioners in the aviation industry, including 15 pilots (44.12%) and 19 avionics engineers (55.88%) with flight experience ranging from 0 hours to 3,000 hours ($M = 436.00, SD = 915.45$). The research proposal has been approved by the research institute ethics committee before conducting the experiment since this research involved collecting data from human subjects. Each participant was required to sign a consent form, which provided detailed information related to the experiment and the content of the data collection. Participants were also informed that they had the rights to terminate and withdraw from the experiment at any stage, even after the data collection phase. This research has followed the Data Protection Act under the UK's general data protection regulation (GDPR).

3.3.2 Apparatus

3.3.2.1 Flight simulator

The experiment was conducted on a Large Aircraft Flight Simulator with a representative model of the Boeing 747 flight deck. It comprises a realistic mock-up of a Boeing commercial aircraft cockpit with functioning flight controls, stick-shaker stall warning, over-speed alerts, primary flight display, navigation display, and a landing gear lever, to name a few. The simplified overhead panel is composed of light switches, engine fire emergency levers and engine ignition switches (Figure 3-1a). The International Civil Aviation Organization (ICAO, 2013) established a new methodology for the development of a recurrent training and assessment programme known as evidence-based training (EBT). The aim of this programme is to identify, develop and evaluate the competencies required to operate safely and efficiently in a commercial flight operation whilst addressing the most relevant threats according to evidence collected during accidents/incidents and training. The scenario investigated by this research is an

ILS task during the final approach. The rationale for selecting an ILS scenario for testing AR interactive modes is that the ILS provides pilots with both vertical and horizontal guidance during an approach to land and is used for the majority of landings in flight operations that relate to HCI and aviation safety. ILS is most beneficial to the pilots when the visibility is poor since it guides the pilots to fly the aircraft all the way down to the runway precisely. For the investigated scenario, the aircraft is set at 2000 ft. and eight nautical miles (NM) from the airfield. As soon as the simulation starts, participants must execute a pre-landing checklist by interacting with the AR device and flying the aircraft to a successful landing.



3-1a



3-1b

Figure 3-1 The cockpit display systems on the flight simulator on the scenario of instrument landing (3-1a); participant wears the head-mounted display Augmented Reality device (HoloLens) during the experiment (3-1b)

3.3.2.2 Augmented reality device

The AR device used in the experiment is the first-generation HoloLens headset (Figure 3-1b). These glasses comprise see-through holographic waveguides, two high-definition (HD) 16:9 light engines and built-in processors that can display holograms with a resolution of 1280×720 pixels per eye, a field of view (FOV) of 30°×17.5° and a refresh rate of 60 hertz. Brightness and audio volume can be adjusted by four buttons located on the headset. The HoloLens comes with built-in sensors: an inertial measurement unit (IMU), four environment-understanding cameras, one depth camera, one two-million-pixel photo/HD video camera, four microphones and one ambient light sensor. Its audio output consists of two speakers located near the user's ears that can emit spatial sound. The colour

contrast of an AR application depends on the light and colour conditions of the user interface design, which can be variable, as there is flexibility to establish rules for AR user interface (UI) design (Microsoft, 2015).

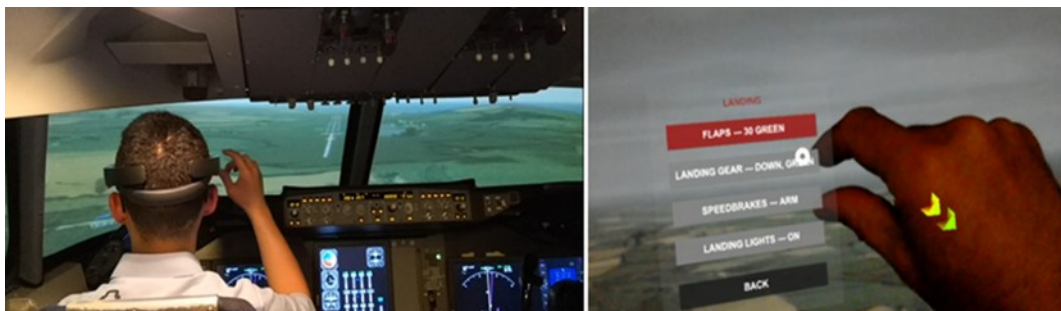
3.3.2.3 NASA-TLX and SART-10D

The NASA-TLX is a popular technique for measuring subjective perceived workload and is composed of six sub-scales, mental demand, physical demand, temporal demand, performance, effort, and frustration. The participant must rate the sub-scales with a score that can range from low (0) to high (100). Ten-dimensional situation awareness rating technique (SART-10D) is an easy-use technique to evaluate situation awareness in operational scenarios with ten elements corresponding to three basic dimensions: Understanding (U), Demand (D), and Supply (S). Participants rated each element with a score from low (1) to high (7). The SART-10D score will be calculated as $SART\ 10D = U - (D - S)$. In the current study, NASA-TLX and SART-10D were applied to assess participants' perceived workload and situation awareness while interacting with the traditional checklist, AR gesture-command checklist, and AR voice-command checklist in an ILS landing scenario.

3.3.3 Augmented reality checklist development

The application to create virtual checklist SOPs on the HoloLens has been developed using the Unity 3D game engine and MRTK (Microsoft, 2022), as well as prepared specifically to be used with the B747 simulator. Participants must follow the procedures to control flap, airspeed, altitude, descent rate, flare, and touchdown for safe operation. The MRTK provides powerful support in interface design for presenting multimedia data and flexibility in interactive modes. Based on the PCP of human-centred design, the AR interactive checklist presents an integrated ILS pre-landing procedure. Once a checklist item is performed, visual cues will be automatically activated to guide pilots' attention to the task-relevant equipment in the flight deck. After finishing the required procedure, the AR interactive checklist will provide visual-auditory feedback to verify the procedure compliance. Furthermore, interacting with the AR checklist can be triggered either by voice control or gesture control ('air-tap'). With gesture control, the participant

moves the central cursor with his hand and selects a checklist item by placing the cursor over it and performing the 'air-tap' gesture (pinch) within the depth camera FOV (Figure 3-2a). With AR voice-command interaction, all visual cues and physical settings in the flight simulator are exactly the same as the gesture-command mode; the only difference is that participants must read aloud the checklist title in order to activate it and validate each checklist item by stating 'Check'. The virtual SOPs on the HoloLens were integrated within the flight simulator, including Flap 30-Degree, Landing Gear-DOWN, Speedbrakes-ARM, and Landing Lights-ON (Figure 3-2b). The symbolic objects on the HoloLens that are linked to the visual appearance provide the user with valuable indications of the functions and actions, such as arrows, circles, QR codes, and text boxes. The yellow arrow indicators and attentional cycles on the AR checklist are to increase participants' situation awareness during flight operations. The corresponding animation within the AR can facilitate participants' attention to the clue to reduce cognitive demand.



3-2a

3-2b

Figure 3-2 Participant wears a HoloLens device using gesture-command in the flight simulator (3-2a); participant's point of view in the flight deck while interacting with virtual SOPs on pre-landing checklist by gesture command, the virtual checklist (red) is the currently SOP item, the crosshair (white) centred shows participant's visual attention, the guiding arrows (yellow) indicate the next SOP action to operate Landing-Gear down (3-2b)

3.3.4 Research design

Participants were briefed that the experiment would involve them wearing a HoloLens AR device. They would also be required to perform the ILS landing

procedures in a flight simulator using different types of interaction modes for checklists. Due to the limitations on collecting flight data and pilots' performance, this study has only analysed pilots' situation awareness and perceived workload based on the subjective questionnaires of NASA-TLX and SART-10D. Participants are required to fill in the questionnaires immediately after each trial. All participants had no previous experience using the HoloLens AR device. Therefore, familiarity with the HoloLens interactive modes is a critical factor in this research. Participants received the same instruction and demonstration on how to interact with HoloLens for instrument landing using gesture-command and voice-command interactive modes. Each participant was offered sufficient time for practising HoloLens until they were comfortable with the different interactive modes. All participants had accurately interacted with the HoloLens using both gesture-command 'air-tap' and voice-command after a practising time ranging between five to ten minutes. All participants were asked to accomplish the following tasks: (1) complete the demographic variables including age, gender, qualifications, and total flight hours (five minutes); (2) complete a briefing regarding the purpose of the study and how to interact with HoloLens on the instrument landing scenario (10 minutes); (3) sit in the flight simulator (Figure 3-3a) to calibrate the AR device (Figure 3-3b) (five minutes); (4) familiarize with the instrument landing checklist on the simulator (10 minutes); (5) complete the briefing on the AR checklist application as shown in Figure 3-3c, with a detailed explanation of the visual highlights by gesture control and voice control (10 minutes); (6) perform a landing using three different checklists randomly: traditional checklist, HoloLens AR gesture command checklist and AR voice command checklist (each scenario lasting between three and five minutes depending on the participant's experience and operational performance). A random table for these three different types of checklists was generated to counterbalance practice effects; (7) complete evaluation forms using both NASA-TLX and SART-10D and provide feedback regarding the cognitive demands of using an AR device during flight operations (15 minutes). The duration of the experiment lasted around 70 minutes for each participant.



3-3a

3-3b

3-3c

Figure 3-3 The visual cue design of application on HoloLens for instrument landing, the yellow guiding arrows directing to the position for next action, the yellow text indicating the current SOP (3-3a); HoloLens view of QR code and alignment with a square with a cross in blue colour indicate registration calibration completed in the flight deck (3-3b); visual cues of guiding position for confirmation the execution of checklist in red colour (3-3c)

3.3.5 Statistical analysis

To investigate the effects of the three interactive modes of checklist on both pilots' perceived workload and situation awareness when performing ILS pre-landing checklists, one-way repeated measures analysis of variance (ANOVA) is applied in data analysis. The application of one-way repeated measures ANOVA can eliminate the influence of participants' individual differences (such as flight experience) so that an unbiased analysis of the three interactive modes (traditional paper-based checklist, AR gesture-command checklist, and AR voice-command checklist) can be obtained. The outliers were tested based on the lower quartile (Q1, 25th percentile) and upper quartile (Q3, 75th percentile) in the boxplot. The upper and lower fences are set at 1.5 times the interquartile range (Q3-Q1), and any observation outside these fences is considered a potential outlier. The assumption of normality was checked visually by quantile-quantile (Q-Q) plots. The observed values lie close to and approximately distributed evenly on both sides of the reference line of standardized normal distribution, which indicates that these data sets are in the normal distribution. Mauchly's test was used to verify the homogeneity of covariance assumption. The Huynh-Feldt correction would be applied if Mauchly's test were violated. The post-hoc pairwise

comparisons were performed using the Bonferroni test, and the effect sizes of samples were quantified by partial eta square (η_p^2).

3.4 Results

3.4.1 Sample characteristics

The sample size is a crucial characteristic of experimental analysis, especially when the population parameters are unknown. Based on the central limit theorem (CLT), a sample size of 30 can increase the confidence interval of the population data set enough to warrant assertions against the findings of statistical analysis (Chang et al., 2006). In the current study, the 34 samples for one-way repeated measures ANOVA are an acceptable sample size for applied research in the aviation domain. Based on the visual examination of the quantile-quantile (Q-Q) plots, the NASA-TLX and SART-10D data on three interactive modes were distributed normally. The analysis of the six dimensions of NASA-TLX boxplots demonstrated that potential outliers were found in physical demand on AR gesture-command (5.88%), temporal demand on AR voice-command (2.94%), performance on both AR gesture-command (2.94%) and voice-command (8.82%); and effort on AR gesture-command (5.88%). According to the sensitivity analysis by running one-way repeated measures ANOVA on both entire and without-outlier data, the outliers show no influence on statistical analysis results. As a result, these outliers were included in further data analysis and results report. The dimension of temporal demand violated the homogeneity of covariance assumption on Mauchly's test ($\chi^2 = 10.36, p < .01, \varepsilon = .82$); therefore Huynh-Feldt ($\varepsilon > .75$) was applied to correct the degree of freedom. There is no outlier, and all assumptions are met on SART-10D. Participants' perceived workload and situation awareness on three interactive modes (Mode 1: traditional, Mode 2: AR gesture-command, and Mode 3: AR voice-command) by NASA-TLX and SART-10D are analysed and compared. The descriptive statistics of each item and subdimension of NASA-TLX and SART-10D scores on three interactive modes whilst performing ILS pre-landing checklists are shown in Tables B-1 & B-2 in Appendix B.

3.4.2 Augmented reality application impacts perceived workload

There is a significant difference in perceived workload by NASA-TLX total score while pilots interacted with three modes on the pre-landing checklist, $F(2, 66) = 41.36, p < .001, \eta_p^2 = 0.56$. Therefore, 'H₁: There are significant differences in pilots' perceived workload using different AR interactive modes on ILS landing' is supported. The post-hoc comparison indicates that the AR gesture-command induced a significantly higher workload than the traditional mode ($p < .001$) and AR voice-command ($p < .001$). Furthermore, there is a significant difference in pilots' Mental demand among the three interactive modes, $F(2, 66) = 12.40, p < .001, \eta_p^2 = 0.27$. The post-hoc comparison shows that the mental demand for the AR gesture-command interaction is significantly higher than traditional ($p = .002$) and AR voice-command ($p < .001$) modes. There is a significant difference in physical demand among the three modes, $F(2, 66) = 44.89, p < .001, \eta_p^2 = 0.58$. The post-hoc comparison shows that the physical demand for the AR gesture-command interaction is significantly higher than the traditional checklist ($p < .001$) and AR voice-command interaction ($p < .001$). There is a significant difference in temporal demand among the three interactive modes, $F(2, 66) = 14.32, p < .001, \eta_p^2 = 0.30$. The post-hoc comparison shows that the temporal demand for the AR gesture-command interaction is significantly higher than the traditional checklist ($p = .008$) and AR voice-command interaction ($p < .001$). There is a significant difference in performance among the three interactive modes, $F(2, 66) = 18.71, p < .001, \eta_p^2 = 0.36$. The post-hoc comparison shows that participants' performance while using the AR gesture-command checklist is significantly lower than the traditional mode ($p < .001$) and AR voice-command interaction ($p < .001$). There is a significant difference in effort among the three modes, $F(2, 66) = 38.56, p < .001, \eta_p^2 = 0.54$. The post-hoc comparison shows that participants' effort when interacting with the AR gesture-command checklist is significantly higher than the traditional mode ($p < .001$) and AR voice-command mode ($p < .001$). There is a significant difference in frustration among the three different interactive modes, $F(2, 66) = 31.64, p < .001, \eta_p^2 = 0.49$. Post-hoc comparison shows that participants' frustration using

the AR gesture-command mode ($M = 69.12, SD = 19.44$) is significantly higher than the traditional mode ($p < .001$) and the AR voice-command mode ($p < .001$). The differences in perceived workload by NASA-TLX among three interactive modes of performing ILS pre-landing checklists are shown in Figure 3-4.

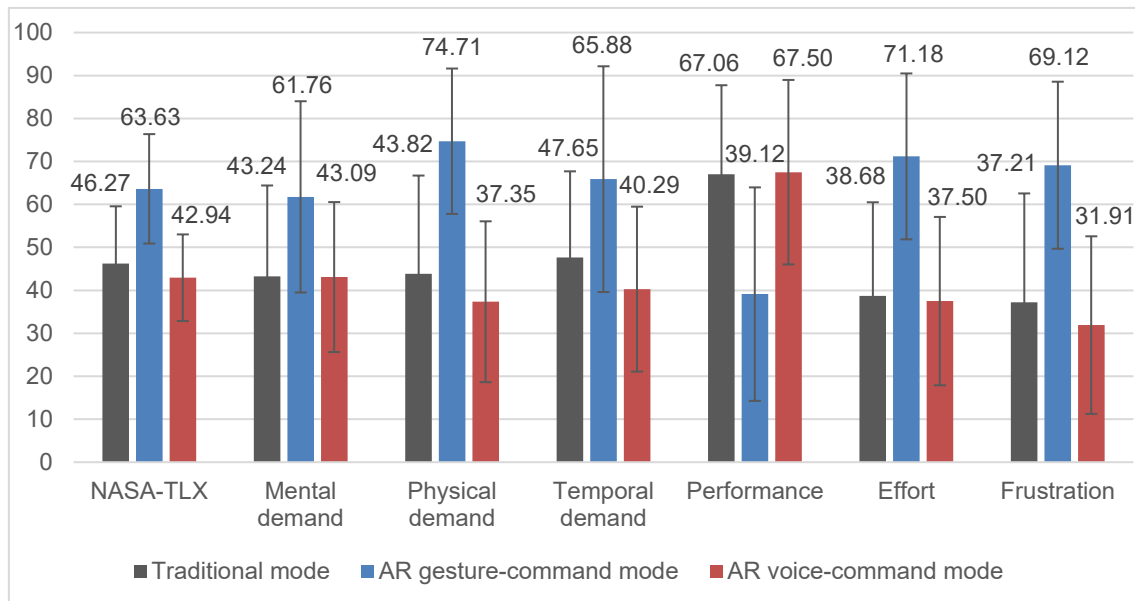


Figure 3-4 The differences of perceived workload by NASA-TLX total scores and six dimensions among three interactive modes on performing ILS pre-landing checklists

3.4.3 Augmented reality application impacts situation awareness

There is a significant difference in pilots' situation awareness among the three interactive modes, $F(2, 66) = 19.87, p < .001, \eta_p^2 = 0.38$. Therefore, 'H₂: There are significant differences in pilots' situation awareness while using different AR interactive modes on ILS landing' is supported. The post-hoc comparisons show that the SART-10D total score of the AR gesture-command interaction is significantly lower than of the traditional mode ($p < .001$) and AR voice-command ($p < .001$). Furthermore, there is a significant difference in the dimension of demand among the three interacted modes, $F(2, 66) = 36.56, p < .001, \eta_p^2 = 0.53$. The post-hoc comparisons indicate that the traditional mode showed the lowest demand, followed by the AR voice-command, and the AR gesture-command ($p < .01$). There is a significant difference in the dimension of supply

among the three interacted modes, $F(2, 66) = 3.35, p < .05, \eta_p^2 = 0.09$. The post-hoc comparisons showed no significant difference in supply among the three interactive modes, though the AR voice-command is relatively higher than others. There is no significant difference in the dimension of understanding among the three interacted modes, $F(2, 66) = 2.82, p = .067, \eta_p^2 = 0.08$. Participants' SART-10D scores among the three interactive modes while performing ILS pre-landing checklists are shown in Figure 3-5.

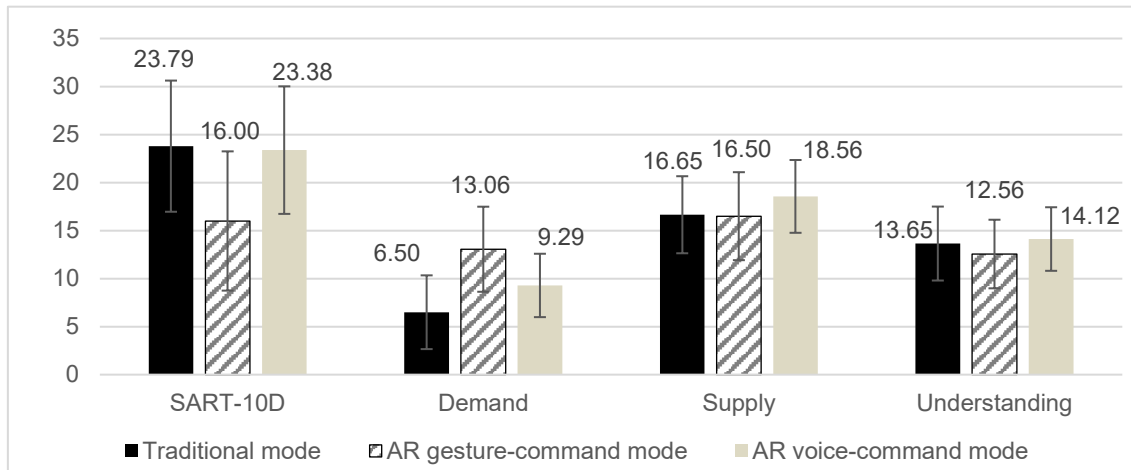


Figure 3-5 The differences in participants' situation awareness on SART-10D to three interactive modes on performing ILS pre-landing checklists

3.5 Discussion

3.5.1 Voice-command augmented reality checklist reduces perceived workload

Suitable human-centred design can have positive effects on boosting users' performance and reducing cognitive workload (Tobaruela et al., 2014), increasing cognitive capacity to achieve multitasking simultaneously during flight operations (Wickens, 2008). The results of this research support the first hypothesis that 'there is a significance on pilots' perceived workload using different AR interactive modes on ILS landing'. Participants rated the AR voice-command mode with the lowest perceived workload with a large effect size ($\eta_p^2 = 0.56$) and the highest score for performance with a large effect size ($\eta_p^2 = 0.36$) when compared with the gesture-command AR and traditional checklist (Figure 3-4). This finding may

only be applicable to this research related to the ILS operations, since it is not suitable for over-interpretation to other scenarios without further investigation. By integrating the MRTK in the AR interface, the AR checklist provides augmented visualisation information in a more intuitive and flexible interactive mode. The application of the voice-command AR leads to a better perception of the current operational status in the flight deck. In essence, the positive effects of the voice-command were observed while participants performed the ILS pre-landing checklist whilst interacting with augmented artefacts, which integrate the augmented visualization information with physical objects (such as directing to the position of landing gear) and the subsequent required actions (Figure 3-3c). The AR voice-command conveys both semantic guidance and visual cues to guide participants' attention to the next required action without additional cognitive efforts. Participants had experienced various degrees of frustration due to a lack of response to voice commands - especially if participants could not pronounce in a standard English accent. Furthermore, some participants felt frustration whilst trying to make gesture-command control input using the 'air tap'. Participants must perform multiple tasks using their hands to operate the landing gear, landing lights and speed brakes. The results demonstrated that participants' frustration levels on voice-command were lower than gesture-command in general (Table 3-1).

Table 3-1 The ranking of three checklist modes on perceived workload and situation awareness by NASA-TLX and SART-10D

	Traditional	AR gesture-command	AR voice-command
NASA-TLX	Medium	High	Low
Mental demand	Medium	High	Low
Physical demand	Medium	High	Low
Temporal demand	Medium	High	Low
Performance	Medium	Low	High
Effort	Medium	High	Low
Frustration	Medium	High	Low
SART-10D	High	Low	Medium
Demand	Low	High	Medium
Supply	Medium	Low	High
Understanding	Medium	Low	High

Note: Cells in grey highlighting the most rewarding mode

In normal circumstances, pilots only have one hand available to execute required actions, as the other hand must handle the control column/stick to fly aircraft. Pilots must interact and monitor several dynamic visual artefacts, including flight information displays, switches, knobs, and levers related to ILS procedures. The challenge of flight operations is that there are various tasks that must be executed precisely in a limited time frame using one hand. If the pilots' voice can be used as an additional input channel to execute required actions, it will enhance pilots' performance and reduce cognitive task loads. This may be the reason that participants in this research prefer AR voice-command and dislike the gesture command, which increases their workload by requiring only free hand to be occupied using the 'air-tap' for the ILS procedure (Figure 3-6a). This hand must perform multiple tasks simultaneously, including manoeuvring the flaps lever (Figure 3-6b), landing gear (Figure 3-6c), speed-brakes lever (Figure 3-6d), and landing light switches (Figure 3-6e). Furthermore, due to the small field of view on HoloLens not always being able to recognize a user's gesture accurately, participants feel frustrated with the failures of the gesture-command interaction. On the other hand, the AR voice-command combines both virtual SOPs with the physical operational environment with guiding cues (Figures from 3-6b to 3-6e),

which match the principle of human-centred design and being able to reduce participants' mental and physical demands.

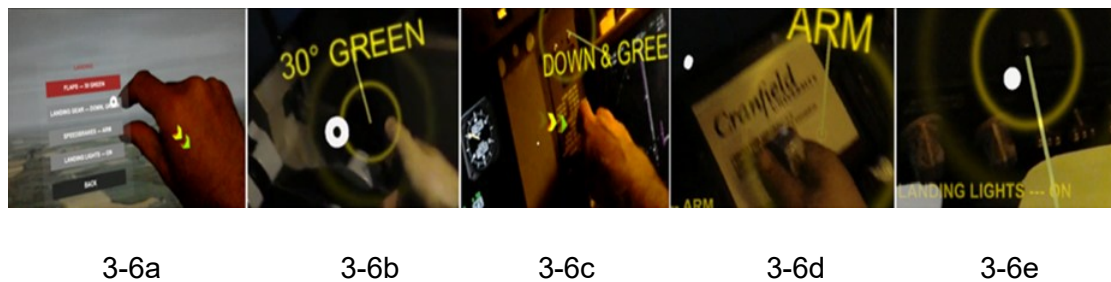


Figure 3-6 Participant's point-of-view on wearing HoloLens conducting ILS checklists by gesture-command (3-6a); both gesture-command and voice-command checklists including moving flaps lever to 30-degree (3-6b); moving landing gear DOWN and check green light (3-6c); moving speed-brakes to ARM position (3-6d); and switching landing light ON (3-6e)

3.5.2 The interactive mode of augmented reality influences situation awareness

The wearable AR display can provide real-time visual feedback to increase user's task performance and support decision-making (Rowen et al., 2019; Stanton, 2016). To examine the differences in situation awareness among three different interactive modes, participants' situation awareness was evaluated using SART-10D after performing ILS operations. The results supported the second hypothesis that 'there are significant differences in pilots' situation awareness while using different AR interactive modes on ILS landing'. Participants obtained the highest Supply (moderate effect size, $\eta_p^2 = 0.09$) and Understanding (moderate effect size, $\eta_p^2 = 0.08$) when performing an ILS landing with AR voice-command compared to gesture-command and the traditional checklist (Figure 3-5 & Table 3-1). Again, this finding on pilots' situation awareness relating to AR interactive modes may only be limited to the current research using an ILS scenario and further research is required to examine the applicability in other scenarios. With the voice-command interactive mode, participants can pick up the timely augmented information of the pre-landing procedure in an intuitive and easy semantic control method, which benefits their level-1 situation awareness of perception. Furthermore, the additional visual cues, which are automatically

activated after the semantic command, can direct participants' attention quickly and correctly to the equipment in the flight for required procedure actions. This function will improve the level-2 situation awareness of comprehension. Therefore, the voice-command AR improves participants' perception (situation awareness level-1) and comprehension (situation awareness level-2), both often associated with aspects of supply and understanding on SART-10D assessment (Klueber et al., 2019). However, the graphic salience and visual clutter of AR head-up displays might lead to operator cognitive distraction (Sharfi & Shinar, 2014) and thus induce higher attentional demand (Burnett & Donkor, 2012). Some participants were unfamiliar with AR applications in flight operations, which might influence their responses to SART. This could also be the reason why participants evaluated the traditional checklist as the highest for situation awareness (large effect size, $\eta_p^2 = 0.38$) and lowest for Demand (large effect size, $\eta_p^2 = 0.53$) (Figure 3-5 & Table 3-1). Furthermore, participants' experience with AR devices might be an important factor in human cognition and preference - people might prefer familiar things because of their previous experience compared to the novel ones (Liao et al., 2011).

The aspect of Demand on SART-10D might have an association with participants' perceived workload on NASA-TLX. Participants' situation awareness was lowest (large effect size, $\eta_p^2 = 0.38$) when performing an ILS pre-landing checklist with AR gesture-command compared with the voice-command and the traditional checklist. Furthermore, the AR gesture-command could induce the highest cognitive demand (large effect size, $\eta_p^2 = 0.53$) and provide the lowest Supply (moderate effect size, $\eta_p^2 = 0.09$) and Understanding (moderate effect size, $\eta_p^2 = 0.08$) (Figure 3-5 & Table 3-1). The reasoning for this might be that the complicated interactive procedures required physical movements during the 'air-tap' gesture (Figure 3-6a), which most participants might have to learn how to use as first-time users. Therefore, the learnability may have to be investigated in future research. Due to the novel features of an AR display and the unfamiliar interaction mode of the 'air-tap', participants committed more attentional and cognitive efforts to the gesture-command interaction itself rather than the flight

operations. Furthermore, participants must use one hand to perform an 'air-tap' to command the AR checklist while the other hand is busy with engaging ILS pre-landing checklists on the final approach. Performing multiple tasks (flying the aircraft and using the AR device) by using both hands simultaneously required bi-manual coordination and psychomotor skills, which would be associated with large cognitive loads (Fernandes et al., 2016) and depleting attention resources, thus decreasing their situation awareness performance. This research demonstrated that augmented visualization and spatial mapping capabilities of AR can allow it to be integrated into a user's decision support system, which is consistent with previous studies (Rohacs et al., 2019). AR applications may be able to facilitate single pilot operations (SPO) in the future flight deck design.

3.5.3 Considerations of augmented reality applications in the future flight deck

The design of the AR application has integrated audio cues for guiding the current checklist items by combining them with visual highlights and text in current research. The audio sources of voice are located at the centre of each yellow highlight circle; therefore, users can hear semantic instructions as if they were emitting from the operational environment. The AR also verifies that the user has completed the checked item before allowing the user to move to the next SOP. The user is required to fixate their view on the highlighted instrument (e.g. flap, landing gear or speed-brakes lever) by bringing the central cursor (white dot) over the yellow target circle highlight for at least a duration of 500ms to validate the checklist (Figure 3-6b). A notification sound will be activated when this required action has been done. When a checklist is completed, a notification sound is played and followed by the announcement of 'checklist complete'. These audio and visual feedbacks were designed to confirm the task completion, induce satisfaction and reduce workload in flight operations. It is very interesting to find that participants' perceived workload and performance between voice-command and traditional checklist show almost no differences in NASA-TLX total score (Figure 3-4). A large number of participants (75%) admitted that they preferred voice control to gesture control. Some mentioned that the gesture-command was very 'frustrating', 'cumbersome to use' and 'distracting'. Furthermore, 55% of

participants also highlighted the effect of practising with an AR device that would improve their performances, especially when using voice-command. 33% of professional pilots mentioned that some of the instrument checks could only be performed without looking at the corresponding switch or lever and touching the item, such as the switching landing lights. In this case, the voice-command interaction was particularly useful (Figure 3-6e). 85% of participants agreed that the AR application could be a great tool for training, as they believe junior pilots could easily learn flow checks and scanning patterns of checklists.

The key utilization of Augmented Reality in aviation is its capability to overlay and integrate information at the point of need. It promotes the visualisation of navigation systems, automation systems, weather, terrain, and airspace information in a 3D intersection – where it is easy to perceive changes, understand a developing situation and predict future actions. The dynamic arrow indicators (Figures 3-6) and attention guidance circles on the AR checklist effectively promote participants' performance and prevent omissions from the checklist. The yellow arrows and corresponding animation within the AR visualisation represent an efficient multimodal cue that can facilitate operators' attention to the cue and reduce mental demand on 'thinking' and physical demand on 'searching'. The dynamic indication of these arrows assists in preventing distraction on the flight deck and allows pilots to use selective attention to process available information to increase situation awareness (Wickens & Alexander, 2009). The dynamic indication producing a ripple effect is similar to the attention-directing system in a study of 3D crosshairs and a dynamic path to draw operator attention towards the location (Merenda et al., 2018). The attention guidance system also feeds auditory and visual feedback to the participants in the form of checklist item confirmation on execution. The AR device provides semantic feedback after checklist items have been fully executed. This allows participants to mentally move on to the next task and reduces mental workload.

3.5.4 Limitations and future work

There is an increasing prevalence of AR applications used in various domains such as manufacturing, medical care, military applications, and aviation (Bowman

et al., 2012; Carey, 2018; Krichenbauer et al., 2018; Aromaa et al., 2020; Borgen et al., 2021). For many participants, wearing an AR headset to perform the checklist is a brand-new experience. Furthermore, there are some barriers to AR applications in flight operations identified by this research. The confirmation action requires participants to guide the cursor to the highlighted area with extra movements of hand and head. This issue may be resolved with new AR devices that are equipped with eye-tracking capabilities that allow participants to control the cursor by their eye movement. Another limitation is the readability of virtual objects (text) on the HoloLens display when targets are located outside the field of view. The AR see-through function may potentially create blind spots. This finding is in line with previous research that one of the key challenges with AR is the difficulty of accurately superimposing virtual objects into the real operational environment (Moussa et al., 2012). The solution to current AR limitations may be to develop a more accurate gaze-control function to serve as additional input within a wider FOV. Moreover, there is a limitation on flight data collection in the current flight simulator. Current research was mainly based on participants' subjective rating of their perceived workload and situation awareness while interacting with an AR device. For applying AR technology on the flight deck, it is necessary to utilise an advanced simulator with full access to flight data and parameters related to the pilots' performance in future research. Simplistic measures of performance such as task completion outcome (safe or crash), task completion time, and response time will also be included in future experiments. Therefore, the pilot's cognitive workload from interacting with an AR device could provide a more detailed overview of how to address these limitations to improve the applicability of AR in future flight operations.

3.6 Conclusion

AR applications have the potential to facilitate pilots' situation awareness performance and reduce perceived workload in differing ways. Therefore, the implementation of innovative AR technology in the flight deck requires further investigation for validation and certification purposes. This study aimed to investigate participants' cognitive demands while interacting with different

interactive modes on an AR device. The results show that the gesture-command interaction increases unnecessary workload, decreases situation awareness, and tends to be cumbersome to use. On the other hand, voice-command checklists could constitute a real improvement in terms of reduced participants' perceived workload and maximum situation awareness performance. The findings provide evidence that interactive modes of AR interface design can influence participants' cognitive information processing and perceived workload associated with task performance in the flight deck. Furthermore, the AR device can be a great tool for aviation training, and the implementation of AR design may provide a potential solution for single pilot operations in the future.

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4 The impacts of input modality of the AR application on system usability and user interface experience during flight operations

4.1 Introduction

The current commercial two-pilot flight deck is a typical multitask environment in which complex flight tasks are assigned to pilot-flying (PF) and pilot-monitoring (PM). Augmented visualisation technology, such as the head-up display (HUD) and wearable augmented reality (AR) of the see-through head-mounted display (HMD), provides integrated information rendered in the physical operational environment to decrease head-down time and improve situation awareness while executing multiple tasks simultaneously (Gregoriades & Sutcliffe, 2018; Woodward & Ruiz, 2022). During flight operations, the PF is responsible for flying the aircraft to an approved flight plan, and the PM focuses on navigating, communicating, and monitoring tasks. The PM may also support the PF by assisting with high-workload situations and taking control in emergency situations (Lim et al., 2017). Throughout the flight, the foremost mission of the PM is to monitor the state of aircraft systems, aircraft configuration, flight path, and the confirmed actions taken by the PF. Accident and incident investigation has revealed that pilots' monitoring failures and deviation from standard operating procedures (SOP) have an unfortunately long history in aviation (Dismukes & Berman, 2010). Approximately 50% of controlled flights into terrain (CFIT) fatal accidents are related to inadequate monitoring on the flight deck (ICAO, 1994). The line operations safety audit (LOSA) tool developed by NASA and the University of Texas demonstrated that flight crews rated with poor monitoring performance had three times more mismanaged errors and threats than crews who are rated with good monitoring performance (Flight Safety Foundation, 2014). The AR technology provides multimedia data superimposed in the real world, which can improve information presentation in a limited operational environment. Furthermore, the interactive AR system provides visual-auditory feedback to help operators verify the completion of the required action. Therefore, the augmented visualisation tool of the interactive AR support system offers a

potential solution to improve PM's monitoring performance and PF's procedure compliance during flight operations. Hence, it can further enhance aviation safety.

4.2 Related work

Accident reports have shown that flight crew are not always good at following SOPs, including performing checklist items from memory and monitoring the other pilot's non-compliance or errors during flight operations (AAIB, 2021). Previous research revealed that violations and deviations from SOPs were associated with 68.3% of accidents (Li et al., 2008). AR technology has the potential to improve SOP compliance and cross-check communication as critical task-relevant information can be provided additionally in a see-through heads-up virtual display during multi-task scenarios in flight operations. Furthermore, AR proposed several natural and intuitive interaction techniques, such as sensor-based, audio-based, and visual-based modes, contributing to efficient human-computer interaction and enhanced user experience (Nizam et al., 2018). Therefore, AR with integrated information presentation can provide more intuitive and accessible interaction to improve operational safety and cost-efficiency in next-generation flight operations and training.

4.2.1 Multimodal augmented reality technology improves human performance

AR technology applications have become a popular method to increase or complement the operator's perception by adding virtual objects and information within the physical environment (Han et al., 2019). AR can be an excellent tool for enhancing the performance of operators by combining critical information in the real and virtual worlds and providing them with an enhanced mental model (Grabowski et al., 2018). This combination of information can produce spatially integrated scenes. These scenes aim to optimise and enhance human performance, giving the operator a real-time view of the world around them. Furthermore, AR technology can provide multimodal interaction processes with various input and output modes, such as gesture, gaze, and voice controls, as well as auditory and visual feedback (Aaltonen & Laarni, 2017; He et al., 2017). Compared to unimodal technology, the multimodal system can support a more

natural, robust, and flexible form of human-computer interaction, which contributes to improvements in the overall user experience and system usability (Turk, 2014). Based on the significant benefits of providing augmented visual information and facilitating human-computer interaction, as well as advances in ergonomics hardware and software design, the AR technique is becoming more mature and applicable to be adopted in everyday life and industrial workplaces (Aromaa et al., 2020). Previous research demonstrated that AR training tools were widely applicable and equally effective at enhancing human performance in a variety of domains with time-saving and cost-saving training mechanisms (Kaplan et al., 2021). Implementing an AR-based real-time support tool in the manufacturing system can reduce approximately 100,000 euros of operation and maintenance costs in ten years and significantly shorten the mean time to repair (MTTR) by up to 60% (Mourtzis et al., 2020). Furthermore, head-mount mobile AR devices provide quick access to information that is beneficial to enhance productivity, improve decision-making processes, and reduce human errors and cognitive loads (Huang, 2021).

In the aviation industry, AR applications with integrated information presentation can be effective solutions to several ergonomic and human-factor-related issues to improve operational performance and safety (Brown et al., 2021). The see-through HUD is a precursor to an AR device that provides conventional augmentation of the real world by adding two-dimensional (2D) visualisation on a non-wearable fixed screen (Gorbunov, 2014). The first implementation of HUD was in a fighter aircraft cockpit known as the Blackburn Buccaneer in 1958 (Aukstakalnis, 2016). With the rapid development in technology nowadays, wearable interactive AR support systems have been widely applied in many scenarios of aviation operations. Several studies have identified the applicability of using AR systems in aircraft maintenance, repair, and overhaul (MRO) operations and training to improve operators' procedure compliance and task-relevant performance (e.g. Ceruti et al., 2019; De Crescenzo et al., 2010). Bagassi et al. (2020) proposed an innovative airport traffic control concept based on AR technology, allowing controllers to have a heads-up view of the airport traffic, especially in low visibility conditions. The AR-based airport control service

can provide benefits in terms of reducing perceived workload, increasing task performance, and ensuring operational safety. A three-dimensional (3D) AR weather visualisation system for educational purposes can effectively enhance trainees' knowledge acquisition and training experience (Meister et al., 2022). The AR-supported training for procedures compliance with visual flight rules (VFR) demonstrated significant benefits in improving visual detection performance, as well as training engagement and immersion (Moesl et al., 2023). The conceptual design of wearable AR applications in the future flight deck was also gradually emerging. Recent studies demonstrated that AR could be a promising support tool through augmented task-relevant information presentation to improve flight crews' situation awareness, attention distribution, and cognitive information processing in flight operations (Coleman & Thirtyacre, 2021; Tran et al., 2018). Numerous studies have demonstrated the potential benefits of AR in aviation operations. However, there are still limitations to be considered and addressed from the human-centred perspective and in line with the task characteristics in flight operations (Ariansyah et al., 2022; Blundell & Harris, 2023).

4.2.2 Human-centred flight deck design

Human factors experts focus on flight deck human-computer interaction designs, which are the prime drivers for new technology development and application (Harris, 2007; Boy, 2014). For the human-centred design of flight deck information presentation and management interface, the visual saliency of task-critical objects is an overarching factor to be considered to improve pilots' attention allocation and situation awareness (Dill & Young, 2015). Furthermore, the proximity compatibility principle (PCP) requires integrating different sources of information in close spatial vicinity to facilitate operators using one gaze to catch all critical information (Wickens & Carswell, 1995; Wickens & Ward, 2017). The human-centred design of the flight deck suggests that information shall be displayed in an integrated configuration rather than in separate formats (Marino & Mahan, 2005). Pilots must monitor constantly changing parameters and select appropriate control modes by cross-checking various displays (Burian, 2006). Li

et al. (2020) developed an augmented visualisation design on primary flight display (PFD) with salient mode transition information and an integrated configuration interface. This augmented PFD was optimised using a green border around the instrument's raw data of airspeed, altitude and heading indications to highlight activated mode changes, which significantly reduces pilots' cognitive efforts and perceived workload by eliminating the requirement to read text compared to a traditional PFD. An interactive datalink user interface providing air-ground communication information displayed in a salient position of the flight deck display can facilitate crew resource management as well as decrease pilots' cognitive efforts and task completion time (Jorna, 1997). Appropriate human-centred flight deck design can also facilitate the usage of the high-level automation system and support the development and implementation of single pilot operations to significantly improve cost efficiency (Harris, 2007).

Moreover, the human-centred application of new technology or devices with innovative interactive modes in the flight deck can support pilots' decision-making process and improve situation awareness and flight performance (Carroll & Dahlstrom, 2021). The head-mounted display (HMD) and see-through function of AR could allow virtual objects to be integrated and synchronised into the physical operational environment, which is consistent with PCP of human-centred design to present virtual task-relevant within pilots' perceptual area. The augmented visualisation of AR can assist pilots with retrieving flight data, checking SOPs and controlling the aircraft's flight path, thus improving their cognitive information processing and procedure compliance (Wickens & Carswell, 1995). Holographic AR glasses can offer an optimal solution to reduce operators' workload and stress levels by presenting critical information in a timely manner (Jetter et al., 2018; Tran et al., 2018). The flight-deck checklist devices have evolved over the years with various types and interactive modes ranging from mnemonic and vocal to computer-aided versions (Degani & Wiener, 1990). AR can add salient audio-visual pointers and feedback to distinguish between accomplished and non-accomplished items. Also, by allowing multimodal input of the AR-based checklist, human-computer interaction during flight operations will be improved as a more intuitive and efficient process. A previous study demonstrated that the

application of the voice-command AR checklist could improve pilots' situation awareness and reduce cognitive workload during flight operations since augmented visualisation cues and accessible interactive mode do not require pilots to divert attention resources away from tasks in hand (Li et al., 2022). Therefore, in the current study, the human-centred AR checklists allowing multimodal input modes were developed to improve procedure compliance and human-computer interaction in flight operations.

4.2.3 Input modalities in human-computer interaction

Apart from the visual presentation capacity of the interface, the control input mode is also a critical factor in influencing human-computer interaction effectiveness and operational performance. Based on the human-centred design principle of natural user interfaces and reality-based interaction, interfaces based on simulations of physical systems can facilitate operators' engagement and performance (Johnston, 2014). The input modes in natural and intuitive human-computer interaction processes are diverse, including gesture, voice, eye movement, etc. Hand gesture control is one of the mainstream forms of non-verbal communication in modern human-computer interaction systems. Konstantoudakis et al. (2022) developed an intuitive AR system for drone and camera motion control through gesture recognition to facilitate operators' situation awareness and user experience. However, Hürst and Van Wezel (2013) investigated the limitations of mid-air gesture-based interaction. The air-tap interaction significantly improved fun and engagement compared to the traditional touchscreen-based interaction with physical touch; nevertheless, the operational performance was compromised, especially in serious scenarios. The modern flight deck is a complex interactive environment in which various interactive devices run their own interaction methods independently. The inappropriate or incoordinate application of gesture-command AR devices can cause conflicts between multiple interaction channels to undermine human-computer interaction effectiveness and aviation safety (Zhang et al., 2022).

Speech recognition is also a common input modality in modern human-computer interaction processes. Voice input showed significant advantages while

performing hands/eyes-busy tasks in motion or natural field scenarios (Oviatt, 1997). Previous research also demonstrated that users tend to prefer voice interaction in describing objects/events and issuing commands for actions or iterative actions (Cohen & Oviatt, 1995). Voice-input interface has been widely applied in dynamic vehicle driving scenarios to improve operators' cognitive information processing and operational safety, surpassing the traditional haptic interaction (Bilius & Vatavu, 2020). Several conceptual designs of implementing a voice control system for command input tasks (such as light planning, radio tuning, etc.) in the flight deck were also proposed as a pilot-support tool in emergency scenarios and next-generation single pilot operations (Trzos et al., 2018; Ziakkas et al., 2023). However, the implementation of voice input in the flight deck still has several safety concerns, such as noise condition, communication conflict, recognition error, etc., which requires further human factor considerations and technology developments. Furthermore, gaze control mode based on eye tracking technology is also an emerging natural input modality to facilitate human-computer interaction and task performance (Zhang et al., 2017). The multimodal interaction integrated two or three modes among gesture, voice, and gaze inputs also presented a huge potential to be implemented in various operational scenarios to improve human performance and operational efficiency (Chen et al., 2020; Su et al., 2021).

4.2.4 Motivation and hypotheses

In the current research, innovative human-computer interaction paradigms of the AR system blending virtual visual information within the operational environment were applied in flight operations. The user interface (UI) of the AR checklist has holographic interactive feedback and spatial highlights to reduce pilot reaction time during an emergency situation (Tran et al., 2018). Furthermore, to cope with the narrow field of view issue of the AR device, the directional indicators in the form of guiding arrows with the saliency of texts have been added to help pilots locate spatial highlights. To investigate the application method of the AR interactive system in instrument landing scenarios, the system usability and user interface satisfaction of different input modalities (gesture-command vs. voice-

command) on the AR device were compared (H_1 & H_2). The system usability was evaluated using the system usability scale (SUS), focusing on the human-computer interaction process with the AR checklist in this specific instrument landing operation. The user interface satisfaction was assessed by the questionnaire for user interface satisfaction (QUIS), which is a more holistic scale with the extension of hedonic and emotional aspects compared to the SUS (Hassan & Galal-Edeen, 2017). Moreover, QUIS largely reflect participants' experience and preference for the user interface design, especially for the visual information presentation, of the AR interactive checklist. The consistency of participants' preferences towards different input modalities was also examined (H_3 & H_4). Based on the comparison of participants' ratings on gesture- and voice-command interactive AR checklists, further analysis was to investigate if participants have consistent preferences/attitudes on difference interactive methods of the AR checklist or not. With the hypotheses of significant differences in system usability and user interface satisfaction, for example, a consistent preference (positive correlation) can suggest a general acceptance of the AR interface design in flight operations; the inconsistent preference (negative correlation) may imply the applicability issues caused by different input modalities in the specific instrument scenarios. The detailed explanations of the preference consistency were based on the different characteristics of SUS and QUIS. Therefore, four hypotheses were proposed as follows:

H_1 : There is a significant difference in system usability between voice-command and gesture-command with AR applications during instrument landing.

H_2 : There is a significant difference in user interface satisfaction between voice-command and gesture-command with AR applications during instrument landing.

H_3 : There is a significant correlation of system usability between voice-command and gesture-command AR interactions.

H_4 : There is a significant correlation of user interface satisfaction between voice-command and gesture-command AR interactions.

4.3 Method

4.3.1 Participants

There were 40 participants, including seven females (17.5%) and 33 males (82.5%), aged between 21 and 55 years old ($M = 27.90, SD = 8.09$) attending the simulated flight trial. All participants were recruited from aviation research institutes including 11 pilots (27.50%) and 29 avionics engineers (72.50%) with flight experience ranging from 0 hours to 2,800 hours ($M = 122.70, SD = 468.29$). A research proposal was approved by the research ethics committee before conducting the experiment, as this research involved collecting data from human participants. All participants signed a consent form, which provided them with detailed information related to the experiment and were guaranteed the right to withdraw from the experiment at any stage. Data collected has been used and stored in accordance with Cranfield's Research Ethics Policy and Management of Research Data Policy.

4.3.2 Apparatus

4.3.2.1 Flight simulator

The experiment was run on the flight simulator with a representative model of the Boeing 747 flight deck. It was comprised of functioning flight controls, stick-shaker stall warnings, over-speed alerts, primary flight and navigation displays, and landing gear levers, among other standard controls. The simplified overhead panel was comprised of light switches, engine fire emergency levers and engine ignition switches (Figure 4-1a). The scenario was based on an Instrument Landing System (ILS) final approach from 2,000 ft and eight nautical miles (NM) from the airfield. When the experiment was run, participants executed a pre-landing checklist by interacting with the AR device during the final approach and landing.

4.3.2.2 Augmented reality device

The AR device used in the experiment is a Microsoft HoloLens headset (Figure 4-1b). These glasses comprise see-through holographic waveguides, two high-definition (HD) 16:9 light engines and built-in processors that can display

holograms with a resolution of 1280 x 720 pixels per eye, a field of view of 30° x 17.5° and a refresh rate of 60 hertz. The symbols, fonts, colours, and text used in the user interface (UI) design are optimised to improve pilots' attention and situation awareness. (Microsoft, 2021).



4-1a



4-1b

Figure 4-1 The flight deck display systems of a flight simulator for the experiment of instrument landing (4-1a); the participant wearing a HoloLens (shown in the top left-hand inset) and the perspective while operating the Landing Gear DOWN command following UI instruction (4-1b)

4.3.2.3 Augmented reality applications for instrument landing

The pre-landing checklist was developed as an interactive AR system and deployed to the HoloLens device with different interactive modes (gesture and voice). The checklist items included the following: (a). Flap 30-Degree; (b). Landing Gear-DOWN (Red colour for status, Figure 4-2a); (c) Speedbrakes-ARM, and (d). Landing Lights-ON. Participants followed the standard operating procedures to control airspeed, altitude, descent rate and the distance of touchdown for safe operation. The AR checklist application was developed with the Unity game engine and a combination of the Microsoft mixed reality toolkit (MRTK) and Vuforia software development kit (SDK). Animated yellow arrow symbols provided visual guidance to participants regarding the position of the current checklist item. The animated yellow symbols always point towards the physical flight deck element of the relevant SOP and disappear when the user gets closer to the check item (top, Figure 4-2b). The yellow circular target animations are check-item indicators that are overlaid at the position of the

lever/switch to direct the user's attention to confirm the completion of the check item (bottom, Figure 4-2b). With gesture control, participants move the central cursor with their head and select a menu/checklist item (such as Landing Light On) by holding the cursor and performing an 'air-tap' (Figure 4-2c). This 'air-tap' gesture represents the mouse click commonly found in a graphical user interface (GUI). With the voice-command interaction, the user reads out the menu/checklist title to activate it and validates each checklist item by saying 'check'. The physical flight deck had been mapped using the HoloLens depth camera and was registered and aligned with the Unity software to obtain a specific visual orientation on the operational environment (Figure 4-2d). Each checklist highlight (yellow circles and spatial text) was precisely positioned according to the spatial mapping registration alignment with Vuforia.

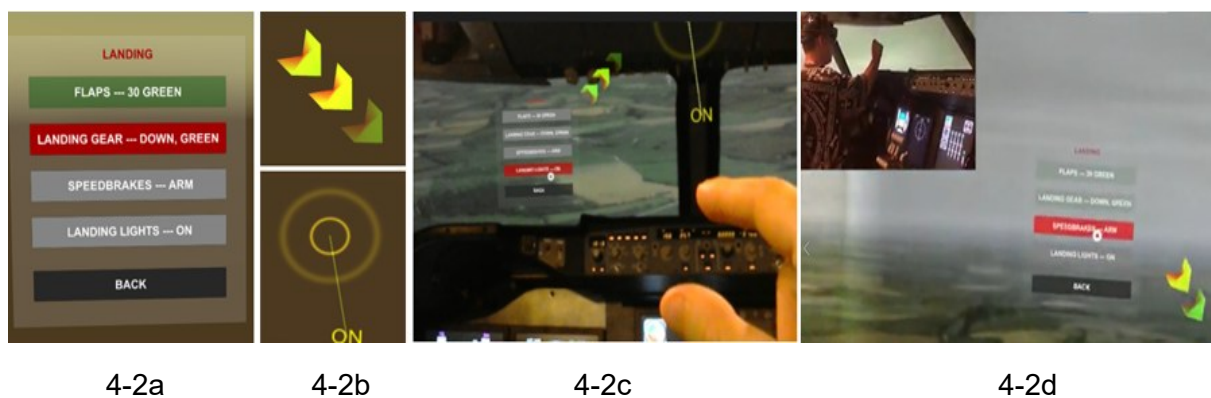


Figure 4-2 The opaque SOP menus that use different colours to indicate the status of operations, green indicating executed, red for the current operational step, and grey for standby (4-2a); visual cues of guiding arrows and position indicator (4-2b); 'Air-tap' gesture used for AR interactive mode using yellow arrows for directing pilot's attention to check Landing Light On (4-2c); pilot conducting gesture-command wearing HoloLens while performing 'Speedbrakes On' (4-2d).

4.3.2.4 System usability scale and questionnaire for user interface satisfaction

To successfully implement AR technology in flight operations, the system usability and user interface satisfaction of AR should be assessed at the early stages of design. The system usability score (SUS) developed by Brooke (1996) has been widely applied in human-computer interaction evaluation (Lewis, 2018;

Rudi et al., 2020). SUS consists of 10 questions with a five-point Likert response continuum to measure two dimensions: Usability (Q1, Q2, Q3, Q5, Q6, Q7, Q8, & Q9) and Learnability (Q4 & Q10). Participants were required to rate each question with a score ranging from strongly disagree (1) to strongly agree (5). For odd-numbered questions (Q1, Q3, Q5, Q7, & Q9), subtract one from the user's score; for even-numbered questions (Q2, Q4, Q6, Q8, & Q10), subtract the user's score from 5. The final SUS score is calculated by multiplying the sum of all the adjusted scores by 2.5, which ranges from 0 to 100 with a higher score indicating better system usability. The questionnaire for user interface satisfaction (QUIS) has been widely used to assess users' subjective satisfaction with specific aspects of the interface design and user experience of innovative systems (Su et al., 2011; Helin et al., 2018). There are six dimensions evaluated by 20 questions: overall user reactions, screen visibility, system information, learning, system capabilities, and usability and user interface, with measures on an ascending scale from 1 to 10. The final QUIS score is calculated by the arithmetic mean of all six dimensions' ratings.

4.3.3 Research design

This study evaluated the applicability of the interactive AR device (HoloLens) in flight operations while performing an ILS pre-landing checklist. Participants were instructed that the experiment involved wearing a HoloLens device whilst performing an instrument landing task in a flight simulator using AR gesture-command compared with AR voice-command. The procedures for all participants were as follows: (1) complete the demographic data including age, gender, qualifications, type hours and total flight hours (five minutes); (2) complete a briefing regarding the purpose of the study and how to use a HoloLens AR device for human-computer interactions (10 minutes); (3) sit in the Boeing 747 simulator to calibrate the AR device by placing visual gaze cursor on the QR code with a blue indicator confirming calibration completed (five minutes); (4) familiarise with the pre-landing checklists on flight simulator (ten minutes); (5) complete the briefing on the AR checklist software, with a detailed explanation of how the item can be highlighted by gesture control and voice control (ten minutes); (6) perform

a landing using HoloLens AR gesture-command (five minutes) and AR voice-command (five minutes); (7) conducted SUS and QUIS assessments (separately) based on his/her experiences on different AR interactive modes and provided additional descriptive feedbacks (20 minutes). As this study was a repeated-measures design, a random table for two different interactive modes was generated to counterbalance the practice effects on participants. It took approximately 70 minutes for each participant to complete the experiment.

4.3.4 Statistical analysis

To investigate system usability and user interface satisfaction while performing AR-assisted pre-landing procedures, participants' subjective rating scores of all sub-dimensions of SUS and QUIS were analysed by paired samples t-test. The within-subject factor was AR interactive modes, which consisted of participants' ratings of voice-command and gesture-command. Correlations between gesture-command and voice-command were analysed by Pearson's correlation coefficient. Prior to statistical analysis of the t-test and Pearson correlation, the outliers were identified through results shown on boxplots. The assumption of normality was checked visually by quantile-quantile (Q-Q) plots. The effect sizes of samples were quantified by Cohen's d value.

4.4 Results

4.4.1 Sample characteristics

This research consisted of 40 participants who were invited to perform an instrument landing using different AR interactive modes. Participants then evaluated the system usability and user interface satisfaction of the AR device in flight operations using SUS and QUIS. The dependent variables were concerned with the scores of all dimensions in SUS and QUIS. There was no outlier observed by boxplots. Based on the visual examination of the Q-Q plots, the SUS and QUIS data on two AR interactive modes were distributed normally.

4.4.2 Augmented reality interactive modes impacts system usability

Paired samples t-tests were used to examine the difference between two interaction models for the same subject. The results showed that the usability of the AR voice-command was significantly higher than that of the AR gesture-command, $t(39) = 6.08, p < .001, d = 0.96$. The learnability of AR voice-command is significantly higher than that of AR gesture-command, $t(39) = 3.01, p = .005, d = 0.48$. Finally, the SUS score of the AR voice-command is significantly higher than that of the AR gesture-command, $t(39) = 5.72, p < .001, d = 0.90$. Therefore, the 'H₁: there is a significant difference in system usability between voice-command and gesture-command with AR applications during Instrument Landing' was supported. The differences in usability, learnability, and SUS scores between AR gesture-command and voice-command are illustrated in Figure 4-3.

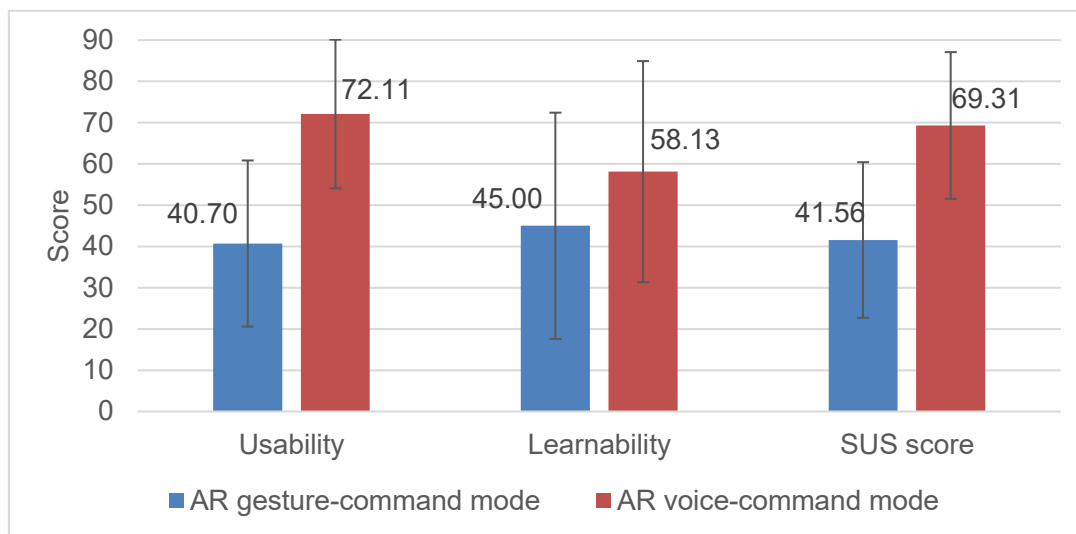


Figure 4-3 The differences in usability, learnability and SUS scores between AR gesture-command and AR voice-command modes in flight operations based on paired sample t-tests

4.4.3 Augmented reality interactive modes impacts user interface satisfaction

The differences between six QUIS sub-dimensions and the QUIS average score between AR gesture-command and AR voice-command mode were examined using paired sample t-tests. The overall user reaction for the AR voice-command

was significantly higher than that of the AR gesture-command, $t(39) = 8.11, p < .001, d = 1.28$. The screen visibility for the AR voice-command was rated significantly higher than that of the AR gesture-command, $t(39) = 3.63, p = .001, d = 0.57$. The system information for the AR voice-command is rated significantly higher than that of the AR gesture-command, $t(39) = 3.82, p < .001, d = 0.60$. The learning factor for the AR voice-command was rated significantly higher than that of the AR gesture-command, $t(39) = 6.02, p < .001, d = 0.95$. The system capabilities for AR voice-command were rated significantly higher than that of AR gesture-command, $t(39) = 5.22, p < .001, d = 0.82$. The dimension of usability and user interface for the AR voice-command was rated significantly higher than that of the AR gesture-command, $t(39) = 4.16, p < .001, d = 0.66$. Finally, the QUIS average score for the AR voice-command was rated significantly higher than that of the AR gesture-command, $t(39) = 4.16, p < .001, d = 0.66$. Therefore, the 'H₂: there was a significant difference in user interface satisfaction between voice-command and gesture-command with AR applications during Instrument Landing' was supported. The differences in QUIS subdimensions and average scores between AR gesture-command and voice-command are illustrated in Figure 4-4.

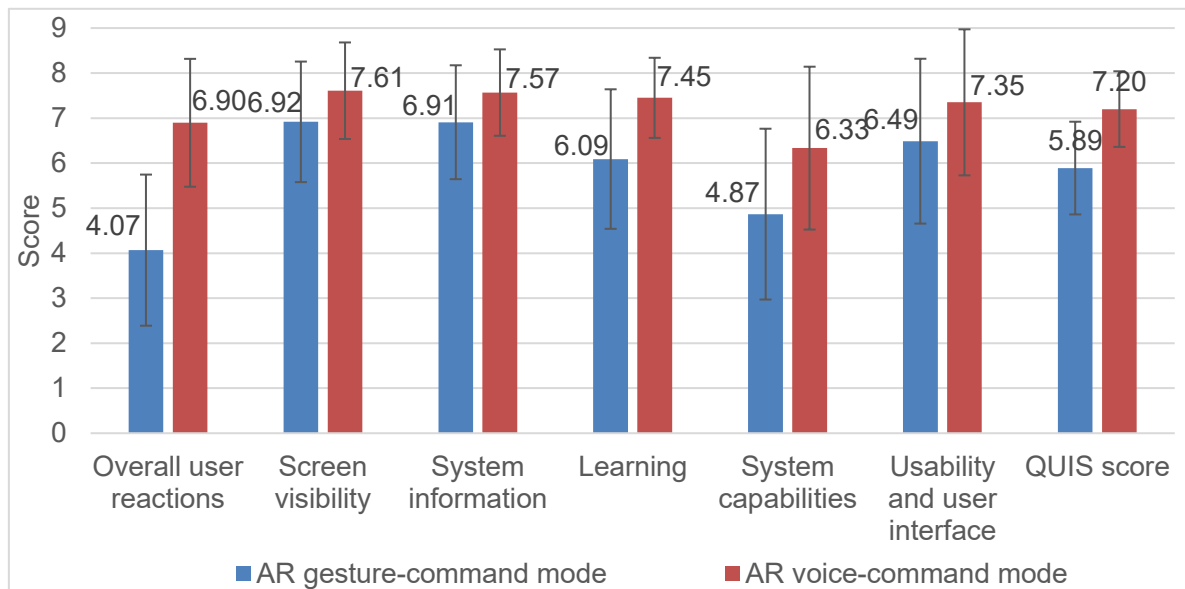
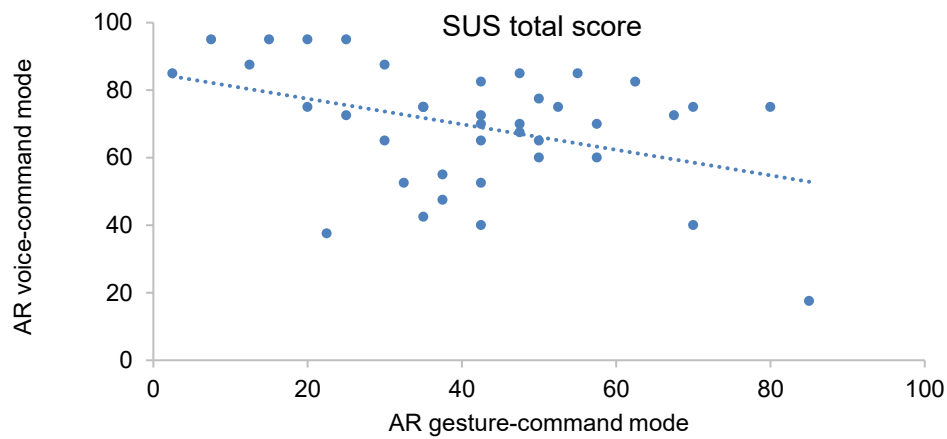


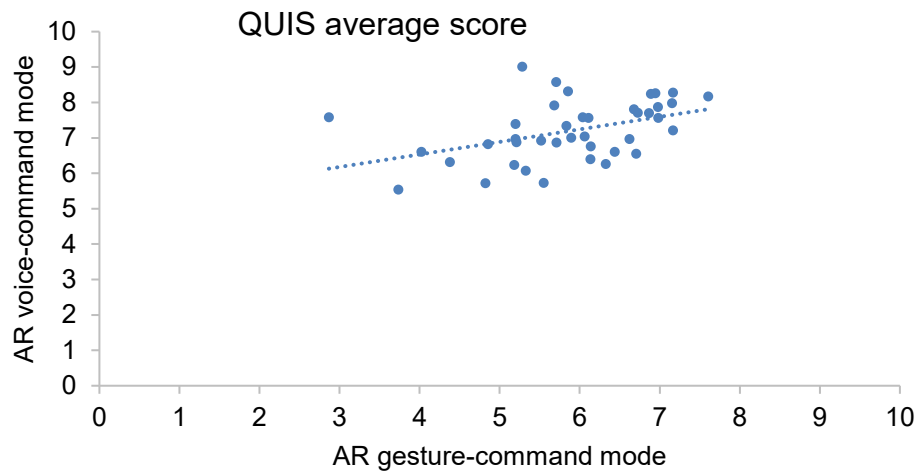
Figure 4-4 The differences in QUIS dimensions between AR gesture-command and AR voice-command in flight operations based on paired t-tests

4.4.4 Correlation between gesture-command and voice-command augmented reality interactions

According to the Pearson correlation coefficient analysis, there was a significant negative correlation between AR gesture-command and voice-command based on SUS total scores, $r = -0.40, p = .010$ (Figure 4-5a). Therefore, the 'H₃: There was a significant correlation of system usability between voice-command and gesture-command AR interactions' was supported. Furthermore, there was a significant positive correlation between AR gesture-command and voice-command based on QUIS average scores based on Pearson correlation, $r = 0.44, p = .005$ (Figure 4-5b). Therefore, the 'H₄: There is a significant correlation of user interface satisfaction between voice-command and gesture-command AR interactions' was supported.



4-5a



4-5b

Figure 4-5 The negative correlation of SUS total scores (4-5a) and positive correlation of QUIS scores (4-5b) between AR gesture-command and AR voice-command modes

4.5 Discussion

It is well known that monitoring and cross-checking issues of PF and PM still occur in the contemporary two-pilot flight deck configuration (Harris, 2007; Sumwalt et al., 2002). The line operations safety audit (LOSA) tool indicated that over 80% of human errors in flight operations are related to intentional or unintentional non-compliance with SOPs by flight crews (Thomas, 2003). According to the survey of Lautmann and Gallimore (1987), the improper usage

of checklists will cause procedural errors and further lead to a substantial number of aircraft crashes and incidents. The onboard operational checklists presenting aeronautics procedures can provide an effective means of training and assisting pilots in performing flight tasks with well-designed user interfaces and appropriate human-computer interaction modes (De Brito & Boy, 1999). Pilots' non-compliance on checklist often results from the complex human-device interfaces and human-machine interaction in the modern flight deck under dynamic flight scenarios. Therefore, in implementing an AR device on the flight deck, system designers must ensure that the system is developed with consideration of suitable interactive modes and interface design to support pilots' monitoring and operational performance. The results from the data analysis demonstrated that the AR voice-command mode was rated significantly higher in system usability and user interface applicability than the AR gesture-command mode. These findings can provide scientific evidence for the adoption of advanced AR checklist design and implementation within complicated flight operation scenarios.

4.5.1 The control input modality of augmented reality influences system usability

Multimodal AR technology for system control and information processing has been increasingly applied in dynamic operational scenarios based on the growth of accuracy and efficiency of gesture recognition and voice synthesis technologies (Bilius & Vatavu, 2020). The system control methods of gesture command and voice input have been widely used in the real-world interaction context of AR experiences. The current research illustrated that AR gesture-command interaction of 'air-tap' is rated significantly lower than voice-command in usability, learnability, and SUS scores (Figure 4-3). To successfully commence an 'air-tap' gesture, participants must position their thumb and index finger in front of the HoloLens camera and then pinch the thumb and index finger together. However, due to the limited field of view of the HoloLens device and technical issues of motion recognition, the activation of each procedure item could take a longer time to hinder the interaction process and downgrade participants' rating of system usability. Based on descriptive feedback collected after the questionnaire surveys, around 50% of participants mentioned that the gesture-

command AR was 'frustrating and cumbersome to use' in this flight scenario. The gesture-command required participants to focus on SOPs and initiate an 'air-tap' precisely on time, and the cursor was positioned well to execute the specific action of each SOP. Adding these tasks alongside the high mental and physical task loads of operating a complex aircraft may increase or indeed overload the working memory. Previous research revealed that the AR gesture-command interaction induced higher mental/physical perceived workload and cognitive demands during flight operations (Li et al., 2022)

Currently, the primary input modality in flight operations is unimodal input of hand haptic. pilots control the aircraft movements by handling the flight control inceptors. The voice-command interaction provided a multimodal interface permitting the integration of multiple sensory channels (sight, hearing, and touch) with higher flexibility and reliability to meet the task needs of different flight scenarios. Turk (2014) indicated that operators would prefer the multimodal interaction over unimodal alternatives as the significant enhancements in task efficiency and cognitive information process. Besides the naturalness and intuition characteristics, the voice-command interactive mode has substantial advantages in memorability and learnability. The semantic interaction of AR voice-command mode will be activated by simple words presented in the interface, such as 'check' and 'next', to perform each procedure item in the pre-landing checklist. Compared to the 'air-tap' gesture, which is difficult to perform precisely, the voice-command mode is learnable and applicable in dynamic flight scenarios without the distractions of pilots' manual flight controlling and visual monitoring. The voice-command AR interactive mode requires little effort to achieve simple, accurate, and safe operations in flight scenarios. Furthermore, familiarity is a critical factor affecting learnability in the human-computer interaction process to provide self-explanatory cues for understanding the functions that the system offers (Green & Eklundh, 2003). Participants' familiarity with voice-command mode had a significant influence on their preferences and learnability ratings, as voice-command is intuitive and learnable when compared with gesture-command.

4.5.2 Emotional effectiveness impacts user interface satisfaction

User experience can be seen as the holistic extension of system usability measures, which covers additional details about human-computer interaction from hedonic and emotional aspects (Hassan & Galal-Edeen, 2017). In the current study, the QUIS assessments can reflect the interactive experience and user satisfaction with the utilitarian functions and experiential attributes of the AR gesture- and voice-command interfaces (Chung & Sahari, 2015). The t-test results suggested that the QUIS average score and six sub-dimension ratings on the AR voice-command mode are significantly higher than the gesture-command (Figure 4-4). Previous research demonstrated that, compared to the traditional point-and-click style interface, the voice-command dialogue system could enhance the emotional effectiveness of the VR interactive narratives to improve the user experience and interface satisfaction (Osking & Doucette, 2019). Furthermore, in the current study, voice input especially has the advantage of interface traversals that can help participants cut through multiple steps through the multimodal interaction process to decrease the task completion time. This point can be confirmed by two rating items of the learning and system capacities sub-dimensions in the QUIS related to the logical steps and response to complete: the AR voice-command mode allowed participants to follow each step to finish the pre-landing checklist operations with a better logical sequence ($t(39) = 2.30, p = .027, d = 0.36$) and faster completion time ($t(39) = 4.32, p < .001, d = 0.68$) compared to the 'air-tap' interaction (Appendix A, Table A-2). The smooth interaction process and significant time saving also provide a positive emotional effect on the interactive experience (Microsoft, 2022).

In the sub-dimensions of the overall user reactions, participants showed a significant preference for the voice-command AR interface over the gesture-command mode due to the higher system functionality and accessibility, as well as better interaction experience with voice input. Also, the higher ratings in the learning and system capacities revealed the advantages of the voice-command mode in a straightforward and understandable control manner with emotional effectiveness and operational efficiency. The qualitative feedback also supported this point: Around 60% of participants highlighted that they preferred intuitive

voice control to gesture control with improved performance and engagement, as well as decreased cognitive workload during performing the prelanding procedures. The hand-gesture-command interaction during the approach can cause distraction and frustration while the participant's attention is entirely focused on flight operations. The additional execution of the 'air-tap' would downgrade the user experience. Furthermore, there were three dimensions related to visual display and information presentation designs: screen visibility, system information, and usability & user interface. These three dimensions are supposed to provide the same information with the same level of visual presentation and have theoretically no difference between the voice-command and 'air-tap' interactive modes. However, the t-test results still demonstrated significant differences between the two interactive modes in these sub-dimensions (Figure 4-4). One possible explanation might be that the participants are biased by the general impression and operational experience of the gesture-command interaction that they tend to mark lower on the user interface satisfaction compared to the voice-command mode. Such bias can be concluded as an emotional response to influence participants' operational experience and engagement (Shepherd & Cardon, 2009).

4.5.3 Applicability of voice-command augmented reality in flight operations

The Pearson correlation analysis results demonstrated a significant positive correlation of user interface satisfaction based on QUIS average scores between gesture-command and voice-command modes, $r = 0.44, p = .005$ (Figure 4-5b). Participants generally rated higher on AR voice-command mode and also scored higher on gesture-command with a consistent opinion towards the visual presentation design of the AR interactive checklist and procedural adherence instructions (Figure 4-2). This pattern revealed a general acceptance of the AR interface for presenting additional task-relevant information in-flight operations. Previous studies also confirmed that AR interactive technology has the potential to provide adequate integrated information and intuitive human-computer interaction without distraction due to head-down observations of instruments (Kim & Grabbard, 2019; Lu et al., 2020). However, there is a significant negative

association of the SUS total scores between the voice-command mode and the 'air-tap' control ($r = -0.40$, $p = .010$). It reveals an exact opposite preference in system usability of different input modalities of the onboard AR systems in this specific instrumented landing scenario (Figure 4-5a). The user interface and human-computer interaction design of AR applications are critical factors in influencing system operational performance and human cognitive performance. If the system design does not follow human-centred principles, undesirable difficulties and overloaded cognitive demands will be added for the end-users (Pane et al., 2002). Based on the Pearson correlation analysis results, it can be concluded that the onboard AR interface can provide sufficient information with the augmented visualisation presentation. Based on an identical visual interface design of the AR virtual checklist, the opposite preference of different input modalities of interactive AR can be attributed to the applicability issues of interactive methods (gesture-command vs voice-command) under the specific flight task characteristics. The voice-command interaction is apparently more appropriate in human-centred design to improve system usability and user interface satisfaction in this scenario of instrumented landing operations.

The challenge with flight operations is that various tasks and SOPs must be executed precisely in a specific time frame. In the current study, the AR interface not only provided relevant checklist items required during the instrument landing procedures but also allowed augmented visualisation cues of visually blended virtual SOPs within the physical environment of the flight deck (Figure 4-6). These augmented visualisation instructions directed pilots' attention and action to perform each procedure in a simple and intuitive workflow through the voice-command interaction for improving the checklist completion accuracy and speed in dynamic flight scenarios. With the support of the AR voice-command checklist, pilots can hold the control column by the left hand, simultaneously operate the flap to 30 degrees (Figure 4-6a), place the landing gear down (Figure 4-6b), move the speed-brakes lever arm (Figure 4-6c), switch landing lights on (Figure 4-6d) as well as any additional interactions required with the flight deck instruments by the free hand following the AR instructions. In this process, pilots can simply say 'check' to go through every item in the pre-landing checklist without additional

hand movements or haptic interactions. Furthermore, via the AR voice-command interaction while performing flight procedures, pilots' monitoring performance, situation awareness, and working memory capacity will be enhanced. Therefore, the AR voice-command interactive system can be further developed and generalised in flight procedures training of various segments in flight operations to improve trainees' motivation, working memory, and practical skills (Squires, 2017).



4-6a

4-6b

4-6c

4-6d

Figure 4-6 The augmented visualisation cues to guide pilots in executing required actions to perform instrument landing procedures consisted of the following actions: move the Flap to 30 Degree (4-6a); put the landing gear down (4-6b); move speed brakes to ARM (4-6c); switch landing light on (4-6d)

4.5.4 Limitations and future work

The current research demonstrated the applicability of the voice-command AR application in the flight deck. However, there are still several limitations of an AR application in flight operations, which may require further research and development. The first issue is the efficiency of voice recognition, as some participants experienced various degrees of frustration due to a lack of response to some unique accents of spoken English. The second issue was that 'air-tap' recognition required more accuracy for the identification of the users' intended gesture. Some participants were frustrated while trying to make commands using an 'air-tap' that was not recognised by the camera due to the limited field of view on the HoloLens. The third issue is the readability of virtual objects (text) on the HoloLens display, which may potentially create blind spots when targets are located outside the field of view or text superimposed by other visual elements. These issues may be improved with the new generation of AR technologies such as HoloLens 2, which has integrated real-time eye tracking with two-handed, fully

articulated gesture control technology and a wider field of view display system (52 degrees). The gaze control based on the eye-tracking function will also be applied as an innovative input modality in future work. In the current research, although the voice-command AR provided multiple interaction processes in flight operations, it is still an unimodal input method. The multimodal input mode to integrate multiple modalities in the control input stage will also be further investigated. Furthermore, the nature of see-through AR can induce potential issues of motion sickness and attentional tunnelling effect, which require careful consideration regarding the task and context characteristics before the implementation of AR in real-world operations (Fadden et al., 2001; Kaufeld et al., 2022; Syiem et al., 2021). Finally, due to the data accessibility limitations of the simulator system, the operational performance indicators, such as task completion accuracy/time, were assessed through the relevant items in SUS and QUIS surveys. In future studies, objective measurements of participants' flight performance will be conducted to investigate the influence of AR applications in human augmentation.

4.6 Conclusion

The semantic voice-command interaction on an AR device has high system usability and user interface satisfaction, which can potentially increase pilots' monitoring performance and reduce physical task loads. AR technology blends virtual checklists with the real operational environment and provides guidance cues to direct pilots' attention using intuitive voice-command. The use of the voice as an effective input modality for the interactive AR to execute intended actions can facilitate human-centred design concepts on the flight deck. There are some limitations related to voice recognition, limited display field of view and obstacles from augmented vision superimposed in the flight deck that must be improved in the future. However, the benefits of applied AR voice command in flight operations and training still present promising opportunities for further research and development. AR applications in flight operations need to be assessed carefully so that all stakeholders, pilots, avionic engineers, system designers,

manufacturers, and regulators can be satisfied with the potential benefits and associated risks.

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5 Quick coherence technique training effects on pilots' psychological well-being and stress management

5.1 Introduction

The outbreak of the COVID-19 pandemic induced an unprecedented impact on the aviation industry with the grounding of aircraft, cancellation of flights, strict travel bans and closure of international borders. According to the International Air Transport Association (IATA, 2021), there were over 18,000 aircraft parked up, representing 66% of the world's commercial transport fleet; the number of airport pairs in March 2021 was only 50% of the connections of pre-pandemic. The International Civil Aviation Organization (ICAO, 2022) noted that COVID-19 has caused an overall reduction of 60 % in passengers and around a 372-billion-dollar loss of airline revenue compared to pre-pandemic levels in 2019. The rapid reduction of scheduled flights caused by the pandemic led to thousands of commercial pilots not flying, and many were furloughed or laid off by airlines. Commercial pilots were threatened with redundancy, unwelcome changes to their employment contracts, such as lower pay, and the prospect that some may never fly for a living again. It further resulted in a lack of stability, with many also suffering financial pressure, which could undermine their mental/physical health, cognitive functions, and wellness (Alaminos-Torres et al., 2021). Airline pilots' mental health and psychological states have been brought to the forefront and have been the focus of increasing attention in aviation since the Germanwings Flight 9525 crash in 2015. ICAO (2016) identified flight crews' psychological issues as a critical contributing factor to air accidents and incidents. The European Union Aviation Safety Agency (EASA, 2016) also introduced new rulemaking related to the management of pilots' mental health issues. More recently, the aviation industry and pilot unions have been addressing the promotion of positive well-being and the practice of healthy behaviours for aviation professionals (Cullen et al., 2021; Flight Safety Foundation, 2020). Effective mitigations for these negative impacts are required to improve pilots' stress resilience and cognitive functions in order to maintain aviation safety.

5.2 Related works

The quick coherence technique (QCT) is a mental and emotional self-regulation technique that has been shown to increase one's level of heart-rate variability (HRV) coherence. Psychophysical coherence is associated with the alignment of physical and mental functions, which can facilitate a well-established relationship between cognitive information processing and task performance (Bradley et al., 2010). Learning the breathing technique was facilitated using HeartMath Inner Balance technology. The breathing technique has been proven to be effective in improving psychological resilience and contributing to coping with stress and anxiety, controlling emotions, and facilitating decision-making (Kloudova et al., 2019). Breathing techniques have been used by military pilots to prevent loss of consciousness when facing prolonged hypoxia and hyperventilation conditions for decades (FAA, 2016). In the context of the COVID-19 pandemic, there are increasing risks that pilots may experience burnout due to overload stress and serious mental health issues above the normal baseline stressors, which can negatively influence their well-being and job motivation (Demerouti et al., 2019). Currently, there are thousands of pilots worldwide suffering from redundancy, unpleasant changes to their contracts, and increased duty hours with lower pay rates, which has the potential to induce mental/physical health issues and may jeopardise aviation safety (Vuorio & Bor, 2020). And this impact will persist and translate into further consequences with health and safety threats to pilots and airlines even after the pandemic crisis has passed.

5.2.1 Pilots' psychological states affect aviation safety

The commencement of the COVID-19 pandemic caused an abrupt cancellation of flight operations, which not only limited pilots' proficiency in performing routine tasks but also increased pilots' stress levels and operational risk due to new procedures related to COVID-19 safety and health regulations (Olaganathan & Amihan, 2021). The requirements to wear personal protective equipment (PPE), including face masks, gloves, and goggles, may have had negative effects on pilots' operational performance, as the PPE may reduce pilots' performance by diminishing their perception of sight, hearing, touch, and communication during

flight operations. This can then increase crews' mental/physical workload and reduce handling abilities and crew resource management skills (IFALPA, 2020; CAA, 2020). Pilots' psychological issues persist as an insidious threat to aviation safety due to the impairment of the pilot's cognitive functions and task performance (Marin et al., 2011). According to the causes review of aviation accidents from the database of the National Transportation Safety Board (NTSB) and National Aviation Safety Data Analysis Centre (NASDAC), 13.3% of the accidents are associated with the mental or physical conditions of the pilots (Shappell et al., 2007). Furthermore, a survey based on thousands of active pilots showed that 12.6% of airline pilots met the depression threshold, and 4.1% of pilots reported having suicidal thoughts (Wu et al., 2016). Commercial airlines have focused on pilots' mental health through the management of crew fatigue and alertness (Cahill et al., 2021). However, pilots are still exposed to the risk of psychological health issues due to inadequate stress management strategies and concerns about losing medical certification (Vuorio & Bor, 2020).

Social isolation, mental stress, and anxiety at the time of the severe acute respiratory syndrome (SARS) epidemic in 2003 resulted in an extremely high rate of suicide deaths (Yip et al., 2010). The risk of suicide has been increased due to economic deterioration and social isolation, particularly affecting aviation professionals; even worse, pilots were conscious that they were exposed to a potentially high risk of infection with COVID-19. Pilot aircraft-assisted suicide, such as Germanwings Flight 9525 in commercial aviation, is an unusual event. However, research proposed that pilot aircraft-assisted suicide is 0.33% in general aviation in the United States (Vuorio et al., 2014). It is recognized that the pandemic may increase suicide rates, just as during the SARS crisis of 2003. However, the association between pilot suicides and social change, such as unpaid leave, furlough, financial risks and quarantine isolation, have not been studied yet. A study of 442 commercial pilots demonstrated that mental health was found to be associated with occupational dispute, fatigue, insufficient flying time and flying patterns, together with an inability to relax and a lack of social support. (Cooper & Sloan, 1985). To effectively manage the negative impact of pilot's psychological issues, mental health professionals work closely with

aeromedical professionals for pilot selection, assessment, and monitoring of pilots' mental health (Bor et al., 2002). Relevant policies and strategies aimed at improving screening, evaluation, and management of pilots' mental health have been taken by aviation authorities and airline operators. FAA (2016) made a commitment to combat the dangers of mental health issues in aviation by removing the stigma surrounding psychological problems in the aviation industry so that pilots are more likely to self-report, get treatment, and return to work. EASA (2018) required aviation medical examiners to focus on pilot mental health and well-being in their annual pilot assessment after the Germanwings accident. The quick coherence breathing technique has been demonstrated as an effective method to increase air traffic controllers' fatigue resilience and operational risk management (Li et al. 2022). In the current study, psychophysiological intervention based on QCT training was proposed and implemented in an international airline. The training effectiveness in both day-to-day life (off-duty) and flight operations during controlled rest breaks (on-duty) was investigated. An alternative hypothesis to be tested is proposed as follows: 'H1: there is a significant interaction effect on pilots' psychophysiological coherence between practising QCT and flight duty'.

5.2.2 Biofeedback technique improves mental health

Individual resilience is the ability to cope with a crisis and return to pre-crisis status quickly using mental processes and behaviours to promote personal assets and protect oneself from the potential negative effects of stressors (Robertson et al., 2015). Self-regulated QCT can provide individuals with a greater awareness of how they can regulate their own psychological and cognitive functioning using physiological signals. With the breathing technique, it is possible for one to shift one's own physiology into a more coherent state. QCT can effectively enhance individual resilience, which is associated with improved psychophysiological coherence, cognitive functions, and general health (Edwards et al., 2022; McCraty & Tomasino, 2006). Research has demonstrated that breathing conciliation is able to facilitate individuals' autonomic nervous system (ANS) functions by monitoring physiological responses to stress (Carroll

& Winslow, 2017). QCT has been proven to be an effective intervention to improve air traffic controllers' fatigue resilience and mitigate the negative impact of accumulated workload (Li et al., 2022). QCT is a self-regulation technique based on a breathing pacer which provides real-time response to the trainee's current state (HeartMath, 2022).

Increased coherence reflects the abilities of self-regulated emotions more consistent with the intuitive, intelligent, and stable inner reference, which is correlated with improved mental health, wellness, and cognitive functioning (McCraty, 2011; Ireland, 2010). The social, economic, and personal challenges of COVID-19 threaten a pilot's mental health and well-being in several ways. There is a pressing need to develop psychological support in order to address pilots' stress, distress and the potential for increased pilot suicides as a direct impact of the pandemic. Previous research demonstrated that practising an eight-week intervention programme of breathing techniques can significantly reduce stress and mental health issues, as well as increase psychological and physical functions (Ehsan et al., 2019). Psychophysiological coherence can boost the ability of individuals to resist and recover from negative experiences such as stress and fatigue (Rutter, 2007). Paced breathing is a simple technique which requires individuals to breathe deeply and slowly at a fixed rate of around six to ten times per minute to achieve the maximum benefits. Paced breathing can lead to a better psychological state through modulation of ANS, which has been proven to have positive effects in the reduction of feelings of stress and anxiety (Ma et al., 2017; Aristizabal et al., 2020). Therefore, two alternative hypotheses are raised in this research as follows: 'H₂: there is a significant improvement in pilots' wellness score based on QCT training' and 'H₃: there is a significant decrease in pilots' perceived stress based on QCT training'.

5.2.3 Self-regulation enhances well-being

Self-regulation has been defined as recurring efforts to optimize one's cognitive, motivational, and behavioural processes leading to goal fulfilment (Winne & Jamieson-Noel, 2002). It has been suggested that one's self-regulation capacity is significantly associated with developing expert levels of competence and task-

specific cognitive performance (Ericsson, 1997; Singer, 2000). Specific skill acquisition can be achieved progressively with regular practice that learners self-regulate in three sequential phases: forethought, performance, and self-reflection (Zimmerman & Kitsantas, 1997; Derossis et al., 1998). Previous research has demonstrated that the paced breathing technique can provide a clear awareness of the psychophysiological coherence state and improve self-regulation in practising engagement (Field et al., 2018). Moreover, the long-term practice of psychological interventions can significantly improve cognitive information processing and task performance in the workplace (Thomas & Fogarty, 1997; Slimani et al., 2016). Regular practice of breathing techniques has been proven to have positive effects on an individual's ANS functions by facilitating heart rate response and thus improving both physical and psychological health (Joshi et al., 1992; Mourya et al., 2009). The long-standing practice of mindfulness can significantly increase wellness and stress management skills (Kingston et al., 2007; Roeser et al., 2012). Similarly, the long-term practice of the paced breathing technique has been proven to have effective moderation effects on perceived stress and improvements in cognitive functions and mental health (Szulczewski, 2019).

Maintaining mental health and wellness requires regular practice of intervention techniques over a prolonged period of time (Ericsson et al., 1998; Gardner & Rebar, 2019). Regular practice over the long term is associated with better training outcomes and skill acquisitions compared to short-term mass practice (Spruit et al., 2015). Long-term practice has multiple effects on task performance and autonomic behaviours, including increasing the response speed and accuracy of goal-directed action selection, reducing the demand of cognitive workload and stress required to perform the task, and rendering the practised behaviour habitual (Haith & Krakauer, 2018). Habit has been proposed to represent a form of self-control and autonomy, protecting regular practice in the longer term against shorter-term motivation losses (Galla & Duckworth, 2015). Therefore, the formation of a positive habit of practising QCT can optimize pilots' coherence and task performance. Consistent practice of the paced breathing technique can effectively improve psychophysical coherence and emotion-

regulation ability (Reyes, 2014) and reduce health care costs (Bedell & Kaszkin-Bettag, 2010). Therefore, the current study applies psychophysiological coherence as the hallmark indicator of pilots' perceived stress and resilience in the cockpit and in everyday life. Based on the above literature, there are two alternative hypotheses to be tested as follows: 'H₄: there is a significant correlation between frequency of practising QCT and pilots' stress level' and 'H₅: there is a significant correlation between frequency of practising QCT and pilots' wellness score'.

5.2.4 Motivations

COVID-19 significantly reduced the volume of flights by up to 70% in 2020 compared with 2019, which caused the majority of pilots to be furloughed and mental and physical issues. Furthermore, new regulations of wearing PPE during flight operations induced additional procedures, risk of infection, long and irregular working hours, isolation during quarantine and potential loss of employment, which can lead to psychological strains and physiological issues (IATA, 2020). There is a pressing need to improve aviation safety by providing coherence training to increase pilots' resilience to manage the impacts of a pandemic. Furthermore, mental health has been a critical factor in aviation safety for a long period. The proposal and implementation of an effective psychological intervention strategy based on QCT training have further implications for improving aviation safety and operational performance. Not only limited to addressing social changes or serving as a pilot support programme, but the QCT can also be developed as a psychological training strategy for all aviation personnel to improve non-technical performance and operational safety. Perceived stress and psychological well-being are two main components that should be concomitantly measured in mental health assessment (Massé et al., 1998). Therefore, in this research, the effectiveness of the QCT training on moderating pilots' psychophysiological coherence, perceived stress, and wellness was investigated.

5.3 Method

5.3.1 Participants

Eighteen commercial pilots who are working for an international airline volunteered to participate in this research. The participants' ages ranged from 30 to 58 years old ($M=45.11$, $SD=7.45$), with different aircraft type ratings and flight hours ($M=11597.22$, $SD=5496.75$). Participants' service years are between 3 years and 26 years ($M=14.72$, $SD=7.81$). The ethical approval of this research was granted in advance of the research taking place. All participants were informed that this research is evaluating the effectiveness of the quick coherence technique (QCT) on stress and fatigue risk management in flight operations as related to the impacts of the COVID-19 pandemic. Participants were guaranteed their rights to withdraw from this research at any stage and provided their signed consent form. All collected data is managed in accordance with the United Kingdom Ethical Code and the General Data Protection Regulation (GDPR).

5.3.2 Apparatus and materials

5.3.2.1 Inner Balance device

The Inner Balance Bluetooth sensor and Inner Balance App are developed by HeartMath (Figure 5-1). It is a mobile Bluetooth device that measures psychophysiological coherence, which indicates how physical and mental states are affected by the autonomic nervous system (ANS), including both the sympathetic and para-sympathetic systems. It can be easily connected with personal mobile devices (using Android or iOS) for training purposes. Furthermore, it provides additional information on start and end times of practice, average coherence and cumulative achievement scores, which are also available on the HeartCloud apps, as shown on the right-hand side of Figure 5-1. Visual feedback on coherence scores comprises red (low, 0 to 0.6), blue (medium, 0.6 to 2.1), and green (high, 2.1 to 6.0) coloured bars with percentage indicators summed up to 100%. This study uses the percentage of high coherence as the psychophysiological coherence indicator for data analysis. A coherent heart rhythm is a stable regular repeating rhythm resembling a sine wave at a single frequency between 0.04-0.24 hertz. The scoring algorithm updates the

coherence score and achievement score at five-second intervals. The achievement score is the sum of all individual low, medium and high coherence scores (HeartMath, 2014).



Figure 5-1 The Inner Balance device is a state-of-the-art, ultra-low Bluetooth device with 125 hertz sample rate measuring HRV parameters to optimize accurate HRV and QCT training

5.3.2.2 Perceived stress scale

The perceived stress scale (PSS) is a self-reported subjective questionnaire, which was developed to measure stress degree using ten scenarios in an individual's life that are considered stressful (Cohen et al., 1983). The PSS has become one of the most widely used psychological instruments for measuring perceived stress. It has been used in studies assessing the stressfulness of situations and the effectiveness of stress-reducing interventions (Lee, 2012; Oró et al., 2021). The PSS consisted of ten items evaluating the degree to which individuals believe their life has been unpredictable, uncontrollable, and overloaded during the previous month. Participants were required to rate each item by how often they felt or thought a certain way described in the item from 0 (never) to 4 (very often). The PSS also includes a number of direct queries about current levels of experienced stress. The assessed items are general in nature rather than focusing on specific events or experiences. Therefore, it can be used

to assess both long-term and short-term situations in one's life which are considered stressful (Bastianon et al., 2020).

5.3.2.3 Ardell wellness self-assessment

Ardell wellness self-assessment (AWSA) is often applied to diagnose participants' state of wellness and stress index using a seven-point Likert scale (from +3 to -3) that measures individual wellbeing. Ardell Wellness test consists of 25 questions incorporating physical, mental, emotional, and social aspects of health, which offer a balanced assessment of varied stress sources. The higher the total score, the higher the happiness of that participant, and vice versa (Ardell, 1983). The AWSA scale is used to collect data on the subjective well-being of pilots during the furlough related to the COVID-19 pandemic.

5.3.3 Training syllabus

The current QCT training programme took two days. The training syllabus consisted of the introduction of the theoretical framework of psychophysiological coherence, stress resilience, energy depletion, autonomic nervous system balance, etc., and demonstrations and exercises of the QCT breathing technique. Two licensed resilience instructors and coherence advantage instructors from HeartMath UK delivered the training. The applications of Inner Balance, together with QCT, aimed to boost commercial pilots' psychophysiological state via simple and effective breathing techniques. There are two steps to QCT, including (1) heart-focused breathing and (2) activation of a positive feeling. The Inner Balance device facilitates pilots' practising QCT by providing visual signs reflecting heart rhythms and recharging energy based on moment-to-moment changes in heart rate via a personal mobile device.

5.3.4 Research procedures

Participants voluntarily attended this two-day psychophysiological coherence training program following notification of the study on the airline's internal notification system. There was neither an incentive nor a financial allowance for individuals participating in this research. All participants went through the same procedures as follows: (1) participants attended a briefing on the research

objectives and two-day training syllabus; (2) participants provided their signed consent form with agreed data management plan; (3) participants conducted pre-training subjective assessments on AWSA and PSS; (4) participants attended two-day coherence training on practising QCT and stress management; (5) participants performed their post-training assessments on AWSA and PSS once training was completed. (6) Participants were encouraged to perform 5-minute baseline measurements and 5-minute QCT practice as often as they could, either off duty in day-to-day life or on duty in the flight deck. Before each QCT practice session of a 5-minute HRV biofeedback breathing exercise, baseline data of psychophysiological coherence should be measured for 5 minutes. During the baseline measurements, participants were instructed to follow their normal patterns of flight deck or daily life activity, respective to the environmental context in the current QCT practice being undertaken. While pilots are in the flight deck, they must comply with the airline's controlled rest policies at all times while using inner balance to collect baseline data and then practising QCT for 5 minutes. It is absolutely fine if this is interrupted by an emergency event; the safety of the flight takes priority; (7) Debriefing and response to participants' comments; (8) participants were informed that the subjective assessments on both AWSA and PSS will be forwarded to them two months later to trace the QCT training effects. All participants were advised to forward their experiences and comments on practising QCT to the principal researcher on a weekly basis. All participants' coherence data were stored on the HeartCloud, which can only be accessed by the project leader using encrypted usernames and passwords to follow GDPR requirements.

5.4 Results

5.4.1 Sample characteristics

One-way repeated measure analysis of variance (ANOVA) is applied to investigate QCT training effects on pilots' AWSA and PSS levels among pre-training, post-training and after two months of practising. The correlations between pilots practising QCT sessions with AWSA and PSS were analysed by Pearson's correlation coefficient. There was no outlier observed by boxplots. The

assumption of normality is verified by quantile-quantile (Q-Q) plots, and the homogeneity of covariance assumption was verified by Mauchly's test ($p > .05$). The post-hoc pairwise comparisons were accomplished by Bonferroni, and effect sizes of samples were quantified by partial eta square (η_p^2). The descriptive statistics are shown in Table 5-1. Furthermore, two-way ANOVA is applied to examine pilots' psychophysiological coherence between QCT training effects (baseline vs. practising QCT) and flight duty (on-duty vs. off-duty) for QCT training effects in flight operations. The descriptive statistics are shown in Table 5-2.

Table 5-1 Means (M) and standard deviations (SD) of pilot's AWSA and PSS scores among three stages of QCT training

	Session	N	Mean	SD
Ardell Wellness Self-Assessment score (AWSA)	Pre-training	18	18.7	14.8
	Post-training	18	27.9	11.1
	Two-months practice	18	25.6	15.6
Perceived Stress Scale score (PSS)	Pre-training	18	19.3	6.4
	Post-training	18	10.8	4.4
	Two-months practice	18	14.8	5.5

Table 5-2 Means (M) and standard deviations (SD) of recorded sessions (N) of all participated pilots' psychophysiological state between baseline and practising QCT while off-duty (day-to-day life) and on-duty (flight operations) for two-month practice

	Flight duty	Practice session	N	Mean	SD
Percentage of high coherence	Off-duty	Baseline	1535	35.28	23.50
		QCT	1529	81.14	23.20
	On-duty	Baseline	118	43.38	22.14
		QCT	107	81.07	22.36

5.4.2 Quick coherence technique improves psychophysiological coherence

The two-way ANOVA results indicated a significant interaction in pilots' psychophysiological state between frequencies on practising QCT and flight duty, $F(1, 3285) = 6.46, p = .011, \eta_p^2 = 0.002$ (Figure 5-2). Therefore, 'H₁: there is a significant interaction effect on pilots' psychophysiological coherence between practising QCT and flight duty' is supported. It can also be noted that the simple main effect analysis on pilots 'practising QCT' within each group on 'flight duty' showed that the psychophysiological state on practising QCT is significantly higher than the baseline on both off-duty and on-duty ($p < .001$). Another simple main effect analysis on pilots' 'flight duty' within each group on 'practising QCT' revealed that pilots' baseline psychophysiological state while off-duty is significantly lower than on duty ($p < .001$). Moreover, a significant main effect was found on the factor 'practising QCT', $F(1, 3285) = 673.62, p < .001, \eta_p^2 = 0.170$. There is also a significant main effect of 'flight duty' on pilots' psychophysiological state, $F(1, 3285) = 6.22, p = .013, \eta_p^2 = 0.002$. The details of two-way ANOVA results are shown in Table 5-3.

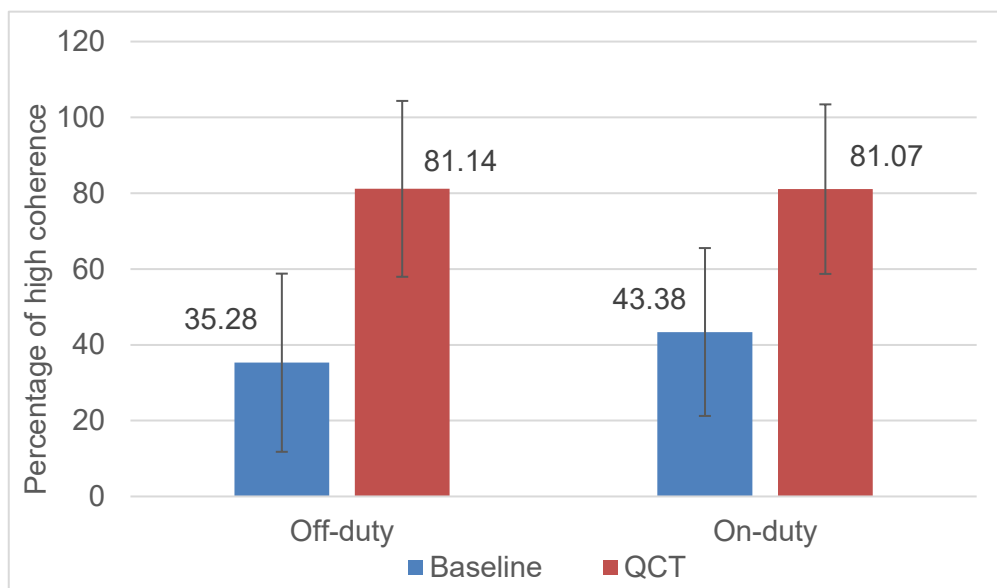


Figure 5-2 The interaction effect of self-regulated practising QCT and flight duty on pilots' psychophysiological coherence

Table 5-3 Two-way ANOVA interactions, simple main effects, and main effects on pilots' psychophysiological coherence between practising QCT and flight duty

2 × 2 two-way ANOVA		<i>df</i> Effect	<i>df</i> Error	F	<i>p</i>	η_p^2
Percentage of high coherence	Interaction effect 'practising QCT × flight duty'	1	3285	6.46	.011	0.002
	Simple main effects 'practising QCT' within					
	Off-duty	1	3285	2973.88	.000	0.475
	On-duty	1	3285	147.08	.000	0.043
	Simple main effects 'flight duty' within					
	Baseline	1	3285	13.28	.000	0.004
	QCT	1	3285	0.001	.974	0.000
	Main effect 'practising QCT'	1	3285	673.61	.000	0.170
	Main effect 'flight duty'	1	3285	6.22	.013	0.002

5.4.3 Quick coherence technique training effects on well-being and perceived stress

The results of one-way repeated measures ANOVA indicated that there is a significant improvement in pilots' wellness scores among three stages of QCT training, $F(2, 34) = 5.12, p = .011, \eta_p^2 = 0.23$. Furthermore, post-hoc pairwise Bonferroni comparison revealed that the post-training wellness score is significantly higher than pre-training ($p = .007$) and two-month practice (Table 5-1 & Figure 5-3). Therefore, 'H₂: there is a significant improvement on pilots' wellness score based on QCT training' is supported. Also, there is a significant decline in pilots' perceived stress levels among the three stages of QCT training, $F(2, 34) = 23.07, p < .001, \eta_p^2 = 0.58$. Furthermore, post-hoc pairwise Bonferroni comparison revealed that pilots' stress level is the lowest in the post-training stage, followed by the two-month practice stage, and in the pre-training stage is the highest ($p = .021$) (Table 5-1 & Figure 5-3). Therefore, 'H₃: there is a

significant decrease in pilots' perceived stress based on QCT training' is supported.

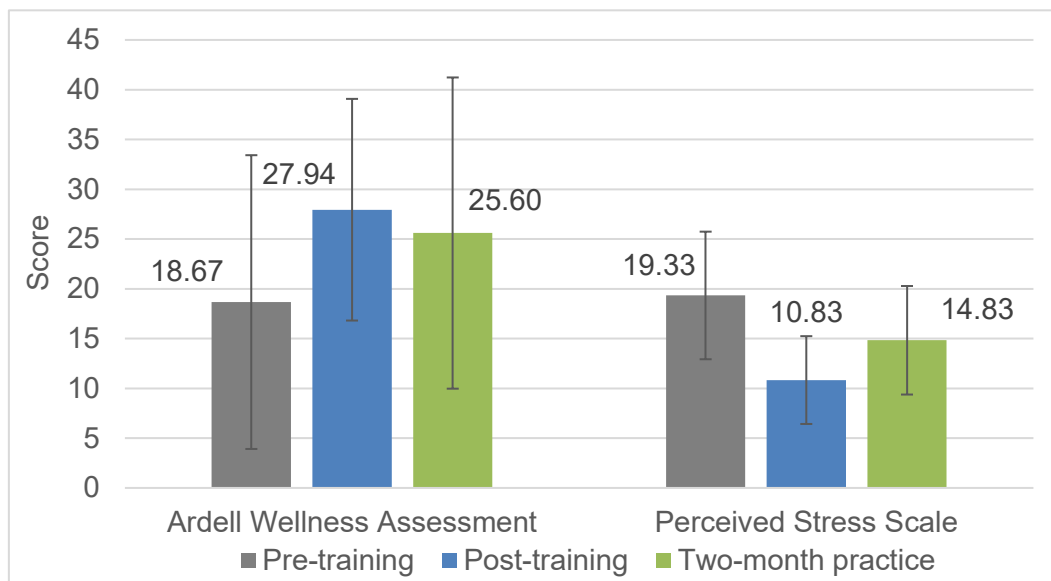
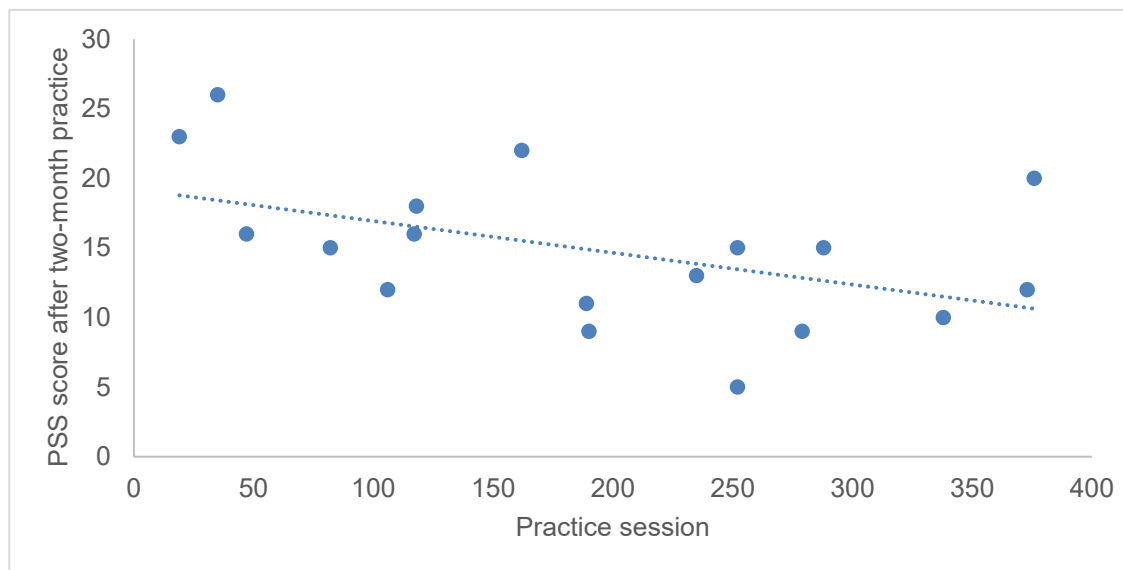


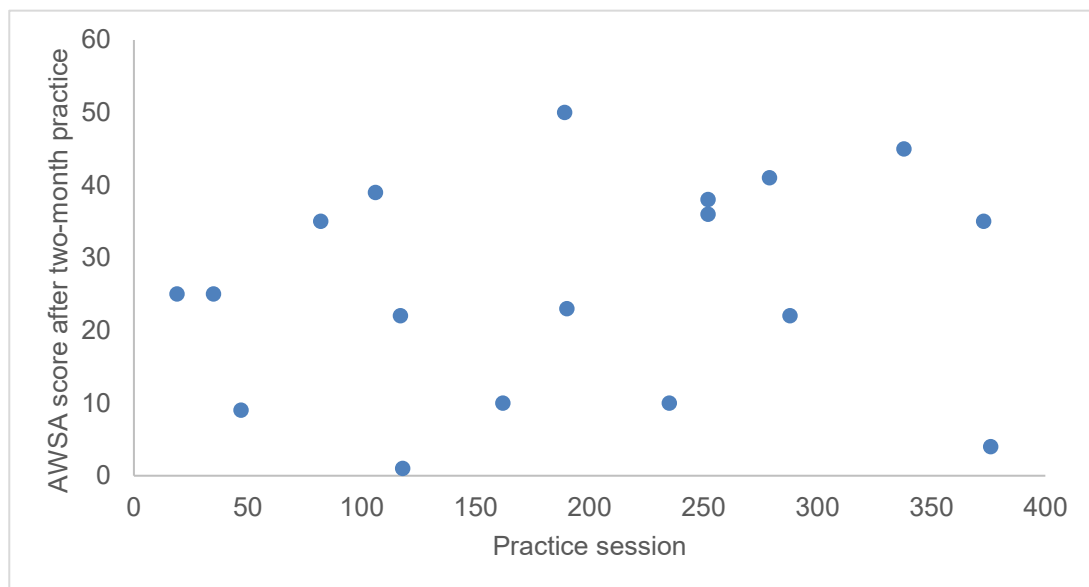
Figure 5-3 The differences in AWSA and PSS scores among three different stages of QCT pre-training, post-training, and two-month self-regulated practising

5.4.4 Correlation between practice sessions and perceived stress

Pilots' self-regulation of practising QCT for two months varied from 19 to 376 sessions ($M = 192.11, SD = 113.99$). Pearson's correlation analysis is applied to examine the association between the frequencies of practising QCT with PSS and AWSA scores. The frequencies of practising QCT showed a negative correlation with the PSS score after two-month trials, $r = -.48, p = .045$ (Figure 5-4a). Therefore, 'H₄: there is a significant correlation between frequency of practising QCT and stress level' is supported. Pilots who conducted more sessions of practising QCT are associated with lower stress levels. However, there is no significant correlation between practising QCT sessions and pilots' AWSA scores ($r = .13, p = .622$) (Figure 5-4b). Therefore, 'H₅: there is a significant correlation between frequency on practising QCT with wellness' is not supported. The frequencies of practising QCT have no association with pilots' wellness for two-month trials.



5-4a



5-4b

Figure 5-4 The significant negative correlation between PSS score after two-month QCT practice and practice session (5-4a) and nonsignificant association between AWSA score and practice session (5-4b)

5.5 Discussion

Pilots have suffered from the impact of the Covid-19 pandemic in many ways (Olaganathan & Amihan, 2021). This unprecedented challenge and disruption led to a range of negative stressors for pilots, including uncertainty of employment and a high risk of infection. The forecasts for air transportation recovery also increased pilots' stress as global flight restrictions were foreseen to run through the post-pandemic (Miani et al., 2021). Suffering from prolonged furlough, pilots appreciated the opportunity to return to the flight deck again. However, the lack of recency in practising operational procedures and operating automation systems resulted in pilots suffering from skill fade, which induced additional stressors during flight operations and associated with incidents and accidents (EASA, 2021). The effectiveness of QCT in the flight deck (on-duty) and day-to-day life (off-duty) were evaluated and discussed in relation to the hypotheses in the current research.

5.5.1 Quick coherence technique biofeedback training increases pilots' psychophysiological health

The research finding confirms H₁: 'there is a significant interaction on pilots' psychophysiological coherence between practising QCT and flight duty' is supported. The main effects of 'practising QCT' showed that pilots' coherence significantly increased from 35.86% to 81.38% after practising QCT. The simple main effect of 'flight duty' demonstrated that pilots' coherence levels off duty and on duty are different; however, practising QCT increased pilots' coherence to an equal level (81.14% off-duty vs 81.07% on-duty) without statistical significance ($p = .974$), which indicated the effectiveness of QCT in improving pilots' coherence on both day-to-day life and in the flight deck (Table 5-2). This finding is consistent with previous research, which proposed that QCT training significantly improved air traffic controllers' fatigue resilience and perceived workload related to rotating shift works (Li et al., 2022). In this study, pilots practised QCT sessions during the controlled rest in the flight deck, which is an effective strategy of taking breaks at work to help pilots re-charge their mental and physical resources during long-haul flights (Caldwell, 2005), such as 12

hours from London to Hong Kong. The results also support H₂: ‘there is a significant improvement in pilots’ wellness score based on QCT training’, which can reflect the effectiveness of the QCT training programme. The pandemic lockdown caused social isolation, economic stresses and more complicated protection procedures during flight operations, which may induce negative impacts on pilots’ mental and physical health. QCT can increase pilots’ coherence, which is able to improve pilots’ wellness and mitigate pilots’ stress levels related to day-to-day life and flight duty.

The COVID-19 pandemic imposed restrictions on flight operations and created additional stressors that may reduce pilots’ capacity and proficiency to perform their tasks as effectively as would be usual in the flight deck (CAA, 2020). The benefits of practising QCT were reported by pilots based on their experiences both on-duty and off-duty within two months of QCT trials. In the same vein, H₃: ‘there is a significant decrease in pilots’ perceived stress based on QCT training’ is supported. Practising QCT can increase individuals’ emotional calmness and wellness, as well as reduce perceived stress (Table 5-1). According to the qualitative feedback, 89% of pilots were impressed that the simple biofeedback could have such astonishing power with a positive impact on their performance in the flight deck and day-to-day life. QCT was reported by 33% of pilots in relation to increased resilience to stressful situations, such as annual license revalidation. 22% of pilots felt significant improvements in their task performance (simulator check and flight operations), and 39% of pilots reported enhanced physical functions after QCT practice (improved sleep quality, COVID-19 jabs recovery and blood pressure back to normal; detailed information see Table 5-4). 56% of pilots also mentioned that the QCT practice could effectively promote fatigue recovery and stress management during the controlled rest in the flight deck. The objective data analysis and pilots’ subjective feedback support the contention that practising QCT biofeedback can significantly improve mental resilience and enhance ‘good mood’ while on duty in the flight deck and in everyday life.

Table 5-4 Summaries on pilots' experiences shared while practising QCT both on controlled rest in the flight deck and day-to-day life

Practising QCT related to flight operations	Practising QCT related to day-to-day life
<p>I definitely felt less stressed after practising QCT in the flight deck</p> <p>It was not always practical practising QCT in the flight deck, although I am happy to say that my anecdotal experience is that I am feeling more focused and less fatigued</p> <p>It's interesting to feel I've had a noticeably more chilled attitude towards both of my annual simulator checks.</p> <p>After practising QCT on control rest, I felt much better and no need for more controlled rest. Usually, I would take more rest.</p> <p>One significant observation is that I had my annual medical check for my license, and my blood pressure was as low as it has ever been! Maybe the QCT breathing has helped.</p> <p>I've practised QCT around my annual 2-day license revalidation in the simulator. I'm not sure if it is of any interest; however, as it was my highest score ever, perhaps QCT played a part in my performance.</p>	<p>I found it very useful on a personal and professional level. More and more sessions, I am feeling a calmness.</p> <p>This was the day after COVID jab 2. I felt awful with a headache. After practising QCT, I felt much more alive, and the headache almost completely went away.</p> <p>I appreciated the science backing what is essentially a seemingly simple principle.</p> <p>Having practised breathing and meditation techniques before, it was interesting to discover there is science behind the techniques that prove resilience.</p> <p>I'm starting to feel the change already, and I'm feeling a greater sense of calm from each QCT session; it's quite addictive.</p> <p>Slept without interruption for 9 hours, which was very unusual for me, and practised QCT before bed.</p> <p>More useful actually has been towards the normal family/kids challenges that come our way.</p> <p>It's been invaluable to see the way the QCT can change mental/physical health just by positive thought and breathing.</p>

5.5.2 Habitually practising quick coherence technique enhances training effect on stress management

According to the results of Pearson Correlation Analysis, hypothesis H4: 'there is a significant correlation between frequency of practising QCT and pilots' stress level' is confirmed (Figure 5-4a). Pilots who self-regulated by practising more QCT sessions are associated with lower levels of perceived stress after the two-month trials, which is consistent with the research by Field et al. (2018): the biofeedback intervention can benefit both psychophysiological coherence and

self-regulation by improving the awareness of practice effects. This finding also supports that pilots' habit behaviours are critical to strengthening their learning from the two-day training. Effective QCT biofeedback training must be regularly practised, achieving effective stress management in both everyday life and flight duty. In the process of habitual behaviour formation, the effectiveness and strength of habitual behaviours have strong positive correlations with higher frequency and longer duration of self-regulated practice (Gardner et al., 2011; Rebar et al., 2016). Pilots also shared their experience of practising QCT with the following benefits: 'lower blood pressure on the annual medical check, relief of headache after COVID-19 jab, calmness, good sleep, simple technique with science backing'. The phenomenon of self-regulated QCT practice allows pilots to moderate their physiological and psychological wellness, which positively influences cognitive processes, emotional stability, and stress resilience to improve the quality and accuracy of in-flight decision-making and critical operational manoeuvres in emergency scenarios (Winne & Jamieson-Noel, 2002). Increasing coherence will also assist pilots in adapting to stress scenarios and maintaining mental and physical equilibrium while facing challenging situations and adversity. Previous research also indicated that self-regulation in continuously practising a task leads to improved skill levels and reduced cognitive workload while performing complex tasks (Haith & Krakauer, 2018; Slimani et al., 2016).

The results of Pearson Correlation Analysis did not support H₅: 'there is a significant correlation between frequency of practising QCT and pilots' wellness score' (Figure 5-4b), although abundance of practice is necessary to generate proficiency and autonomicity of specific actions (Fisk & Schneider, 1983; Dolan & Dayan, 2013). This finding is inconsistent with previous research on practising more sessions of the biofeedback technique associated with better psychological wellness (Kruskal et al., 2019). There are several factors which may have influenced this finding, including the small sample size, individual differences in motivation, and the inherent differences in the psychophysical characteristics between perceived stress level (H₄) and wellness (H₅). Wellness is a holistic perspective integrating a standard of both psychological and physical

characteristics, including five key elements: self-responsibility, nutritional awareness, physical fitness, stress awareness and management, and environmental sensitivity (Ardell, 1983). Compared with PSS, AWSA contains a broad range of concepts of physical, emotional, and spiritual well-being. The moderation of perceived stress tends to be associated with stress management and emotion regulation skills while facilitating wellness involves incorporating all five dimensions, which are more challenging to validate. It is believed that the promotion of wellness is more complicated and more vulnerable to individual differences, which led to the difficulty in obtaining a significant association between practice QCT sessions and wellness on the small-size samples of 18 commercial pilots.

It is important to note that the regular practising of the biofeedback technique learned from the training syllabus is to strengthen behaviour by autonomically enacted support and is insusceptible to context changes (Nilsen et al., 2012). With some behaviours, one practice is sufficient to gain desired health outcomes, such as a single vaccination may yield immunity to the virus, but practising one mindfulness session will not achieve the same health benefits as regular activity over a prolonged period of practice (Gardner & Rebar, 2019). Therefore, the self-regulated practice of QCT at a regular frequency and over a prolonged period will gradually form a habitual behaviour that can facilitate pilots' performance to respond rapidly and appropriately with less cognitive workload and mental stress. Therefore, long-term QCT practice can effectively moderate pilots' perceived stress and negative emotions to address the negative impacts of the COVID-19 pandemic, leading to promoted psychophysiological coherence and mental/physical health. Pilots' mental and physical issues have a significant capacity to influence aviation safety, which may have deteriorated after the COVID-19 pandemic (Marin et al., 2011; CAA, 2020). Therefore, encouraging pilots to practice self-regulated QCT regularly will not only improve their coherence and mental/physical health but also enhance their performance and aviation safety for long-standing effects.

5.5.3 Limitations and future work

This empirical study demonstrated a biofeedback QCT intervention could increase commercial pilots' coherence and stress resilience. However, there are a few constraints and more potential applications identified with this research. Firstly, only 18 pilots' subjective data has been collected among QCT pre-training, post-training, and two months later post-training on both AWSA and PSS levels. Such a small sample size may decrease statistical power and skew the results. The validity and reliability will be improved when further data are collected with future research. Secondly, there are only 225 QCT datasets collected while pilots were on-duty in the flight deck compared with 3,064 QCT data collected while pilots were off-duty. Nevertheless, those 225 sessions of QCT data are extremely valuable for empirical research and very difficult to collect due to the limitations on the environment of flight operations and airline safety regulations. There are some invalidated data due to emergency situations on the flight deck in which pilots interrupted the QCT sessions for operational safety reasons. It is desirable to conduct further research to accumulate more validated data in the flight deck in the future. Thirdly, there are individual differences in self-regulation, which may be a confounding variable to the psychophysiological coherence. Also, the stress intervention demand of pilots can be a critical influencing factor in training effectiveness. Relevant questions in pre-training questionnaire surveys and cognitive tests before the training programme will be added in future studies. Fourthly, in further research, a control group without any psychophysiological intervention should also be involved in comparison to investigate the effectiveness of QCT practice. Finally, the collection of pilots' coherence data in the flight deck was only available on long-haul flights, which had a 'controlled-rest' policy allowing pilots to practice QCT while discharged from flight duty. On the other hand, the subjective data on pilots' AWSA and PSS were able to collect from both long-haul and short-haul flights. The differences in the operational characteristics between long-haul and short-haul flights may be associated with different stress levels and mental and physical demands, which will have to be investigated in a future study.

5.6 Conclusions

The COVID-19 pandemic induced medical risks to commercial pilots, including mental and physical health issues. Furthermore, the social, economic, employment, emotional and personal relationship challenges are presented as threats affecting pilots' emotional stability and wellbeing. This research applies QCT biofeedback as an intervention to increase pilots' resilience and mitigate COVID-19 negative impacts during flight operations. Empirical data collected on both pilots' everyday life (off-duty) and in the flight deck (on-duty) demonstrated that biofeedback training can effectively improve pilots' psychophysiological coherence and reduce stress levels if pilots maintain a regular practice of QCT. Self-regulation of practising QCT biofeedback was found to be significantly associated with higher coherence and lower perceived stress levels for commercial pilots after the two-month training programme, which can strengthen training effects. In summary, a short session of practising QCT for five minutes during controlled rest breaks in the flight deck can significantly increase pilots' psychophysiological coherence by improving cognitive function and stress resilience. It is also noted that regular practice of QCT has long-standing benefits in boosting pilot's resilience and stress management capacity during flight operations or off-duty. QCT biofeedback can be an effective intervention for aviation authorities and airline operators to develop peer support programs for pilots to increase resilience and maintain mental and physical health.

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6 Quick coherence technique practice effects on pilots' psychological resilience and cognitive associated biomarkers in flight operations

6.1 Introduction

The global spread of COVID-19 has caused widespread health problems and economic hardships, leading to significant changes in society and aviation organisations. The aviation industry has a history that has been impacted heavily by natural and economic shocks in the last two decades, such as the severe acute respiratory syndrome (SARS) epidemic, the 9/11 terror attack and the 2008 financial crisis. Due to the COVID-19 pandemic, the scheduled passenger flights in 2020 were reduced by around 50% compared to the normal level in 2019, causing approximately 372 billion dollars in loss of gross passenger operating revenues for commercial airlines (ICAO, 2022). The very different pandemic environment with additional stressors has a detrimental impact on pilots' financial security, well-being, and flight performance. According to a survey targeted at all aviation workers, 47% of participants indicate that their job motivation has deteriorated since the COVID-19 pandemic, and around 15% are concerned that they will not be fit to return to work after the pandemic (Cahill et al., 2021). The limited access to the flight deck caused by the abrupt cancellation of flights decreases the proficiency of commercial pilots in performing routine flight tasks. Pilots' perceived stress and operational risk also go up with new procedures related to COVID-19 safety and health regulations (Olaganathan & Amihan, 2021). Prolonged furlough can lead to a lack of recency in practising operational procedures and operating automation systems, resulting in pilots suffering from skill fades, which induces perceived stress and is associated with incidents (Kiouleogloua & Blundell, 2022; Li et al., 2023a). In the current study, an effective intervention strategy based on the quick coherence technique (QCT) was implemented for commercial pilots to improve their stress resilience to the negative impacts of the COVID-19 pandemic.

Resilience is the capacity to recover from negative experiences through flexibly and positively coping with challenges to homeostasis. Heart rate variability (HRV)

serves as a promising biomarker of resilience to reflect the flexibility and efficiency of multiple aspects of physiological, emotional, and cognitive responses to stressors regulated by the autonomic nervous system (ANS) functions (Perna et al., 2020). According to the polyvagal theory, stress response and resilience are complex integrative processes supported by the ANS regulations, in which a sympathetic-adrenal system increases metabolic output and an inhibitory vagal system promotes immobilisation behaviours (Porges, 2001). Therefore, to validate the QCT training effectiveness on commercial pilots' stress resilience and cognitive functions, HRV measurements were applied to investigate the dynamic stress resilience and cognitive functioning processes regulated by ANS activities. QCT is a powerful technique based on heart-focused breathing to regulate individuals' respiration rate at approximately ten breaths per minute, thus improving the ANS balance for stress resilience and emotional regulation. Widdicombe and Sterling (1970) noted a direct association between breathing and ANS activities controlled by complex psychophysiological interactive mechanisms. Previous research also examined the modification effects of paced breathing techniques on autonomic and central nervous systems activities as well as the psychological status to improve mental/physical health and stress resilience (Zaccaro et al., 2018). Additionally, real-time HRV biofeedback will also be provided during the QCT practice to effectively train individuals in the voluntary control of the HRV state through audio-visual feedback mechanisms to improve psychophysiological well-being (Shaffer & Ginsberg, 2017).

The current study contributes to the literature in several ways. First, based on HRV measurements, the current research aims to investigate the ANS regulation mechanism during the stress resilience process under the intervention of psychophysiological treatment. Numerous studies have examined the connection between the HRV state and the stress response to explore the homeostatic process of the ANS activities to cope with external stressor stimuli (e.g. Kim et al., 2018; Negrao et al., 2000). The stress resilience and recovery processes were rarely tested. In this empirical study, the dynamic resilience process associated with multiple stressors is explored via HRV fluctuation. Thus, an

insight into the ANS activities during the stress resilience process in day-to-day life and flight operations is provided. Second, an alternative strategy of five-minute QCT practice for controlled rest on the flight deck during long-haul flights is proposed. In the current training programme, the QCT practice is applied during the controlled rest in flight operations to help pilots recharge their mental/physical resources and sustain alertness for long-haul flights. Compared to the traditional controlled rest strategy (cockpit nap, chatting, etc.), a five-minute QCT practice can be more effective and efficient in addressing the unanticipated fatigue/stress in flight operations. Furthermore, it has huge potential to improve pilots' capacity and performance through the regulation of cognitive functions and ANS activities in terms of HRV. Third, through the analysis of both time-domain and frequency-domain HRV, the complex interaction mechanism of cardiac autonomic regulation during the resilience process was explored, in which the activities of the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) were indicated by different HRV parameters. The current research tests the fluctuation of some controversial frequency-domain parameters (e.g. Billman, 2013; Von Rosenberg et al., 2017) in the specific context of an intervened resilience process regulated by paced breathing exercise. The findings can provide a better understanding of the ANS regulation effects during the resilience process, which may also contribute to the development of advanced and generalised stress intervention strategies.

6.2 Related works

6.2.1 COVID-19 pandemic influences psychological health and cognitive function

Since the end of 2019, COVID-19 has caused over 526 million infections and 6 million deaths globally, according to the World Health Organization (WHO, 2022). Beyond its core feature outcomes of the prominent respiratory distress syndrome and inflammation, many downstream consequences of psychological health and cognitive functioning impairments are also caused by the COVID-19 pandemic. In a rapid scoping review study by Lakhan et al. (2020), during the first seven months since the COVID-19 pandemic, the prevalence of all forms of stress was

53%, and anxiety 35% in the study population of 113,285 individuals. The prevalence rate of all forms of stress, anxiety, sleep disorders, and psychological distress in the general population was found to be higher during the COVID-19 pandemic. There has been an abundance of research demonstrating the deleterious effects of stress and anxiety on many aspects of cognitive functioning, including working memory (Banks et al., 2015), emotional regulation (Kinner et al., 2014), attention allocation (Sanger & Dorjee, 2015)), and human performance (Helton & Head, 2012). In the context of the COVID-19 pandemic, De Pue et al. (2021) investigated the cognitive functioning changes through online surveys, and the results showed that participants reported a significant decline in task memory, concentration, recalling, and dual-task performance. Recent studies also noted that stress-related declines in cognitive functioning are inevitable for even the most resilient individuals, leading to frequent mind wandering with negative emotions, poor performance of sustained attention tasks, and decreased situation awareness (Boals & Banks, 2020). Metin et al. (2021) found a significant decrease in the psychological well-being and stress resilience of people from almost all countries and industries during the COVID-19 pandemic.

The psychological health effects of the COVID-19 pandemic are especially profound to airline commercial pilots due to the great shock to the aviation industry as well as the following problems of unemployment threats and financial recession. Such significant and sudden changes in society can bring serious psychological health problems and cognitive functioning impairments to pilots and even increase the pilot aircraft-assisted suicide risks. A previous study found that after the 9/11 terrorist attacks, the risk of suicide by aircraft in the year following the attack was almost four times the average risk in the five years prior to the terrorist attack (Vuorio & Bor, 2020). Furthermore, the impairments of cognitive functioning during the pandemic may have long-term after-effects on flight performance and aviation safety in the post-pandemic era. Cognitive functioning has been identified as crucial to piloting abilities such as situation awareness (Ji et al., 2018) and decision-making (Causse et al., 2013), and thus to influence flight performance (Causse et al., 2011). The risk to safe operations is that the COVID-19 pandemic presents additional stressors and can reduce

human capacity and ability to perform or monitor themselves as effectively as would be usual (CAA, 2023). The impact, in terms of human factors and operational performance, is a compound risk. Therefore, it is vital to recognise and monitor pilots' psychological problems and cognitive declines arising from the COVID-19 pandemic to avoid adverse consequences of underperforming flight operations and aircraft-assisted suicide accidents. Practical intervention tools for improving pilots' resilience from these negative impacts are in urgent need for the aviation industry to be fully prepared to return to normal operations in this post-pandemic era.

6.2.2 Heart rate variability biofeedback paced breathing training improves stress resilience

The HRV biofeedback paced breathing training requires the person to breathe at a low frequency (around ten breaths per minute), lengthening the exhalation period to moderate the baroreflex and increase the amplitude of the respiratory sinus arrhythmia (RSA) as well as improve the physical/emotional resilience (Lehrer & Gevirtz, 2014). The final goal of this procedure is to increase the flexibility and recovery capacity of the cardiovascular system when facing stressful situations, allowing the individual to return to homeostatic equilibrium states with adequate psychological resilience (Gevirtz, 2013). The paced breathing technique is easy to learn and can be appropriately integrated along with other forms of intervention, with rare negative side effects on individuals' general well-being and task performance. The biofeedback technique as an approach to improve HRV has widespread beneficial effects. Via HRV biofeedback, individuals learn through biofeedback to monitor the practice effects in real time so that they can self-regulate their breath rate to ensure the gradually improved HRV in a dynamic process. Furthermore, a previous study has demonstrated that HRV biofeedback breathing exercise has a strong, long-standing influence on baroreflex and resilience gain: when people practice the self-regulated paced breathing training with HRV biofeedback regularly over a period of time, the moderation effects on both RSA and HRV will not disappear even when people are not practising this technique (Lehrer et al., 2003). Thus, these two important regulatory reflexes, the RSA and baroreflex, appear to be

strengthened by regular practice of HRV biofeedback paced breathing exercise, with expected effects of improved immunity to and recovery from stress and adaptability to various mental and athletic demands on the human body systems and cognitive functions (Lehrer et al., 2020).

In recent years, the HRV biofeedback technique has become an increasingly popular intervention tool for psychophysiological-minded psychotherapists (Lehrer, 2018). Previous studies have provided strong evidence that HRV biofeedback based on paced breathing at approximately six breaths per minute has positive effects on a variety of psychological and cognitive conditions and performance. Deschodt-Arsac et al. (2020) demonstrated that a five-week HRV biofeedback paced breathing training could effectively reduce chronic stress and cognitive fatigue while modulating the PNS or vagal activities via facilitating the HRV state during the stress-cognition interaction process. According to the stimulation of HRV state and PNS activities, HRV biofeedback is also believed to facilitate emotional regulation: Mather and Thayer (2018) indicated that after the regular practice of resonance HRV biofeedback training, the blood flow oscillations throughout areas involved in the emotional generation and modulation show large increases, proposing a potential mechanism whereby paced breathing exercise with HRV biofeedback modulates emotional swings. Furthermore, engaging in a brief HRV biofeedback breathing practice can effectively moderate relevant psychophysiological symptoms following a stressful experience and improve stress resilience as well as psychological well-being (Hunter et al., 2019). Shahirah Sha'ari and Amin (2021) indicated that individuals' frequency-domain HRV and resilience are significantly improved by paced breathing training with HRV biofeedback. The efficacy of the HRV biofeedback paced breathing technique as a resilience training intervention to cope with the post-traumatic stress disorder (PTSD) symptom of soldiers has also been proven, and this effectiveness can last for one year or longer (Pyne et al., 2019). Therefore, the current study applies HRV biofeedback paced breathing training as a resilience intervention in both day-to-day life (off-duty) and flight operations during controlled rest breaks (on-duty) to cope with the negative influence of the pandemic on commercial pilots.

6.2.3 Heart rate variability reflects cognitive performance and psychological resilience

The neurovisceral integration model proposed by Thayer and Lane (2009) described the neural structures of the cardiovascular system indexed by HRV regulating individuals' cognitive performance and executive functions. The psychophysiological characteristics of HRV can promisingly reflect cognitive functioning as HRV parameters are considered indices of autonomic control of the heart. HRV indicates the oscillations in the interval between consecutive heartbeats that result mainly from the dynamic interaction between the PNS and the SNS functions (Malik, 1996; Reyes del Paso et al., 2013). Pioneering research noted that individuals' HRV state represented by the root mean square of the successive differences (RMSSD) could be an effective predictor to assess the cognitive load, arousal level, attention distribution, and task performance as its association with parasympathetic activities (O'Keeffe et al., 2020). Except for the HRV time-domain parameters of RMSSD, low-frequency to high-frequency power (LF/HF) is also an index of vagal tone in the frequency domain, can also vary as a function of sustained attention load, working memory and other task-related cognitive components (Luque-Casado et al., 2016). Furthermore, Usui and Nishida (2017) demonstrated that the very low frequency (VLF) power and LF/HF can represent the recovery process regulated by ANS activities after induced mental stress. Mansikka et al. (2016) also indicated that the standard deviation of normal-to-normal RR intervals (SDNN) and mean heart rate are sensitive to the variations in pilots' mental workload and flight task performance due to different levels of cognitive complexity.

Psychological resilience is a dynamic regulation process in which individuals deal with traumatic events successfully and maintain cognitive functioning after exposure to severe stress (Bonanno et al., 2011). Previous research has found a positive association between psychological resilience and cognitive functioning of nonverbal memory (Wingo et al., 2010). In a longitudinal study, Yang et al. (2021) demonstrated that a high level of psychological resilience has significant mediation effects on the cognitive information process, which makes long-standing benefits on well-preserved cognitive functioning later in life. A balanced

and flexible autonomic nervous system is considered healthy as it is resilient to self-regulate with a wide variety of physiological and environmental demands (Kim et al., 2018). Therefore, HRV serves as an easily measured output of autonomic activities, providing quantitative information regarding stress response and psychological resilience. The elevation of the vagal tone reflected by reducing heart rate and RMSSD of time-domain HRV during the psychological resilience period indicates an activation of the PNS function after stressful events (Lau et al., 2021). An et al. (2020) explored the association between the frequency-domain HRV parameter of LF/HF and psychological resilience factors: the results demonstrated that during baseline rest, the LF/HF reflecting PNS dominance is negatively correlated with stress resilience, while a positive correlation between LF/HF and psychological resilience revealing SNS dominance after experiencing startle-inducing stressors. High vagally mediated HRV, such as RMSSD and LF/HF, before or during specific stressful tasks are associated with enhanced cognitive functioning, psychological resilience, and appropriate emotional regulation (Perna et al., 2020).

6.2.4 Hypotheses development

The widespread COVID-19 pandemic has brought unprecedented impact on the aviation industry, especially posing long-standing threats and risks to commercial pilots' psychological health and cognitive performance. To help pilots appropriately cope with the additional stressors induced by the pandemic and to be prepared for returning to normal operation in the post-pandemic era, the self-regulated QCT training program based on HRV biofeedback paced breathing technique is implemented in an international commercial airline. HRV is closely associated with the stress resilience process, as well as the task-relevant workload recovery in flight scenarios (An et al., 2020; De Rivecourt et al., 2008). HRV is also sensitive to varying task demands and complexity in flight operations, thus effectively reflecting pilots' decision-making, situation awareness, and flight performance (Sirevaag et al., 1993; Mansikka et al., 2016). Therefore, HRV was measured to test the effectiveness of QCT training on pilots' stress resilience and cognitive associated biomarkers in both day-to-day life and flight operations.

Through the analysis of time-domain and frequency-domain HRV indices, indicating different aspects of SNS and PNS activities, the regulation mechanism of QCT on pilots' psychological resilience was also investigated. Thus, four hypotheses were proposed as follows:

Hypotheses 1a and 1b: The 5-minute QCT practice can regulate commercial pilots' respiration rate for stress-coping purposes in day-to-day life (a) and flight operations (b).

Hypotheses 2a and 2b: The 5-minute QCT practice can decrease commercial pilots' stress levels in day-to-day life (a) and flight operations (b).

Hypotheses 3a, 3b, 3c, and 3d: The 5-minute QCT practice can moderate commercial pilots' HRV states (a: SDNN, b: RMSSD, c: VLF power, d: LF/HF) to improve cognitive processes and stress resilience in day-to-day life.

Hypotheses 4a, 4b, 4c, and 4d: The 5-minute QCT practice can moderate commercial pilots' HRV states (a: SDNN, b: RMSSD, c: VLF power, d: LF/HF) to improve cognitive processes and stress resilience in flight operations.

6.3 Method

6.3.1 Participants

Forty-four commercial pilots with various flight experiences between 3,000 and 20,000 hours ($M = 10,811.25, SD = 4,736.59$) voluntarily underwent this research. They were recruited via an internal newsletter and registered themselves without any financial incentive from the research institute and the airline. Their ages were between 29 to 60 years old ($M = 44.75, SD = 7.07$) and their service years in this international airline were from 2 to 32 years ($M = 14.41, SD = 8.26$). The research ethical proposal was submitted and approved by the research ethics committee in advance (CURES/12817/2021). All participants were informed that this research is based on a biofeedback breathing technique related to psychophysiological coherence training to improve their stress resilience and fatigue management. Participants were assured their rights to withdraw from this research at any stage. By providing their signed consent form,

their psychophysiological data and demographical information will be collected and managed in accordance with the United Kingdom Ethical Code and the Data Protection Act 2018.

6.3.2 Quick coherence technique

Psychophysiological coherence is the degree of order, harmony and stability occurring in the ANS consisting of sympathetic and parasympathetic systems. A coherent HRV pattern reflects effective cognitive and physical functions, which are related to the ease of energy and information processing (McCraty & Zayas, 2014). QCT is based on a paced breathing exercise (six to ten cycles per minute) with real-time HRV biofeedback to alter participants' cardiac activities and visualise HRV moment-to-moment fluctuation. The Inner Balance device and the Inner Balance Application (APP) were used to carry out the HRV biofeedback QCT training. The Inner Balance device is a lightweight Bluetooth sensor that measures psychophysiological data and provides real-time HRV biofeedback information on the Inner Balance APP via connection with personal mobile devices (iOS/Android).

6.3.3 Procedures

The QCT training programme was carried out in an international airline to improve commercial pilots' psychological health and stress management in the context of the COVID-19 pandemic and post-pandemic. In 2021, 18 commercial pilots joined the first QCT training programme, including a two-day training course and a one-month self-regulated QCT practice in both day-to-day life and flight operations. The data collection commenced in May 2021 and ended in June 2021. In 2022, another 26 commercial pilots joined the second QCT training programme with the same syllabus to understand the theoretical background and practical effects of the stress intervention strategy based on QCT. The data collection started in June 2022 and ended in July 2022. After the briefings on research objectives and training syllabus, participants signed the consent form, allowing their demographic information and psychophysiological measurements to be collected and analysed. During the one-month self-regulated practice, participants were encouraged to practise a five-minute QCT three times per day

in everyday life and as much as they could during controlled rest breaks in flight operations using the Inner Balance device. There is an additional five-minute psychophysiological data collection as a baseline before each QCT practice. The in-flight QCT practice was in accordance with the airline's safe operating practices of controlled rest policy to ensure that operational safety is always the priority. Participants' psychophysiological baseline measures and QCT practice recordings were stored in the HeartCloud and further processed by the EmWave and Kubios software.

6.3.4 Measures

6.3.4.1 Heart rate variability

HRV offers a unique window to observe the psychophysiological states related to stress resilience and cognitive functioning (Perna et al., 2020). HRV data were measured by the ear sensor of the Inner Balance device. The Inner Balance device has 80 hours of battery life and a 125 hertz sample rate to measure HRV data 125 times per second. This lightweight and compact device can be easily applied in any situation without additional processing on participants' skin or hair. In previous research, the Inner Balance device has been widely utilised to investigate the neuro-cardiac function and ANS dynamics via HRV measurements in operational scenarios (McCraty & Atkinson, 2012; Li et al., 2023b; Li et al., 2023c).

6.3.4.2 Data processing

Participants' baseline measures and QCT practice recordings were stored in the HeartCloud, which can be accessed by pre-registered usernames and passwords via the EmWave software. The collected HRV data were processed by EmWave software to export as the raw moment-to-moment inter-beat interval (IBI) data (recorded every 500 milliseconds). The raw IBI data were further imported into Kubios software. The R-wave time instants were autonomically detected by the built-in QRS detection algorithm, which is an advanced detection algorithm based on the Pan–Tompkins algorithm (Pan & Tompkins, 1985). For each beat, the quartile deviation of the 90 surrounding beats is calculated and multiplied by factor 5.2 (Tarvainen et al., 2021). Beats within this range cover 99.95% of all

beats if the RR series is normally distributed. However, the RR interval series is not often normally distributed, and thus, also some of the normal beats exceed the threshold. Therefore, the artefact beats in the IBI time series were detected and corrected by an accurate and robust algorithm proposed by Lipponen and Tarvainen (2019). Detected artefact beats were corrected by replacing corrupted RR times with interpolated RR values; missed beats were corrected by adding new R-wave occurrence time; extra beats were corrected by removing extra R-wave detection and recalculating the RR interval series. In this research, the corrected beats percentage is from 0 to 10.81.

6.3.4.3 HRV measurements

Two psychophysiological indicators (respiration rate and stress index), two HRV time-domain parameters (SDNN and RMSSD), and two HRV frequency-domain parameters (log transformed VLF power and LF/HF) were used in statistical analysis to investigate participants' stress resilience and cognitive functioning with the QCT practice. The respiration rate is also an important psychophysiological parameter for HRV analysis, computed from the beat-to-beat RR interval time series data. The respiration rate has been used in a wide range of clinical settings for identifying abnormalities since it is a strong biomarker to respond rapidly to variations in both physiological state and psychological workload (Lipponen & Tarvainen, 2021). The stress index is the square root of Baevsky's stress index, which is a geometric measure of HRV reflecting cardiovascular system stress (Baevsky & Chernikova, 2017). Baevsky's stress index was calculated by the variation scope of RR intervals. In order to transform the tailed distribution of the stress index towards normal distribution, the square root was taken. SDNN is the standard deviation of RR intervals to reflect the overall ANS activities of both SNS and PNS in the short-term HRV measurement (Schneider et al., 2009). RMSSD is the square root of the mean squared differences between successive RR intervals, which is a robust measure of the PNS activation state (Otzenberger et al., 1998). The log-transformed VLF power is the power of the very-low-frequency band (0.0033–0.04 hertz) in the log-transformed scale to indicate the SNS functions primarily (McCraty et al., 2009); LF/HF is the ratio of low-frequency (0.04–0.15 hertz) to high-frequency (0.15–0.4

hertz) power, which is widely interpreted as an ANS balance indicator (Powers et al., 2021). However, LF/HF has become increasingly controversial because of its non-linear and ambiguous association with the sympathovagal balance psychophysiological state (Billman, 2013; Von Rosenberg et al., 2017).

6.3.5 Statistical analysis

To examine the QCT practice effect on commercial pilots' HRV measurements in both day-to-day life and flight operations, two-way analysis of variance (ANOVA) was applied to test the interaction between two within-subject factors, (1) 'practising QCT': baseline measure vs QCT practice, and (2) 'flight duty': day-to-day life vs flight operation. The main effects of each factor of psychophysiological indicators and HRV parameters were analysed to demonstrate the global practice effect of QCT as well as the differences in the psychophysiological state between flight duty and everyday life. There is no extreme outlier observed by boxplots. The assumption of normality is verified by quantile-quantile (Q-Q) plots, and the homogeneity of variance assumption was verified by residuals versus fits plots. The effect sizes of samples were quantified by partial eta square (η_p^2).

6.4 Results

6.4.1 Sample characteristics

During the one-month self-regulated QCT practice, 5193 sets of psychophysiological indicators and HRV parameters were collected from 44 commercial pilots. There are 2410 baseline measures and 2469 QCT practices in day-to-day life; in flight operations, 143 baseline measures and 144 QCT practices were collected during controlled rest breaks in long-haul flights. The means (M) and standard deviations (SD) of commercial pilots' psychophysiological indicators and HRV parameters of baseline measures and QCT practices in day-to-day life and flight operations are shown in Table 6-1.

Table 6-1 Means (M) and standard deviations (SD) of commercial pilots' psychophysiological indicators and HRV parameters of baseline measures and QCT practices in day-to-day life and flight operation

	Session		N	M	SD
Respiration rate (hertz)	Day-to-day life	Baseline measure	2410	0.29	0.05
		QCT practice	2496	0.20	0.07
	Flight operation	Baseline measure	143	0.28	0.05
		QCT practice	144	0.20	0.07
Stress index	Day-to-day life	Baseline measure	2410	10.08	4.04
		QCT practice	2496	8.08	3.70
	Flight operation	Baseline measure	143	8.86	3.36
		QCT practice	144	7.19	2.79
SDNN (ms)	Day-to-day life	Baseline measure	2410	46.96	19.36
		QCT practice	2496	67.86	31.25
	Flight operation	Baseline measure	143	53.39	19.43
		QCT practice	144	74.26	31.63
RMSSD (ms)	Day-to-day life	Baseline measure	2410	50.75	25.03
		QCT practice	2496	52.88	28.98
	Flight operation	Baseline measure	143	57.02	25.13
		QCT practice	144	58.34	27.24
Log-transformed VLF power	Day-to-day life	Baseline measure	2410	4.42	1.05
		QCT practice	2496	3.93	1.12
	Flight operation	Baseline measure	143	4.60	0.90
		QCT practice	144	4.12	0.97
LF/HF	Day-to-day life	Baseline measure	2410	2.34	2.84
		QCT practice	2496	13.23	12.51
	Flight operation	Baseline measure	143	2.43	1.84
		QCT practice	144	11.75	11.37

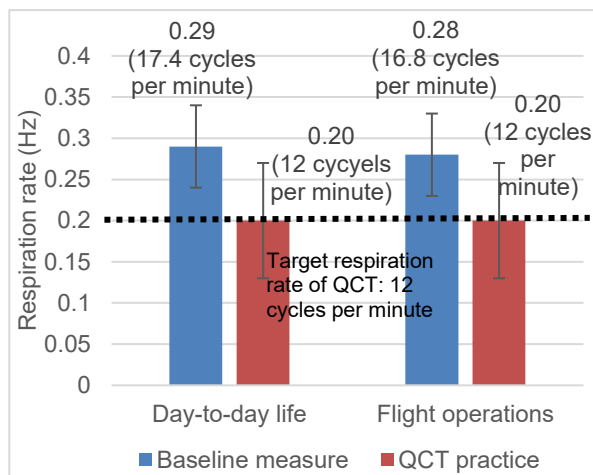
6.4.2 Quick coherence technique practice effects on psychophysiological indicators in day-to-day life and flight operations

The two-way ANOVA results showed that there is no significant interaction effect of 'practising QCT $\times$ flight duty' on respiration rate, $p = .528$. A significant main effect of 'practising QCT' on commercial pilots' respiration rate was found, $F(1, 5189) = 441.27, p < .001, \eta_p^2 = 0.078$. Therefore, '*Hypotheses 1a and 1b: The 5-minute QCT practice can regulate commercial pilots' respiration rate for stress-coping purposes in day-to-day life (a) and flight operations (b).*' were supported. No significant main effect of 'flight duty' on respiration rate was found, $p = .689$.

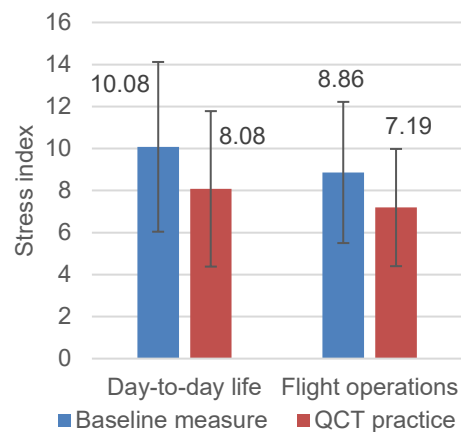
Similarly, there is no significant interaction effect of 'practising QCT $\times$ flight duty' on pilots' stress index, $p = .482$. A significant main effect of 'practising QCT' on pilots' stress index was found, $F(1, 5189) = 62.06, p < .001, \eta_p^2 = 0.012$. Therefore, '*Hypotheses 2a and 2b: The 5-minute QCT practice can decrease commercial pilots' stress levels in day-to-day life (a) and flight operations (b).*' were supported. The factor 'flight duty' also had a significant main effect on the stress index, $F(1, 5189) = 20.51, p < .001, \eta_p^2 = 0.004$. The detailed two-way ANOVA results of psychophysiological indicators between 'practising QCT' and 'flight duty' are shown in Table 6-2. The comparisons of respiration rate and stress index between baseline measure and QCT practice in day-to-day life and flight operations are shown in Figure 6-1.

Table 6-2 Two-way ANOVA results on pilots' psychophysiological indicators between practising QCT and flight duty

Psychophysiological indicators		<i>df</i> Effect	<i>df</i> Error	F	<i>p</i>	η_p^2
Respiration rate	Interaction effect 'practising QCT × flight duty'	1	5189	0.40	.528	.000
	Main effect 'practising QCT'	1	5189	441.27	<.001	.078
	Main effect 'flight duty'	1	5189	0.16	.689	.000
Stress index	Interaction effect 'practising QCT × flight duty'	1	5189	0.50	.482	.000
	Main effect 'practising QCT'	1	5189	62.06	<.001	.012
	Main effect 'flight duty'	1	5189	20.51	<.001	.004



6-1a



6-1b

Figure 6-1 Comparisons of respiration rate (6-1a) and stress index (6-1b) between baseline measure and QCT practice in day-to-day life and flight operations

6.4.3 Quick coherence technique practice effects on heart rate variability in day-to-day life and flight operations

There is no significant interaction effect for 'practising QCT × flight duty' on pilots' SDNN, $p = .993$. A significant main effect of 'practising QCT' on pilots' SDNN was found, $F(1, 5189) = 173.48, p < .001, \eta_p^2 = 0.032$. Therefore, *Hypotheses 3a and 4a* were supported: the 5-minute QCT practice can moderate commercial pilots'

SDNN in day-to-day life and flight operations. The factor 'flight duty' also had a significant main effect on SDNN, $F(1, 5189) = 16.38, p < .001, \eta_p^2 = 0.003$.

For the RMSSD, no significant interaction effect of 'practising QCT $\times$ flight duty' ($p = .804$) or main effect of 'practising QCT' ($p = .295$) was found by two-way ANOVA analysis. There is a significant main effect of 'flight duty' on RMSSD, $F(1, 2903) = 23.11, p < .001, \eta_p^2 = 0.008$. Therefore, *Hypotheses 3b and 4b* were rejected: the five-minute QCT practice has no moderation effect on commercial pilots' RMSSD in day-to-day life or flight operations. The factor 'flight duty' had a significant main effect on RMSSD, $F(1, 5189) = 12.74, p < .001, \eta_p^2 = 0.002$.

There is no significant interaction effect for 'practising QCT $\times$ flight duty' on pilots' log transformed VLF power, $p = .919$. A significant main effect of 'practising QCT' on pilots' log transformed VLF power was found, $F(1, 5189) = 55.11, p < .001, \eta_p^2 = 0.011$. Therefore, *Hypotheses 3c and 4c* were supported: the 5-minute QCT practice can moderate commercial pilots' VLF power in day-to-day life and flight operations. The factor 'flight duty' also had a significant main effect on the stress index, $F(1, 5189) = 8.22, p = .004, \eta_p^2 = 0.002$.

Similarly, there is no significant interaction effect for 'practising QCT $\times$ flight duty' on LF/HF, $p = .154$. There is a significant main effect of 'practising QCT' on pilots' LF/HF, $F(1, 5189) = 217.22, p < .001, \eta_p^2 = 0.061$. *Hypotheses 3d and 4d* were supported: the 5-minute QCT practice can moderate commercial pilots' LF/HF in day-to-day life and flight operations. No significant main effect of 'flight duty' on LF/HF was found, $p = .207$. The detailed two-way ANOVA results of HRV parameters between 'practising QCT' and 'flight duty' are shown in Table 6-3. The comparisons of time-domain and frequency-time HRV indices between baseline measure and QCT practice in day-to-day life and flight operations are shown in Figure 6-2.

Table 6-3 Two-way ANOVA results on commercial pilots' HRV parameters between practising QCT and flight duty

HRV parameters		<i>df</i> Effect	<i>df</i> Error	F	<i>p</i>	η_p^2
SDNN	Interaction effect 'practising QCT × flight duty'	1	5189	0.00	.993	.000
	Main effect 'practising QCT'	1	5189	173.48	<.001	.032
	Main effect 'flight duty'	1	5189	16.38	<.001	.003
RMSSD	Interaction effect 'practising QCT × flight duty'	1	5189	0.64	.804	.000
	Main effect 'practising QCT'	1	5189	1.10	.295	.000
	Main effect 'flight duty'	1	5189	12.74	<.001	.002
Log-transformed VLF power	Interaction effect 'practising QCT × flight duty'	1	5189	0.01	.919	.000
	Main effect 'practising QCT'	1	5189	55.11	<.001	.011
	Main effect 'flight duty'	1	5189	8.22	.004	.002
LF/HF	Interaction effect 'practising QCT × flight duty'	1	5189	2.03	.154	.000
	Main effect 'practising QCT'	1	5189	335.04	<.001	.061
	Main effect 'flight duty'	1	5189	1.59	.207	.000

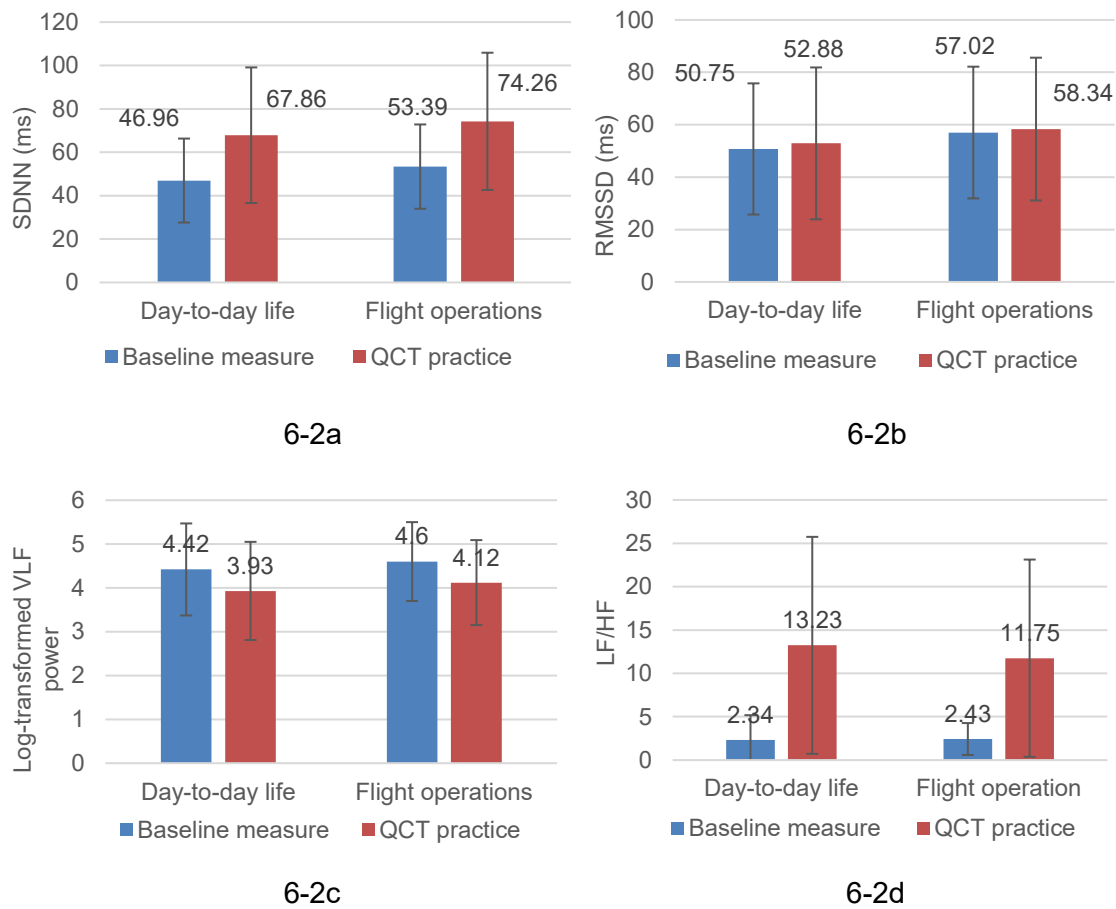


Figure 6-2 Comparisons of HRV time-domain (SDNN, 6-2a & RMSSD, 6-2b) and frequency-time (log-transformed VLF power, 6-2c & LF/HF, 6-2d) parameters between baseline measure and QCT practice in day-to-day life and flight operations

6.5 Discussion

The COVID-19 pandemic has been posing sustaining threats across typical daily life and the entire global aviation industry since 2019. Pilots endureably go through the maladaptive perception of multiple stressors, which are associated with autonomic output dysregulation and cognitive decline (Chrousos & Kino, 2005). The QCT training based on breathing frequency regulation and HRV biofeedback can improve efficiency in respiratory gas exchange and blood pressure control through baroreflex and ANS activities to improve resilience process and cognitive performance when facing stressful situations (Lehrer et al., 2020; Gevirtz, 2013). In the current study, the short-term QCT practice effect on pilots' stress resilience

and cognitive associated biomarkers in day-to-day life and flight operations was investigated through HRV measurements as ANS activity biomarkers. The two-way ANOVA results showed no significant interaction effect of ‘practising QCT’ and ‘flight duty’ on stress index, respiration rate, and HRV indices ($p > .05$), indicating the equal effectiveness of QCT training in facilitating pilots’ stress resilience and cognitive associated biomarkers in day-to-day life and flight operations. The different fluctuations of HRV time-domain and frequency-domain parameters also reflected the dynamic stress resilience process of cardiac autonomic nerve control intervened by paced-breathing-based QCT training. The scientific evidence of developing QCT training as a peer support programme and controlled rest strategy to potentially improve pilots’ psychological resilience and cognitive performance is demonstrated here.

6.5.1 Quick coherence technique training supports commercial pilots’ stress management

The heart-focused breathing technique is the key strategy of QCT to improve emotional and mental self-regulation. When performing QCT practice, pilots are recommended to direct their attention to the heart area and breathe deeply, around ten cycles in one minute. According to the data analysis results, the respiration rate significantly decreased from 0.29 hertz (17.4 cycles per minute) to 0.20 hertz (12 cycles per minute) by QCT practice in daily life and flight operations, $F(1, 5189) = 441.27, p < .001, \eta_p^2 = 0.08$ (Figure 6-1a). Respiration serves as a key connection bridge in linking the individual’s brain and heart. Previous research demonstrated that the 8-cycle paced breathing exercise can significantly decrease individuals’ stress and anxiety (Clark & Hirschman, 1990). In the current study, the moderation effect of the 12-cycle breathing-paced QCT training on commercial pilots’ stress levels was also validated: The Baevsky’s stress index showed a significant reduction from 10.34 to 8.25 after QCT practice, $F(1, 5189) = 62.06, p < .001, \eta_p^2 = 0.01$ (Figure 6-1b). Moreover, in Chapter 5, the one-way repeated measures ANOVA results confirmed the long-term QCT training effects on decreasing commercial pilots’ perceived stress and improving well-being (Li et al., 2023b). A previous study also indicated that a 12-week slow

deep breathing exercise could effectively decrease perceived stress (Naik et al., 2018). This four-week self-regulated QCT training demonstrated consistent long-term effectiveness in decreasing commercial pilots' perceived stress levels after regular practice, in which gradually increased resilience can be accumulated to address not only the daily stressors but also applicable task-relevant stress in flight operations with long-standing benefits.

6.5.2 Quick coherence technique practice promotes the sympathetic-controlled stress resilience process

Baevsky's stress index was calculated based on the changed proportion of HRV pulse fluctuation in the RR interval time series by electrocardiogram framework, and thus to objectively characterise the activities of individuals' cardiac autonomic functions and stress resilience (Baevsky & Chernikova, 2017; Sahoo et al., 2019). Through the baroreflex action and breathing regulation by QCT training, the brain controls the heart directly through the sympathetic and parasympathetic branches of the ANS functions (Adjei et al., 2019). To investigate the moderation mechanism of QCT on ANS balance activities during the dynamic resilience process, SDNN and LF/HF served as the overall ANS balance activity indicators of both SNS and PNS (Schneider et al., 2009); RMSSD as the PNS activation state marker exclusively (Otzenberger et al., 1998); VLF power as the index of sympathetic activities primarily (McCraty et al., 2009). The two-way ANOVA results indicated that the QCT practice could significantly increase commercial pilots' SDNN ($F(1, 5189) = 173.48, p < .001, \eta_p^2 = 0.03$) and LF/HF ($F(1, 5189) = 335.04, p < .001, \eta_p^2 = 0.06$), as well as decrease the log transformed VLF power ($F(1, 5189) = 55.11, p < .001, \eta_p^2 = 0.01$); no significant change in RMSSD was found, $p = .734$ (Figure 6-2). These HRV parameters have been observed to be a strong measure for stress detection in short-term analysis and are closely associated with stress attenuation and psychophysiological resilience (Pereira et al., 2017; Roberto et al., 2022; Usui & Nishida, 2017). The fluctuation pattern of HRV indices indicated the QCT moderation mechanism on ANS functions that mainly promotes the SNS activation to mobilise adequate cognitive resources in the dynamic resilience process but barely influences PNS activities for resting

vagal control. By this means, pilots can effectively recover from the accumulated stress and workload while not causing sleepiness and mind wandering in further actions or tasks. In sum, these findings proved the effective regulation of QCT on SNS activation ANS balance for cognitive resources mobilisation and allocation to promote the dynamic resilience process.

6.5.3 The controversy of LF/HF regarding stress response and resilience intervention

Previous research noted that heightened occupational stress is associated with reduced PNS activation, marked by an increase in LF/HF (Järvelin-Pasanen et al., 2018). However, in the current research, the LF/HF was found to be increased during the stress resilience process. Saboul et al. (2014) demonstrated that LF/HF is negatively correlated to respiration rate. Steffen et al. (2021) indicated that the paced breathing technique as a psychotherapy could significantly increase LF/HF and reduce negative emotional experiences. This point was further confirmed in the current study by higher LF/HF and lower stress index after the 5-minute QCT practice in both everyday life and flight deck. Despite the increasing controversies about the direct correlation between LF/HF and ANS balance, LF/HF still had wide acceptance as a biomarker of cardiovascular autonomic regulation of SNS and PNS activities to stress resilience and emotional regulation (Powers et al., 2021). According to the data analysis results, the fluctuation of LF/HF during the QCT practice showed consistency with the regulated respiration rate (Tables 6-2 & 6-3) compared to other ANS-balance-relevant HRV parameters. It can be deduced that LF/HF is a mediating factor in the dynamic resilience process regulated by the breathing technique to influence sympathetic activities and autonomic balance. Due to the complexity of the interaction mechanism of respiration regulation on cardiac autonomic activities, the association between LF/HF and ANS balance can be non-linear and ambiguous (Billman, 2013). Von Rosenberg et al. (2017) also noted that the ANS balance cannot be accurately revealed by the LF/ HF, and the correspondence between the LF/HF ratio and the psychophysiological state is not constant and unalterable. However, Usui and Nishida (2017) proposed that the LF/HF increased with SNS activities for a quick recovery from mental stress. These

empirical pieces of evidence demonstrated the diverse fluctuation patterns of the LF/HF in stress response and resilience intervention processes regulated by complex ANS activation mechanism: an increased LF/HF can occur in both coherence training practices based on paced breathing technique (Zhang et al., 2022), but also along with stressor/workload stimuli (Skibniewski et al., 2015).

6.5.4 Quick coherence technique improves stress resilience and cognitive associated biomarkers in flight operations

The equal practice effectiveness in daily life and flight operations indicated the huge potential for implementing QCT as an effective and efficient controlled rest strategy. QCT has been proven useful in coping with the accumulated fatigue in air traffic control operations (Li et al., 2023b). In the current study, the improved HRV state demonstrated coherent neuro-cardiac functions and balanced ANS dynamics, thus associated with higher cognitive performance and psychological resilience (Schubert et al., 2009; Thayer et al., 2010). When ANS activity creates oscillations through the cardiorespiratory neuronal network, causing periodic fluctuation in the HRV state, the cognitive process and stress response can be regulated by sympathetic energy mobilisation and parasympathetic restorative function (Spyer, 1994; Hernando et al., 2016). Previous research indicated that a balanced autonomic reactivity marked by increased SNS activation and deactivating PNS tone allows individuals to achieve the best 'fight or flight' response and quick adaptive recovery for stress management and improve executive functioning, including decision-making skills in challenging situations (Alacreu-Crespo et al., 2018; Williams et al., 2009). The flight operation is a typical 'fight or flight' scenario where pilots are facing multiple stressors to perform critical time-limited tasks. In the current study, a five-minute QCT practice on the flight deck provided pilots with more cognitive resources by triggering sympathetic activities to address their perceived stress and accumulated workload related to flight tasks (De Sampaio Barros et al., 2018). Furthermore, according to the coping competition model proposed by Salvador (2005), an active coping response pattern characterised by activated sympathetic functions is associated with positive emotional states and increasing success probability in performing a challenging task. Therefore, the upregulated SNS activation and

enhanced ANS balance via QCT practice during the controlled rest breaks in flight operation not only facilitate pilots' fatigue recovery and stress resilience process but also promisingly improve the decision-making skills and flight performance to cope with the potential risks and emergencies in further flight tasks.

6.5.5 Practical and theoretical implications

The current study carried several implications, both theoretically and practically. First, the current empirical research validated the effectiveness of QCT on commercial pilots' stress/fatigue management and psychological health through five-minute quick practice and long-term self-regulated training. The scientific evidence of QCT's long-standing benefits can support aviation authorities and airlines in developing effective pilot peer support programs based on regular QCT practice to cope with their cumulative stress, distress, and potential risks for aircraft-assisted suicide as an association with the post-pandemic effects. Moreover, the effective moderation of QCT practice on pilots' stress resilience and cognitive associated biomarkers provided an innovative controlled rest strategy for pilots' efficient recovery from task-relevant stressors and workload, as well as recharge cognitive resources to improve flight performance during long-haul flights. The QCT training programme was implemented in an international airline to address the negative influences of the COVID-19 pandemic; however, its efficacy and applicability will not be limited to aviation personnel and pandemic-relevant stressors. The QCT can be applied in various generalised situations and occupational scenarios for global stress management purposes. Furthermore, it has huge potential to support clinical psychotherapy for common mental health problems such as anxiety, depression, PTSD, etc. Second, the investigation of the HRV fluctuation in the dynamic stress resilience process can supplement the framework of the ANS control mechanism on stress response and resilience intervention processes. The neuro-cardiac activities to external stressor stimuli are a complex process varying with individual differences and every slight environmental change. The current study illustrated the HRV fluctuation pattern regulated by SNS activation primarily in an intervened resilience process by the paced breathing technique. Especially for the

controversial LF/HF parameter, this study provided insight into the research of stress detection and intervention research in terms of HRV measurements and ANS dynamics.

6.5.6 Limitations and future work

The current study demonstrated that coherence training based on the breathing pacer technique can facilitate pilots' sympathetic activities and improve stress resilience. However, there are still a few constraints that should be noted. Firstly, there are only 185 datasets of baseline and QCT practice collected while pilots were on duty in the flight deck compared to 2722 in day-to-day life. The unequal sample size may reduce the statistical power and skew the results. It is considered to conduct further research to accumulate more validated data in the flight deck in the future. Secondly, the LF/HF is a controversial indicator to reflect the purely ANS balance. Furthermore, the complexity and ambiguity of the LF/HF ratio also lie in its close association with personality traits, and its effectiveness as a stress biomarker can be influenced by the differential application of stress-coping strategies as well as the different stressor types (Kim et al., 2014; Schubert et al., 2009). Further studies would categorise different stressors and flight phases to investigate the stress resilience effects of QCT training on specific stressor types and flight tasks. Moreover, the fluctuation of HRV indices, especially the LF/HF in a dynamic stress resilience process, as well as its complex association with ANS balance, can be further investigated. Thirdly, the HRV measurements in the current research served as indirect biomarkers reflecting pilots' cognitive performance. In future studies, a direct method to evaluate the improvements in cognitive performance should be conducted using reliable questionnaire surveys or cognitive tests. Finally, the in-flight QCT practice sessions were collected during the controlled rest breaks in which pilots can implement work break strategies to recover from fatigue/stress and sustain alertness during long-haul flights (Caldwell, 2005). There is qualitative feedback confirming the superior fatigue recovery effects of QCT practice compared to the traditionally controlled rest strategies, such as chatting and walking around in the flight deck (Li et al., 2023c). The quantitative study should be applied to compare

the effectiveness of conventional short-term break strategies and QCT practice on pilots' stress resilience and fatigue recovery in flight operations.

6.6 Conclusion

The psychological health and stress management of commercial pilots have been brought to the forefront of attention as their significant influences on aviation operational safety. Particularly in the context of the COVID-19 pandemic, commercial pilots are suffering from undesirable furlough, lower income, and skill fade, which can further result in overloaded stress and increased risk of aircraft-assisted suicide. Therefore, the QCT training based on HRV biofeedback and paced breathing technique is proposed in the current study to improve commercial pilots' stress resilience to the negative impacts of the pandemic. The empirical data analysis demonstrated that the QCT practice in both day-to-day life and flight deck could effectively reduce the stress index through the heart-focused breathing technique. The HRV fluctuation reflects a dynamic stress resilience process regulated by sympathetic activities to facilitate energy mobilisation and attention reservation. These benefits not only improve emotional regulation to cope with daily stressors but also promisingly promote cognitive functions and flight performance to ensure aviation safety. By understanding the full implications of QCT training, the aviation industry can move forward by developing effective peer support programmes and training syllabus to improve pilots' psychological well-being, stress management, and aviation safety. Furthermore, the positive effects of in-flight QCT practice demonstrate a potential application of a five-minute QCT session as an efficiently controlled rest strategy to improve pilots' stress resilience and operational performance in long-haul flights.

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7 General discussion

7.1 Overview

Since the Wright Flyer made its first crewed flight in 1903, the aviation industry has experienced a booming period of rapid technical development to cope with hardware and software failures. Until the 1980s, with more robust aircraft structures and avionic systems, aviation safety started a new era to shift the emphasis on human factor problems, especially errors related to pilots' non-technical skills related to cognitive aspects, for preventing accidents (Harris, 2016; Highton, 2005). The current research followed the Five Ms model (Harris & Smith, 1997) from a system perspective of human factors to improve human-computer interaction in the flight deck (physical medium) and pilots' psychological resilience to address the negative influence of the COVID-19 pandemic (social medium). This thesis included two parts: (1) The first part developed a multimodal augmented reality (AR) interactive checklist from human-centred design principles to improve pilots' cognitive information processing and human-computer interaction in flight operations. Pilots' perceived workload and situation awareness while interacting with the AR checklist were investigated in Chapter 3. The system usability and user interface experience of the multimodal AR were evaluated in Chapter 4. (2) The second part proposed a psychophysiological resilience training programme based on the quick coherence technique (QCT) to improve commercial pilots' stress resilience and cognitive associated biomarkers to cope with the negative influence caused by the COVID-19 pandemic. The long-term training effects of QCT as a habitual behaviour on pilots' psychological well-being and psychophysiological coherence were described in Chapter 5. The advantages of QCT practice on pilots' stress resilience and cognitive performance, especially in the flight deck, were examined by heart rate variability (HRV) analysis in Chapter 6.

The research addressed two current pressing challenges facing the aviation industry. The first challenge is the human-computer interaction considerations caused by increasing technological advancements in the flight deck. The interaction issues of high-tech systems in the flight deck have been highlighted

as key factors attributed to several air incidents and accidents (e.g., AAIB, 2020). Unfortunately, the solutions addressing human performance issues and human-computer interaction considerations have always lagged behind the application of advanced technologies (Parasuraman & Riley, 1997). Therefore, it is important to investigate and optimise the human-computer interaction process in the flight deck for aviation safety and operational efficiency. The second challenge is related to the COVID-19 pandemic, which has been posing sustaining threats and long-standing side effects across typical daily life and the aviation industry even after the pandemic. In this context, additional stressors related to pilots' psychological health issues and skill fades can reduce human capacity and performance to perform flight operations as effectively as usual before the pandemic (CAA, 2020). The mental health issues of commercial pilots are high on the list of major causes of aviation accidents. The accessibility to psychological support should be improved in order to cope with pilots' cumulative stress, distress, and potential risks for aircraft-assisted suicide as an association with the social changes caused by the pandemic (Vuorio & Bor, 2020). Thus, effective interventions for these negative effects are required to improve pilots' stress resilience and psychological well-being to ensure human performance and aviation safety in the post-pandemic context.

7.2 Human-computer interaction considerations related to advanced technology implemented

Applying advanced technology in a well-tuned system always calls for concerted improvements in human performance and interaction effectiveness to minimise human-error-related accidents (Lauber, 1989). In the modern flight deck, there are emerging high-tech systems becoming available at pilots' fingertips to provide powerful support in situation awareness, decision-making, cognitive capacity, etc. However, these advanced technology implementations always come with human-computer interaction considerations, which require human-centred solutions and optimisations (Carroll & Dahlstrom, 2021). AR has gained increasing attention as a promising technology to enhance pilots' cognitive information process and operational performance in flight scenarios (Hayden et

al., 2020). In Chapter 3, based on the comparison with the traditional paper-based checklist, the AR voice-command checklist demonstrated significant advantages in decreasing task-relevant workload and improving situation awareness in landing scenarios. However, participants' evaluations of gesture-command and voice-command AR interactive modes regarding cognitive demands exhibited contrasting trends: voice-command AR had the highest ratings on virtually all subdimensions of perceived workload (NASA-TLX) and situation awareness (SART-10D), while gesture-command AR was rated lowest in all subdimensions. To further investigate the differences in system and interface design between voice-command and gesture-command AR interactions, in Chapter 4, system usability and user interface experience were evaluated. AR voice-command mode still had a higher and more acceptable level of system usability and user interface satisfaction compared to gesture-command AR.

The visual presentation of the AR system interface was designed following the proximity compatibility principle (PCP) to declutter and integrate the checklist-relevant information in close spatial vicinity (Wickens & Carswell, 1995). Both voice-command and gesture-command interactive AR applied this human-centred design for the visual interface, allowing pilots to catch all critical information in one gaze and simultaneously monitor the out-of-window view and flight display data. However, the improper system control method can disruptively influence the pilots' cognitive processing and user experience while interacting with the AR system. The inapplicability of the 'air-tap' gesture-command AR resides in two aspects: (1) the limited field of view of the AR device makes accurate motion recognition difficult; (2) the multitask characteristic during landing scenarios increases the difficulty and temporal pressure of using one hand to execute both precise hand-gesture input and required procedural actions (the other hand must handle the control column/stick to fly the aircraft). The voice input AR ideally made up for these deficiencies: little effort was required to achieve the simple, accurate, and intuitive human-computer interaction process without the distractions of pilots' manual flight control tasks. With full consideration of technical limitations, operational characteristics, and human capacity, an optimised human-computer interaction mode must be implemented

along with innovative technology. The integrated human-centred design is the key to practically and applicably improving human performance and operational safety in aviation.

7.3 Psychophysiological approach to improving human performance and aviation safety

The global aviation industry has suffered a substantial and long-standing stroke due to the COVID-19 pandemic. With governments and relevant authorities lifting restrictions, the aviation industry is recovering progressively and transitioning into a 'new normal' post-pandemic era. However, the side effects of the pandemic on the decline of pilots' psychological health, skill proficiency, and cognitive performance will still threaten aviation safety. In Chapters 5 and 6, a training programme based on the quick coherence technique (QCT) was developed and implemented in an international airline to improve commercial pilots' psychological well-being and stress resilience to cope with the negative influence of the COVID-19 pandemic. Based on the analysis of subjective questionnaire scores (Ardell wellness self-assessment, AWSA and perceived stress scale, PSS), pilots' psychological well-being increased, and perceived stress decreased after the two-day training course and two-month self-regulated QCT practice. In this case, QCT demonstrated effective improvements in pilots' psychological health and stress management in both the short term and the long term. During the two-month training, pilots practised self-regulated QCT as a habitual behaviour in daily life and flight operations to strengthen the training effects on long-term psychological well-being. Empirical data demonstrated that pilots practising QCT with a higher frequency of self-regulation achieved a significantly lower perceived stress level, indicating that habitual practice is critical to enhancing their learning from the two-day training course.

The physiological data were also collected during QCT practice to investigate the psychophysiological regulation of pilots' stress resilience and cognitive performance. HRV is a promising physiological indicator to reflect the psychological resilience process and cognitive functioning, reflecting the dynamic interaction between two branches of the autonomic nervous system (ANS):

sympathetic (SNS) and parasympathetic (PNS) activities (Thayer & Lane, 2009; Yang et al., 2021). The foremost contributive finding is that the QCT practice had equal effectiveness in improving pilots' cognitive performance and stress resilience in day-to-day life and flight operations. The QCT training not only provided positive effects on psychological well-being and stress management as other psychophysiological interventions, such as yoga, meditation, and mindfulness training (e.g. Auty et al., 2017; Baer et al., 2012). QCT is also perfectly applicable during flight operations or any other operational scenarios (such as air traffic control operations, Li et al., 2023) to recharge cognitive resources and facilitate human performance with a five-minute quick practice. The effective psychophysiological regulation of pilots' ANS balance and SNS functions can mobilise adequate cognitive resources in the dynamic psychological resilience process. Pilots can thus effectively and efficiently recover from the accumulated stress and workload to be well-prepared to cope with further flight tasks or potential emergencies. Therefore, through regular QCT practice, pilots' psychological health and cognitive capacity can be facilitated to improve aviation safety. A formal project to implement QCT as a pilot peer support programme is currently being signed off between HeartMath UK and British Airways to improve psychological well-being and stress resilience.

7.4 Improving pilots' non-technical performance in flight operational context

Pilots' non-technical skills refer to cognitive and social skills in the flight deck, which are crucial factors that complement technical skills to ensure operational performance and aviation safety (Flin et al., 2003). The main categories and key elements of pilots' non-technical skills in flight operations, which were modified and integrated based on previous studies by Flin and Maran (2015), Flin et al. (2003; 2017), and Endsley (1995), are listed in Table 7-1. Within a series of major air accidents during the late 1970s, the crash of United Airlines Flight 173, which is attributed to pilots' human error caused by non-technical failures, was a catalyst for the aviation industry to realise the importance of identifying and managing human factors for improving aviation safety (NTSB, 1979). A designated training

programme of crew resource management (CRM) for training pilots' non-technical skills to enhance operational safety and efficiency was established and mandated in a wide range of airlines (EASA, 2014). However, there are increasing criticisms of CRM training courses for not sufficiently integrating pilots' technical and non-technical skills, isolated from real operational contexts, as well as the lack of effective evidence of cognitive/social capacities contributing to operational performance (Mavin & Dall'Alba, 2010; Tsifetakis & Kontogiannis, 2019). Therefore, supplemental strategies to enhance pilots' non-technical skills in flight operational scenarios are urgently needed to improve human performance and aviation safety.

Table 7-1 Main categories and key elements of pilots' non-technical skills in flight operations

Main categories	Key elements
Cognitive skills	Perceiving information in the operational context (Level-1 situation awareness)
	Situation awareness
	Comprehending information related to the current operational situation (Level-2 situation awareness)
	Projecting future states (Level-3 situation awareness)
	Defining problem
	Decision-making
Social skills	Considering options
	Selecting and implementing option
	Reviewing outcome
	Building and maintaining team
	Teamworking and Leadership
	Supporting others
Workload management	Solving conflicts
	Using authority and assertiveness
	Identifying symptoms of stress/fatigue
	Recognising the effects of stress/fatigue
	Implementing stress/fatigue coping strategies

Developing better situation awareness is crucially important to safe flight operations, which requires optimised human-centred design in information presentation and human-computer interaction modes in the flight deck with increasingly complicated aircraft systems (Jensen, 1997). In Chapter 3, the voice-

input AR interactive checklist significantly improved pilots' situation awareness during the landing operations. The AR system presented additional task-relevant information via a see-through virtual screen, which can reduce the 'head-down' time when using the traditional paper-based checklist to enhance pilots' perception of the operational environment (Level-1 situation awareness). The augmented visualisation cues that guide pilots' attention to the procedure-relevant equipment in the flight deck can support pilots' cognitive information processing to quickly comprehend and perform required actions (Level-2 situation awareness). Furthermore, the AR checklist with guiding cues can facilitate pilots' visual attention allocation and reduce human errors in procedure compliance, thus improving decision-making in flight operations (Orasanu, 2010; Schriver et al., 2017). The empirical data also demonstrated a decreased task-relevant workload while interacting with the AR voice command checklist. This finding revealed the moderation effect of the intuitive AR interface with voice interaction mode on accumulated workload during flight operations, indirectly supporting pilots' workload management.

The QCT training had a direct effect on pilots' workload management in the flight deck. In Chapters 5 and 6, both quantitative data analysis and qualitative feedback demonstrated an effective and efficient fatigue/stress recovery through a five-minute QCT practice during the controlled rest in flight operations. Moreover, the psychophysiological data of HRV fluctuation reflected not only the dynamic stress resilience process but also enhanced cognitive processing and executive performance, closely related to situation awareness and decision-making (De Couck et al., 2019; Saus et al., 2012). A quick stress/fatigue resilience of five-minute practice facilitated pilots' autonomic nervous system balance and sympathetic activities to mobilise pilots' cognitive resources for detecting, predicting, and coping with potential risks in further flight operations. Thus, Level-3 situation awareness can also be indirectly improved. Compared to traditional classroom-based or simulator-based non-technical skills training, QCT demonstrated significant advantages in effectively managing pilots' workload in the real flight operational environment. Furthermore, HRV as a biomarker of cognitive processing provided more scientific and reliable evidence (real-time

objective psychophysiological measurements) of improved non-technical performance during flight operations. In sum, the current thesis provided effective solutions of AR and QCT to improve pilots' non-technical performance in direct or indirect manners with the aspects of situation awareness, decision-making, and workload management in the context of flight operations.

7.5 Enhancing cognitive capacity to support single pilot operations

Over the past decades, there has been a progressively 'de-crewing' trend in commercial flight deck design (Figure 7-1). The National Aeronautics and Space Administration (NASA) began to explore the feasibility and challenges of implementing single pilot operations from professional insights (Comerford et al., 2013). European Aviation Safety Agency (EASA) has also engaged in a research project on extended minimum crew and single pilot operations for commercial aircraft to produce an implementation framework by 2030 (EASA, 2021). For regional aircraft, it has been estimated that approximately 15% to 35 % of airline direct operating costs can be accounted for crew costs (Alcock, 2004). With single pilot operations, using the Boeing 737-300 with a 25-year operational life as a baseline, the cost would save between 1.25 and 4.38 million dollars per aircraft (Graham et al., 2014). However, several human factors considerations related to single-pilot resource management, including workload management, situation awareness, human-automation interaction, etc., were identified as hazards and associated risks to operational safety (NBAA, 2016). Compared to single pilot operations, the two-pilot crew does not half the workload, and vice versa, but provides a workload margin with higher operational resilience (Harries, 2023). Furthermore, the high-level automation system intending to simplify flight tasks by automating as many current pilot functions as possible may instead distance the single pilot from flight scenarios and erode situation awareness and cognitive readiness (Bilimoria et al., 2014).

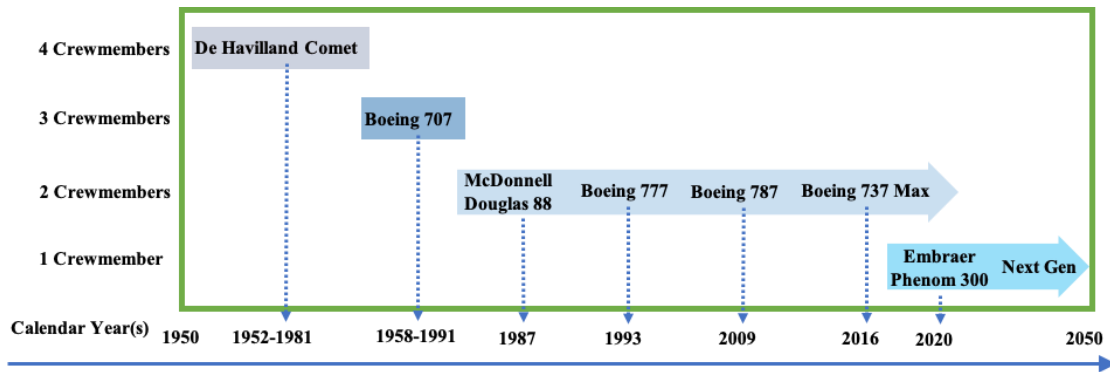


Figure 7-1 The evolution of crew numbers on the flight deck

AR technology is a promising solution towards single pilot operations by providing additional information and supportive cues rendered in pilots' heads-up field of view (Minaskan et al., 2021; Tran et al., 2018). In the current research, Chapters 3 and 4 applied an AR checklist enabling multimodal interaction in ILS landing scenarios. This multimodal AR system presented the pre-landing checklist procedures within a virtual see-through display overlapped with the physical environment in the flight deck. Pilots can interact with the checklist using the 'air-tap' gesture or voice input. Augmented visualisation cues of guiding arrows and procedure information will be automatically provided after activating each checklist item to help pilots quickly direct their attention to the procedure-relevant equipment and perform required actions. A combination of visual and audio feedback for checklist accomplishing confirmation was also integrated into this multimodal AR system. According to the simulated flight trial of the instrumented landing system (ILS) scenario, AR voice-command interaction was evaluated with significant advantages in perceived workload and situation awareness, surpassing the traditional paper-based checklist. Furthermore, voice-command AR was rated with higher system usability and user interface satisfaction, as it provides a more intuitive and familiar human-machine interface with enhanced emotional effectiveness. These findings demonstrated the potential and benefits of implementing the AR system in the future flight deck to improve human-computer interaction and pilots' cognitive capacity to cope with the safety concerns caused by de-crewing single pilot operations.

Previous research stated that single pilot operations with an additional ground pilot to monitor and control the aircraft system could be even more operationally resilient compared to the current dual-crewmember flight deck (Stanton et al., 2016). However, pilots' resilience in psychological and cognitive aspects remains a crucial factor in reducing human errors and improving operational safety (Liu et al., 2016). In Chapters 5 and 6 of the current thesis, QCT was implemented in long-haul flights to improve commercial pilots' psychological resilience and cognitive performance through a five-minute quick practice. This finding demonstrated the promising potential of applying QCT practice as an innovative controlled rest strategy in single pilot operations to support pilots in coping with accumulated workload and stress more effectively and efficiently during flight operations. In single pilot operations, pilots need to monitor the aircraft system and perform necessary manual tasks throughout the entire flight process, which requires more cognitive efforts and induces higher perceived workload/stress during flight scenarios. Furthermore, independently performing tasks by one operator will significantly decrease monitoring performance and increase task-relevant stress compared to collaborative teamwork (Funke et al., 2016). In-flight QCT practice can be an effective intervention to enhance pilots' stress resilience and mobilise cognitive resources. Therefore, the single pilot is able to maintain vigilance, situation awareness, and decision-making performance to handle any unexpected situations properly, even in long-haul flight operations.

7.6 Reference

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8 Conclusion and future work

8.1 Conclusion

Human errors continue to be the major cause of aviation accidents despite many years of effort. From the integrated perspective of human factors, the developments of pilot-friendly interfaces, physically and psychologically, as well as technically and non-technically/cognitively, can contribute to reducing human errors and improving human performance and operational safety. This research provides promising safety-oriented solutions to address the current challenges facing flight operations. Implementing augmented reality (AR) technology with semantic voice-command interaction can significantly improve human-computer interaction and pilots' cognitive information processing during flight operations. The more intuitive and effective voice-command interface reduces pilots' perceived workload and increases situation awareness. Although the current limitations of AR technology require technical developments and human factors considerations, the benefits of AR applications in flight operations and training are still well-presented. Another urgent challenge of the COVID-19 pandemic on pilots' psychological well-being is also adequately resolved. The quick coherence technique (QCT) training based on paced breathing exercises and heart rate variability (HRV) biofeedback can effectively improve pilots' well-being and decrease perceived stress with long-term habitual practice. A five-minute QCT practice during flight operations has equal effects with practising in daily life to significantly facilitate pilots' stress resilience and cognitive associated biomarkers via regulations on sympathetic activities for energy mobilisation and attention reservation. QCT practice has huge potential to be developed as an innovative controlled rest strategy to facilitate pilots' fatigue/stress recovery and cognitive capacity to cope with the potential risks and emergencies in further flight tasks. As significant improvements in pilots' workload management, situation awareness, and cognitive associated indicators are found in this empirical study, the joint applications of AR and QCT have huge potential to effectively supplement crew resource management (CRM) training to enhance pilots' cognitive performance in flight operations. The applicability of applying them in

the real flight environment can mitigate the constraints of the current classroom-based CRM training. The HRV biofeedback can provide scientific psychophysiological measurements of CRM effectiveness in terms of cognitive associated biomarkers and stress management performance. Furthermore, AR technology and QCT training can provide promising support for developing and implementing single pilot operations. The augmented visualisation information provided by AR technology and direct regulation of QCT practice on resilience and cognitive functions can promisingly cope with the safety concerns related to human capacity caused by de-crewing single pilot operations.

8.2 Limitations and future work

Based on the findings of this research, several limitations to be addressed and relevant prospective studies to be taken forward in future work are proposed as follows:

1. The AR interface can render virtual information in a 360-degree panoramic environment to decrease head-down time and improve situation awareness during flight operations. However, due to the limited field of view of the 30-degree AR screen, the virtual objects are usually located outside the field of view. Thus, the selection and confirmation of outside targets require extra head movements, and distracted attention may lead to tunnel vision associated with potential operational risks (Mills et al., 2001). This issue might be resolved by applying new AR devices equipped with a wider field of view and eye-movement control functions for quicker and easier interaction with mitigated attention distraction. Furthermore, the innovative gaze-control interactive mode and multiple pilot-support functions within the AR system will be developed and applied in different flight segments. The applicability should be further evaluated from the human factors perspective in the context of flight operations.
2. Hundreds of QCT practice records are collected during flight operations, which are extremely valuable due to the limitations of real flight scenarios and airline safety regulations. However, compared with thousands of practice records in daily life, the unequal sample size may reduce the

statistical power and skew the results. Further studies will be conducted to accumulate more validated data during flight operations. Also, direct evaluation on pilots' cognitive functions/performance using reliable questionnaire surveys or objective cognitive tests should be involved in future research. Moreover, except for commercial pilots, other front-line personnel in aviation operations, including cabin crews, air traffic controllers, maintenance personnel, etc., can be further involved in the QCT training programme. A control group with the psychophysiological intervention of QCT training should also been compared to verify the training effect in future studies. The innovative concept of 'global coherence' proposes the potential of applying QCT to synchronously improve psychological capacity and interpersonal relationships among a group of people (Edwards, 2019). Global coherence training will be implemented in future work to improve teamwork and communication, which are critical non-technical social skills not addressed in the current research. Also, QCT can be applied in various generalised situations and occupational scenarios, as well as clinical psychotherapy, to cope with common mental health issues and global stress management.

3. The flight data accessibility is also a significant limitation to be addressed in future studies. In the current research, human performance indicators are only evaluated through the relevant items in the subjective surveys and psychophysiological measurements. The flight data, whether in the simulator system or real flight operations, cannot be accessed due to the limitations and regulations of the simulator manufacturer and the airline. In future studies, an advanced simulator with full access to flight data should be utilised. Also, the real flight data are to be accessed and well-managed for research purposes to provide more convincing evidence of improved flight performance and aviation safety. Alternatively, simplistic measures of performance such as task completion outcome (safe or crash), task completion time, and response time should also be included in future experiments.

4. Whether wearing an AR headset to perform landing operations or an ear sensor for QCT training during controlled rest breaks is a brand-new experience in flight operations. Innovative technology implementations always come with human factors consideration related to the system usability and human trust issues. These concerns require long-running efforts not only in technology development and interface design to improve system reliability and functionality but also in investigating operators' attitudes towards innovative applications (Lankton et al., 2015; Parasuraman & Riley, 1997). Bias is found to be related to applying new technology and techniques in the flight deck. This calls for building an appropriate level of human trust and reliance on technology from engineering psychology principles in future work, which is also an indispensable requirement for certification and real-world implementation.

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Appendix A Ethical approval letters

The current thesis includes two research projects involving human participants for a simulated flight trial and resilience training programme. The research proposals were submitted to Cranfield University Research Ethic System (CURES) for reviews and approvals before implementing research activities. The ethical approval letters are shown as follows:

A.1 Ethical approval letter for the simulated flight trial applying interactive AR applications (CURES/13869/2021)



14 June 2021

Dear Miss Zhang ,

Reference: CURES/13869/2021

Title: The Application of Augmented Reality by Human-System Integration to Improve Operational Efficiency

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/13869/2021 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

A.2 Ethical approval letter for the QCT training programme (CURES/15728/2022)



18 May 2022

Dear Miss Zhang ,

Reference: CURES/15728/2022

Title: British Airways Training Course: Fatigue Resilience Training: Increasing Psychophysiological Coherence and Wellbeing

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/15728/2022 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B One-way repeated measures ANOVA results of NASA TLX and SART-10D scores

B.1 NASA-TLX scores and one-way repeated measures ANOVA results of each subdimension

Table B-1. Means and standard deviations of NASA-TLX item scores and one-way repeated measures ANOVA results

Dimension	Interactive modes	N	M	SD	One-way repeated measures ANOVA				
					df1	df2	F	p	η^2
Mental demand	Traditional	34	43.24	21.17					
	AR gesture-command	34	61.76	22.26	2	66	12.40	< .001	0.27
	AR voice-command	34	43.09	17.45					
Physical demand	Traditional	34	43.82	22.90					
	AR gesture-command	34	74.71	16.92	2	66	44.89	< .001	0.58
	AR voice-command	34	37.35	18.72					
Temporal demand	Traditional	34	47.65	20.05					
	AR gesture-command	34	65.88	26.27	2	66	14.32	< .001	0.30
	AR voice-command	34	40.29	19.19					
Performance	Traditional	34	67.06	20.68					
	AR gesture-command	34	39.12	24.85	2	66	18.71	< .001	0.36
	AR voice-command	34	67.50	21.47					
Effort	Traditional	34	38.68	21.82	2	66	38.56	< .001	0.54

	AR gesture-command	34	71.18	19.31					
	AR voice-command	34	37.50	19.59					
Frustration	Traditional	34	37.21	25.35					
	AR gesture-command	34	69.12	19.44	2	66	31.64	< .001	0.49
	AR voice-command	34	31.91	20.67					
	Traditional	34	46.27	13.29					
NASA-TLX	AR gesture-command	34	63.63	12.73	2	66	41.36	< .001	0.56
	AR voice-command	34	42.94	10.08					

B.2 SART-10D scores and one-way repeated measures ANOVA results of each item and subdimension

Table B-1. Means and standard deviations of SART-10D item scores and one-way repeated measures ANOVA results

Dimension	Interactive modes	N	M	SD	One-way repeated measures ANOVA				
					df1	df2	F	p	η^2
Demand	Traditional	34	6.50	3.84					
	AR gesture-command	34	13.06	4.43	2	66	30.67	< .001	0.48
	AR voice-command	34	9.29	3.30					
Q1. Instability of situation	Traditional	34	2.03	1.57					
	AR gesture-command	34	4.24	1.81	2	66	17.18	< .001	0.34
	AR voice-command	34	3.32	1.36					
Q2. Complexity of the situation	Traditional	34	2.24	1.54					
	AR gesture-command	34	4.59	1.73	2	66	28.74	< .001	0.47
	AR voice-command	34	2.65	1.37					
Q3. Variability of situation	Traditional	34	2.24	1.48					
	AR gesture-command	34	4.24	1.56	2	66	17.07	< .001	0.34
	AR voice-command	34	3.32	1.49					
Supply	Traditional	34	16.65	4.01					
	AR gesture-command	34	16.50	4.58	2	66	2.71	.074	0.08
	AR voice-command	34	18.56	3.79					
Q4. Arousal	Traditional	34	3.50	1.62	2	66	7.64	.001	0.19

	AR gesture-command	34	4.47	1.94					
	AR voice-command	34	4.91	1.26					
Q5. Concentration of attention	Traditional	34	4.44	1.58					
	AR gesture-command	34	5.12	1.61	2	66	2.28	.111	0.07
	AR voice-command	34	4.47	1.42					
Q6. Division of attention	Traditional	34	4.00	1.39					
	AR gesture-command	34	3.53	1.78	2	66	3.17	.048	0.09
	AR voice-command	34	4.56	1.48					
Q7. Spare mental capacity	Traditional	34	4.71	1.53					
	AR gesture-command	34	3.38	1.79	2	66	7.77	< .001	0.19
	AR voice-command	34	4.62	1.23					
Understanding	Traditional	34	13.65	3.85					
	AR gesture-command	34	12.56	3.57	2	66	2.39	.099	0.07
	AR voice-command	34	14.12	3.31					
Q8. Information quantity	Traditional	34	4.41	1.69					
	AR gesture-command	34	4.91	1.40	2	66	2.38	.100	0.07
	AR voice-command	34	5.03	1.24					
Q9. Information quality	Traditional	34	4.71	1.45					
	AR gesture-command	34	4.74	1.60	2	66	2.21	.117	0.06
	AR voice-command	34	5.32	1.27					
Q10. Familiarity with situation	Traditional	34	4.53	1.99					
	AR gesture-command	34	2.91	1.87	2	66	11.35	< .001	0.26

SART-10D	AR voice-command	34	3.76	1.99					
	Traditional	34	23.79	6.83					
	AR gesture-command	34	16.00	7.25	2	66	14.89	< .001	0.31
	AR voice-command	34	23.38	6.64					

Appendix C T-test and Pearson Correlation Analysis results of System Usability Scale and Questionnaire for User Interface Satisfaction scores

C.1 System usability scale scores and t-test results of each item and subdimension

Table C-1. Means and standard deviations of SUS item scores and t-test results

SUS items	Interaction mode	M	N	SD	T-test			
					t	df	p	Cohen's d
Q1. I think that I would like to use this system frequently	Gesture-command	2.25	40	1.13	-5.39	39	<.001	-0.85
	Voice-command	3.85	40	1.19				
Q2. I found the system unnecessarily complex	Gesture-command	3.50	40	1.09	6.32	39	<.001	1.00
	Voice-command	2.15	40	0.95				
Q3. I thought the system was easy to use	Gesture-command	2.38	40	0.95	-6.55	39	<.001	-1.04
	Voice-command	4.03	40	0.97				
Q4. I think that I would need the support of a technical person to be able to use this system	Gesture-command	3.45	40	1.28	3.33	39	.002	0.53
	Voice-command	2.73	40	1.36				
Q5. I found the various functions in this system were well integrated	Gesture-command	3.15	40	1.03	-3.86	39	<.001	-0.61
	Voice-command	3.93	40	0.76				
Q6. I thought there was too much inconsistency in this system	Gesture-command	2.95	40	1.32	3.24	39	.002	0.51
	Voice-command	2.10	40	0.93				
	Gesture-command	2.93	40	1.21	-5.03	39	<.001	-0.80

Q7. I would imagine that most people would learn to use this system very quickly	Voice-command	4.23	40	0.97				
Q8. I found the system very cumbersome to use	Gesture-command	3.63	40	1.17	4.35	39	<.001	0.69
	Voice-command	2.45	40	1.22				
Q9. I felt very confident using the system	Gesture-command	2.40	40	0.98	-5.30	39	<.001	-0.84
	Voice-command	3.75	40	1.08				
Q10. I needed to learn a lot of things before I could get going with this system	Gesture-command	2.95	40	1.24	1.73	39	.091	0.27
	Voice-command	2.63	40	1.10				
Usability	Gesture-command	40.70	40	20.13	6.08	39.00	<.001	0.96
	Voice-command	72.11	40	18.02				
Learnability	Gesture-command	45.00	40	27.42	3.01	39.00	.005	0.48
	Voice-command	58.13	40	26.79				
SUS score	Gesture-command	41.56	40	18.85	5.72	39.00	<.001	0.90
	Voice-command	69.31	40	17.78				

C.2 Questionnaire for user interface satisfaction scores and t-test results of each item and subdimension

Table C-2. Means and standard deviations of QUIS item scores and t-test results

QUIS item	Interaction mode	T-test						
		M	N	SD	t	df	p	Cohen's d
Q1. Overall reactions to the system	Gesture-command	4.07	40	1.68	8.11	39	<.001	1.28
	Voice-command	6.90	40	1.42				
Screen visibility	Gesture-command	6.92	40	1.34	3.63	39	.001	0.57
	Voice-command	7.61	40	1.07				
Q2. Characters on the projected screen	Gesture-command	6.58	40	2.35	3.08	39	.004	0.49
	Voice-command	7.60	40	1.52				
Q3. Highlighting on the screen simplifies task	Gesture-command	6.73	40	1.57	3.38	39	.002	0.53
	Voice-command	7.45	40	1.30				
Q4. Arrangement of information on screen	Gesture-command	7.45	40	1.34	1.67	39	.102	0.27
	Voice-command	7.78	40	1.07				
System information	Gesture-command	6.91	40	1.26	3.82	39	<.001	0.60
	Voice-command	7.57	40	0.96				
Q5. Use of terms throughout system	Gesture-command	7.48	40	1.75	1.86	39	.071	-0.29
	Voice-command	7.95	40	1.04				
Q6. Work related terminology	Gesture-command	7.60	40	1.48	1.87	39	.069	0.30

	Voice-command	8.00	40	0.99				
Q7. Position of messages on screen	Gesture-command	6.40	40	2.35	2.01	39	.051	0.32
	Voice-command	6.98	40	1.66				
Q8. The system keeps you informed about what it is doing	Gesture-command	7.28	40	1.66	1.94	39	.060	0.31
	Voice-command	7.73	40	1.26				
Q9. Animated cursors keep you informed	Gesture-command	6.83	40	1.93	1.87	39	.069	0.30
	Voice-command	7.23	40	1.80				
Q10. Performing and operation lead to a predictable result	Gesture-command	5.88	40	2.53	3.89	39	<.001	0.62
	Voice-command	7.53	40	1.36				
Learning	Gesture-command	6.09	40	1.55	4.50	39	<.001	0.71
	Voice-command	7.45	40	0.89				
Q11. Getting started to use the system	Gesture-command	5.25	40	2.53	6.23	39	<.001	0.99
	Voice-command	7.45	40	1.32				
Q12. Time to learn to use the system	Gesture-command	5.33	40	2.68	5.99	39	<.001	0.95
	Voice-command	7.50	40	1.24				
Q13. Tasks can be performed in a straight-forward manner	Gesture-command	5.75	40	2.20	3.65	39	<.001	0.58
	Voice-command	7.15	40	1.56				
Q14. Steps to complete a task follow a logical sequence	Gesture-command	7.33	40	1.35	2.30	39	.027	0.36
	Voice-command	7.78	40	0.86				
Q15. Feedback on the completion of sequence of steps	Gesture-command	6.80	40	2.08	1.94	39	.060	0.31
	Voice-command	7.38	40	1.39				

System capabilities	Gesture-command	4.87	40	1.90	5.22	39	<.001	0.82
	Voice-command	6.33	40	1.81				
Q16. System speed	Gesture-command	5.28	40	2.32	3.98	39	<.001	0.63
	Voice-command	6.63	40	2.05				
Q17. Response time for most operations	Gesture-command	4.85	40	2.47	4.32	39	<.001	0.68
	Voice-command	6.45	40	2.16				
Q18. Correcting mistakes	Gesture-command	4.48	40	2.26	4.99	39	<.001	0.79
	Voice-command	5.93	40	2.15				
Usability and User Interface	Gesture-command	6.49	40	1.83	4.16	39	<.001	0.66
	Voice-command	7.35	40	1.62				
Q19. Use of colours and sounds	Gesture-command	6.95	40	1.88	2.83	39	.007	0.45
	Voice-command	7.43	40	1.75				
Q20. System feedback	Gesture-command	6.03	40	2.18	4.18	39	<.001	0.66
	Voice-command	7.28	40	1.71				
QUIS score	Gesture-command	5.89	40	1.03	4.16	39	<.001	0.66
	Voice-command	7.20	40	0.84				