

Original Article

Psychophysiological coherence training to moderate air traffic controllers' fatigue on rotating roster

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Email: wenchin.li@cranfield.ac.uk**Abstract**

The nature of the current rotating roster, providing 24-h air traffic services over five irregular shifts, leads to accumulated fatigue which impairs air traffic controllers' cognitive function and task performance. It is imperative to develop an effective fatigue risk management system to improve aviation safety based upon scientific approaches. Two empirical studies were conducted to address this issue. Study 1 investigated the mixed effect of circadian rhythm disorders and resource depletion on controllers' accumulated fatigue. Then, study 2 proposed a potential biofeedback solution of quick coherence technique which can mitigate air traffic controllers' (ATCOs') fatigue while on controller working position and improve ATCOs' mental/physical health.

The current two-studies demonstrated a scientific approach to fatigue analysis and fatigue risk mitigation in the air traffic services domain. This research offers insights into the fluctuation of ATCO fatigue levels and the influence of a numbers of factors related to circadian rhythm and resource depletion impact on fatigue levels on study 1; and provides psychophysiological coherence training to increase ATCOs' fatigue resilience to mitigate negative impacts of fatigue on study 2.

Based on these two studies, the authors recommended that an extra short break for air traffic controllers to permit practicing the quick coherence breathing technique for 5 min at the sixth working hour could substantially recharge cognitive resources and increase fatigue resilience. Application: Present studies highlight an effective fatigue intervention based on objective biofeedback to moderate controllers' accumulated fatigue as a result of rotating shift work. Accordingly, air navigation services providers and regulators can develop fatigue risk management systems based on scientific approaches to improve aviation safety and air traffic controller's wellbeing.

KEYWORDS

air traffic services, fatigue risk management, heart rate variability, psychophysiological coherence, rotating shifts

1 | INTRODUCTION

The definition of fatigue in aviation as per the International Civil Aviation Organization (ICAO) is “a physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair an operator's alertness and ability to perform safety-related duties” (ICAO, 2016, p. 2-1). Fatigue is seen as an alarm indicator warning that a recovery rest should be taken, which

is caused by the change in sleep-wake schedule as well as lack of sleep and prolonged wakefulness (EUROCONTROL, 2018). Shift work is highly prevalent in the aviation industry and has negative effects on individual sleep loss, which may induce mental/physical fatigue and physiological sleepiness, impaired performance, increased accident risk, and health issues such as cardiovascular disease and certain forms of cancer (Akerstedt & Wright, 2009). The Fatigue Safety Action Group (FSAG) of the International Air Transport Association (IATA) has reviewed and identified fatigue

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hazards in aviation including subjective sleepiness assessment and fatigue reporting metrics (IATA, 2014). Fatigue is a safety risk which can reduce an air traffic controller's monitoring performance. The effect of fatigue has been proven as a hazard associated with aviation accidents/incidents, while a fatigued air traffic controller (ATCO) could make inappropriate decisions which may place pilots and passengers at increased risk (Li et al., 2021). Therefore, strategies to mitigate the effects of fatigue are primarily centered on regulatory and scientific approaches which limit working hours to prevent chronically sleepy individuals working in the fields of aviation, medical care, and manufacturing industries (Balkin et al., 2011). ICAO requires air navigation service providers (ANSPs) to implement fatigue risk management policies and strategies to mitigate ATCOs' fatigue caused by shift works (ICAO, 2018).

Fatigue is one of the critical factors resulting in increased risks and accidents in the transportation industry (Caldwell, 2005; Lauber & Kayten, 1988; Lyman & Orlady, 1981). The term fatigue is in widespread usage in the occupational medicine domain and can be contributed to many factors, therefore, it is challenging to find a comprehensive definition across different domains (Sadeghniaat-Haghighi & Yazdi, 2015). Fatigue-related fatal accidents are considered to lie around 30% in both road transportation and air traffic sectors (NTSB, 2016). The development of a proactive approach to dealing with fatigue can increase ATCOs' fatigue resilience, allowing regulators and operators to efficiently manage mental/physical fatigue. Resilience is the ability of individuals to resist or recover from negative experiences such as stress and fatigue. Fatigue resilience can be viewed as being on a continuum ranging from low on bounce-back ability to high capacity to recover, which reflects a person's ability to reach a superior level of function following an adverse or stressful event (Carver, 1998). Furthermore, it is medically recognized that individuals suffering from nightshift may require fatigue interventions (Czeisler et al., 2005). Intervention techniques based on cognitive behavioural therapy and mindfulness have been proven to increase psychophysiological coherence which enables people to generate positive emotions to boost their energy, and effectively retrain physiology to sustain longer periods of cognitive function (Joyce et al., 2018).

1.1 | Shift work disturbing circadian rhythm and inducing fatigue

Shift work can interfere with the circadian and homeostatic regulation of sleep which will in several ways create health problem with respect to sleep loss and fatigue at work (Knutsson, 2004). Previous research demonstrated that shift work can reduce the quality of workers' leisure time and sleep time (Ognianova et al., 1998; Wight et al., 2008), induce fatigue (Åkerstedt & Wright, 2009), and increase the risk of work injuries due to sleepiness (Riethmeister et al., 2018). Fatigue and sleepiness may cause mental and physical performance impairments increasing the possibility of

health and safety concerns. ATCO's fatigue is a serious issue affecting the safety of air transportation. The characteristics of shift work including shift length, total number of working hours, night shift, and break opportunities may impact on human operator's performance and well-being. Previous research demonstrated that rapid shift rotations are associated with reduced total sleep duration compared to slower rotation, and night shifts are related to greater loss of total sleep hours than day shifts (Park et al., 2000). Furthermore, the occurrence related to ATCO's fatigue may associate with multiple factors such as traffic volume, roster, quality of sleep, and circadian rhythms, as sleep loss on previous shift with high traffic volumes increase the risks of occurrences (Li et al., 2021). Accidents/incidents related to fatigue could be taken to investigate the parameters of airflow and specifications of manpower per shift to develop effective working schedule for fatigue risk management (Ernst et al., 2004).

The health of human operators may be at risk by rotating schedules due to the changes of working hours on an individual's circadian rhythms, which in turn can alter biological functions including heart-rate variability, body temperature, hormone levels, and quality of sleep (Presser, 2003). The quality of waking cognition and of sleep is determined to a large extent by circadian and sleep homeostatic brain processes. From a circadian perspective, cognition is optimal during the internal biological day and sleep is optimal during the internal biological night. Shift work disturbed circadian rhythm results in impaired cognition, increased sleepiness, and increased propensity for sleep (Åkerstedt & Wright, 2009). Working schedules and rest arrangements can be important to ATCOs fatigue recovery and stress management (EUROCONTROL, 2004). Sleep loss in shift work induced fatigue at work that can reduce a human operator's monitoring performance and diminish an operator's ability to stay alert (Kearney et al., 2019). Working after midnight would damage both physical and mental health and there could not be significant relief produced by a short rest (Sato et al., 2020). The nature of ATCOs' shift works providing 24-h of air traffic services would induce irregular circadian rhythm and poor sleep quality, which could increase cognitive workloads and thus have negative impacts on task performance (French et al., 2019; Knudsen et al., 2007).

1.2 | Prolonged task activities depleting mental and physical resources

The roster cycle seems to be the decisive factor with respect to individual's alertness levels during work hours. When wakefulness is extended, or if inadequate sleep is accumulated across successive days, the physiological drive for sleep builds (Dawson et al., 2011). It is a challenging task for an ATCO to maintain the same level of alertness while on position, and this fluctuation of monitoring performance over the course of the working hours is found as time on task effect (Arnau et al., 2017). Furthermore, prolonged task related

activities inevitably lead to physical and mental fatigue symptoms. There is a trend, the greater the fatigue after work, the less likely it is that recovery will be sufficient (Geurts & Sonnentag, 2006). The risk of chronic health issues arising in the future if the work-related fatigue is repeated increases. Therefore, fatigue may also be regarded as a precursor of severe potential mental and physical problems. Understanding the fluctuations in fatigue may offer opportunities to intervene before serious consequences have developed (Gross et al., 2011).

The cognitive depletion theory proposed that human beings have a limited store of mental and physical resources to devote to decision making and self-control activities. Monitoring performance deficits may occur because of vigilance decrement over time. However, the specific factors that influence sustained performance with complex displays have not been identified precisely (Parasuraman, 1987). In high demanding tasks involving dynamic decisions, ATCOs experienced decreasing alertness due to high mental work requiring many cognitive resources (Smit et al., 2004). The drive for sleep also varies on a 24-h cycle under the influence of the circadian biological clock, which also dictates the preference for sleep at night (Signal et al., 2003). ATCOs' shift work patterns induced sleep deprivation which are related to performance deteriorations, as the link between sleep restriction and insomnia are associated with poor cognitive performance. Therefore, it is important to consider research on both scheduling shift-work matrices and providing effective interventions to increase ATCOs' psychophysiological resilience to fatigue.

1.3 | Motivations

The consequences of shift work are associated with negative health and safety issues which include chronic disease, increased accidents on the duty, reduced quality of sleep, fatigue, and being less alert when performing tasks (Scott et al., 2006; Van der Hulst, 2003). Fatigue at work has been identified as a contributory factor to some of the most significant disasters such as the 2004 Los Angeles runway collision accident in which the ATCO suffered from prolonged shift work and inadequate sleep; and the 2006 Kentucky air crash accident in which the ATCO experienced insufficient sleep between two shifts (Monk, 2007). The use of shift work in air traffic services may cause sleep deprivation which in turn may induce ATCOs fatigue. The negative effects to operator's physiological and psychological capabilities have been observed in conjunction with fatigue due to sleep deprivation and resources depletion (Hartzler, 2014; Smit et al., 2004). To achieve the requirements of fatigue risk management placed required by ICAO (2018), there are two research objectives to this research. The first objective is to investigate ATCO's fatigue levels during rotating shifts and duration time on work (study 1); the second objective is to evaluate the effectiveness of fatigue intervention on psychophysiological coherence training (study 2).

2 | STUDY 1: INVESTIGATING ATCOs' FATIGUE LEVELS ON ROTATING SHIFTS AND DURATION ON WORK

2.1 | Method

2.1.1 | Participants

Fifty-seven volunteers from a total of 121 qualified ATCOs from a European Air Navigation Services provider participated in this research. The participants ages ranged from 23 to 58 years ($M = 41.18$, $SD = 6.52$). The approval of the Research Ethic Committee was granted in advance of the research taking place. All participants were informed that this research was related to ATCO's shift work and sleeping hours before each shift to develop an effective intervention for fatigue risk management. Participants were assured of their right to withdraw from this research at any stage and provided their signed consent form. All collected data are only available to the research team and are managed in accordance with the United Kingdom Ethical Code and the General Data Protection Regulation (GDPR).

2.1.2 | Material

The material used in this study adapts the framework of the Stanford Sleepiness Scale (SSS) which is a one-item self-report form to track fatigue at each working hour. Participants marked their fatigue level each hour preshift, on-shift, and postshift by scoring ranges from 1 to the highest fatigue level of 7, except the hours of sleep. It is a subjective measurement which ATCOs graded their own fatigue levels hourly without interference from the experimenters while on duty. The strength of this self-report diary enables participants to express their feelings and thoughts, but the weakness is that the gathered information is only useful if participants are willing to disclose their thoughts. SSS can collect ATCOs' fatigue levels which are associated with the effects of sleeping hours before duty and accumulated time-on-duty on each shift.

2.1.3 | Research design

The current ATC shift cycle requires air traffic controllers to work a designated roster on five rotating days (Figure 1). There are a minimum of 13.5 h available time to recover from fatigue before the first shift, 17 h of interval to recover from fatigue before the second shift, 9.25 h to recover from fatigue before the third shift, 14.5 h to recover from fatigue before the fourth shift, and 9 h to recover from fatigue before the fifth shift. The core night duty period should be regarded as 00:15 to 06:00 based on the ANSP's regulations. The roster does not start or finish in this period due to safety concerns. Duty starts

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00						
	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00						
Workday 1	At least 13.5 hours to 1 st shift													Working hours																
Workday 2	17 hours between 1 st and 2 nd shift													Working hours																
Workday 3	9.25 hours between 2 nd and 3 rd shift						07:45						Working hours						16:00						14.5 hours between 3 rd and 4 th shift					
Workday 4	06:30						Working hours						13:30						9 hours between 4 th and 5 th shift						22:30					
Workday 5	Working hours						06:30																							

Fig 1 Current roster of ATCO's shift works consisted by five consecutive days rotating around different time of work; the maximum fatigue recover time between the first shift and the second shift (17 h), the minimum fatigue recover time between the fourth shift and the fifth shift (9 h)

Table 1 Means and standard deviations of fatigue levels over eight working hours on five consecutive shifts based on ATCOs' subjective rating

Fatigue level	N	Shift 1		Shift 2		Shift 3		Shift 4		Shift 5		Average	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
1st hour	57	1.55	0.70	1.42	0.64	1.69	0.80	1.86	1.06	1.77	0.79	1.66	0.07
2nd hour	57	1.55	0.70	1.37	0.53	1.67	0.89	1.69	0.98	1.92	1.02	1.64	0.07
3rd hour	57	1.36	0.56	1.53	0.66	1.70	0.82	1.78	0.92	2.33	1.24	1.74	0.08
4th hour	57	1.41	0.58	1.48	0.68	1.44	0.70	1.76	0.91	2.41	1.22	1.70	0.08
5th hour	57	1.45	0.62	1.52	0.75	1.48	0.73	1.66	0.83	2.33	1.48	1.69	0.09
6th hour	57	1.73	0.68	1.65	0.85	1.65	0.89	1.67	0.87	2.48	1.42	1.84	0.10
7th hour	57	2.31	1.04	1.78	0.86	1.70	0.92	2.00	0.95	2.62	1.34	2.08	0.10
8th hour	57	2.00	0.91	1.94	0.91	1.69	0.80	2.43	0.94	3.16	1.31	2.29	0.10
Daily average	57	1.67	0.53	1.59	0.56	1.65	0.67	1.86	0.75	2.38	1.03	1.83	0.99
Preceding Sleep hours	57	7.21	1.21	7.53	0.83	5.07	0.96	7.74	0.79	4.88	0.78	6.48	1.55

of 06:00 are distributed equitably as far as possible. ATCOs are conditioned to a working week of 41 h gross, or 34.75 h net. The policy of Fatigue Reliefs will accrue at the rate of 10 min per continuous hour of duty in a relief attracting position. The aim is to provide a relief after not more than 2 h in designated positions. Shift work will on average reflect the conditioned hours of loading. ATCO's breaks were arranged in compliance with the provisions of the National Legislation and other relevant legislations. Each participant was invited individually to a briefing on how to apply the fatigue rating scale over the course of his/her shift pattern for 2 weeks. Participants rated his/her fatigue levels on each hour both working (W) and resting (R) using a 7-point likert scale of SSS and simply recorded sleep hours using (S). Furthermore, participants were encouraged to add their comments or ideas to the shifts and ideal fatigue risk interventions at the end of the evaluation form.

2.2 | Results

2.2.1 | Sample characteristics

The descriptive statistical data of ATCOs' fatigue levels over eight working hours per day on the five shifts are shown

in Table 1. Furthermore, the average fatigue levels in 24 h during the whole shift are shown in Figure 2. Two-way repeated measure ANOVA is applied to investigate the differences of ATCOs' fatigue levels among five shifts and eight working hours, and Pearson correlation is applied to examine the correlation between preceding sleep hours and fatigue levels. There is no outlier observed by boxplots, and the assumption of normality is verified by Q-Q plots. According to the Mauchly's test, the homogeneity of covariance assumption was violated ($\chi^2 = 189.00$, $p < 0.001$, $\epsilon = 0.51$). Therefore, the results of multivariate test were adopted. There is a considerable deviation from sphericity ($\epsilon < 0.75$), the Greenhouse–Geisser correction was applied. The post hoc pairwise comparisons were performed by Bonferroni, and effect sizes of samples were quantified by partial eta square (η_p^2). The descriptive statistics are shown as Table 1.

2.2.2 | Shift works and accumulated working hours amplified ATCOs' fatigue levels

The two-way repeated measures ANOVA revealed a significant interaction for "roster \times working hours", $F(11.66, 652.96) = 6.31$, $p < 0.001$, $\eta_p^2 = 0.10$ (Figure 3). Simple

Fig 2 The fluctuation of ATCO's average fatigue levels in 24 h based on five shifts circle, the average fatigue level of 2.45 is shown as dotted line

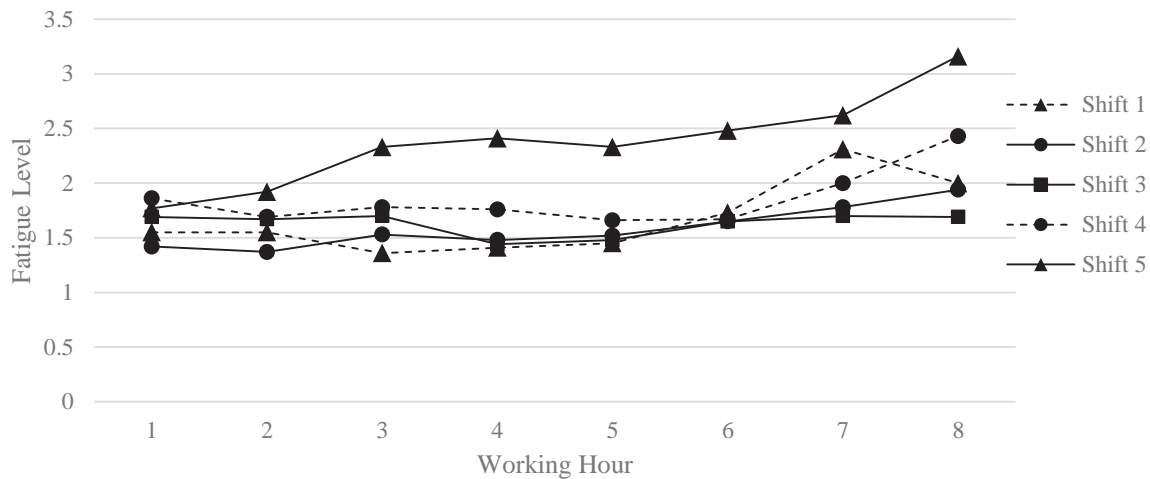
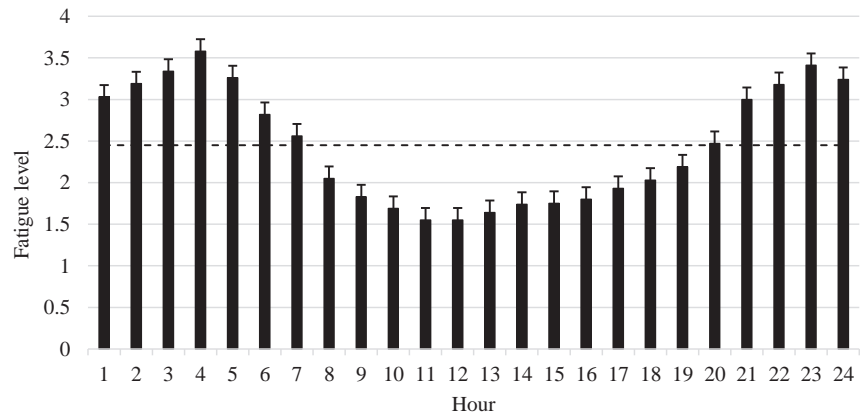


Fig 3 The interaction effect of five-level roster and eight-level working hours

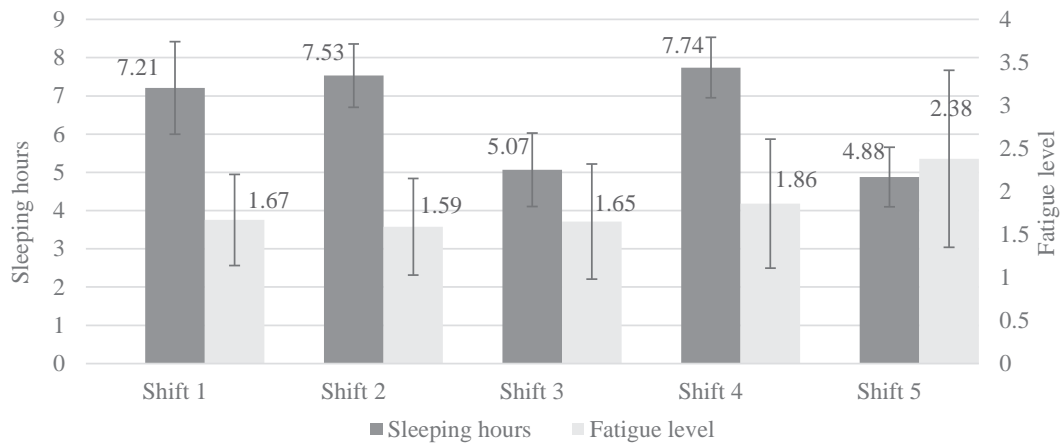
main effect analysis of eight “working hours” within each “shift” showed that the fatigue levels of the last two working hours are significantly higher than other 6 h on each shift, $p < 0.001$. Another simple effect analysis of the significant interaction effect revealed that the last shift rated the highest fatigue level within each working hour, $p < 0.5$. Furthermore, a significant main effect was found for the factor “shift,” $F(2.30, 129.01) = 26.30, p < 0.001, \eta_p^2 = 0.32$. Post hoc comparisons by Bonferroni showed that the fatigue level of the last shift is significantly higher than the other four shifts, $p < 0.001$. The fourth shift was rated higher than the first, second, and third shift, $p < 0.01$. The analysis also showed a significant main effect of eight-level “working hour” factor, $F(2.86, 159.87) = 29.63, p < 0.001, \eta_p^2 = 0.35$. Post hoc comparisons by Bonferroni showed that the fatigue level in the last two working hours is significantly higher than other six hours, $p < 0.01$. The fatigue level of the sixth hour is higher than the fifth one, $p < 0.05$. There is no significant difference among the first five working hours by Bonferroni post hoc comparisons, $p > 0.05$. The details of two-way repeated measures ANOVA are shown in Table 2.

2.2.3 | Correlation between fatigue levels and preceding sleeping hours

The means and standard deviations of fatigue levels on roster and preceding sleeping hours are shown in Figure 4. The Pearson correlation analysis suggested that there are significant correlations between fatigue levels and preceding sleeping hours on five shifts, $p < 0.05$ (Table 3). There is a significant negative correlation between the preceding sleeping hour and fatigue level on the second shift, $r = -0.31, p < .05$. Negative correlations between preceding sleep hours and fatigue levels are also found on the third shift ($r = -0.58, p < 0.001$), the fourth shift ($r = -0.31, p < 0.05$), and the fifth shift ($r = -0.43, p < 0.01$). Furthermore, the accumulated fatigue levels on the last two shift days have significant correlations with the preceding sleeping hours on previous shifts ($p < 0.05$), which indicates that the insufficient sleep at night could influence not only the fatigue level of the following working day, the accumulated sleep deprivation and fatigue also has profound influences on the end of the day. There is a significant correlation between the accumulated fatigue level on shift four and preceding sleeping hours on

Table 2 Two-way repeated measure ANOVA results with Greenhouse–Geisser correction

5×8 two-way ANOVA for fatigue level	<i>df</i> Effect	<i>df</i> Error	<i>F</i>	<i>p</i>	η_p^2
Interaction effect “roster × working hours”	11.66	652.96	6.31	0.000	0.10
Simple main effects “working hours” within					
Shift 1	3.57	200.04	20.70	0.000	0.27
Shift 2	3.09	172.83	7.60	0.000	0.12
Shift 3	4.10	229.75	3.98	0.004	0.07
Shift 4	4.50	251.90	11.08	0.000	0.17
Shift 5	3.60	201.40	18.23	0.000	0.25
Simple main effects “roster” within					
Working hour 1	2.71	151.58	3.80	0.014	0.06
Working hour 2	3.10	173.76	4.67	0.003	0.08
Working hour 3	2.54	142.03	15.27	0.000	0.21
Working hour 4	2.90	162.65	23.63	0.000	0.30
Working hour 5	2.18	122.27	16.53	0.000	0.23
Working hour 6	2.44	136.61	16.54	0.000	0.23
Working hour 7	2.85	159.46	12.12	0.000	0.18
Working hour 8	3.09	173.02	30.11	0.000	0.35
Main effect “roster”	2.30	129.01	26.30	0.000	0.32
Main effect “working hours”	2.86	159.87	29.63	0.000	0.35

**Fig 4** The fatigue levels and preceding sleeping hours of each shift on five consecutive shifts

shift three, $r = -0.34$, $p < 0.01$. The accumulated fatigue level on the last shift is also correlated to ATCO's preceding sleeping hours on shift three ($r = -0.35$, $p < 0.01$) and shift four ($r = -0.29$, $p < 0.05$). The details of Pearson analysis are shown in Table 3.

2.3 | Discussion

Based on Table 1, ATCOs' fatigue levels during the last three working hours (sixth, seventh, and eighth) are significantly higher. The significantly increased fatigue lev-

els from shift four ($M = 1.86$, $SD = 0.75$) to shift five ($M = 2.38$, $SD = 1.03$) also demonstrated the accumulated effects of fatigue. A possible explanation for this incremental in ATCO's fatigue at the end of the working day is resource depletion. Air traffic control is an intensive working environment with high task demands which can deplete ATCO's vitality in the long run. ATCOs must perform monotonous work monitoring radar screens for hours, which could be more likely to increase sleepiness and may act as a multiplier of fatigue. Furthermore, ATCOs must provide air traffic services over a 24-h basis over five irregular rotating shifts, which can induce circadian rhythm disorders. It can

Table 3 Pearson correlation between fatigue level and preceding sleeping hours on five shifts

	1	2	3	4	5	6	7	8	9
Fatigue level on shifts									
1. Fatigue level on shift 1	–								
2. Fatigue level on shift 2	0.53**	–							
3. Fatigue level on shift 3	0.55**	0.70**	–						
4. Fatigue level on shift 4	0.55**	0.73**	0.82**	–					
5. Fatigue level on shift 5	0.27*	0.72**	0.60**	0.72**	–				
Preceding sleeping hours on shifts									
6. Preceding sleep hours on shift 1	–0.18	–0.12	–0.07	–0.08	–0.09	–			
7. Preceding sleep hours on shift 2	–0.13	–0.31*	–0.12	–0.03	–0.07	0.35**	–		
8. Preceding sleep hours on shift 3	–0.43**	–0.51**	–0.58**	–0.34**	–0.29*	–0.02	0.31*	–	
9. Preceding sleep hours on shift 4	–0.34*	–0.41**	–0.48**	–0.31*	–0.35**	0.22	0.10	0.28*	–
10. Preceding sleep hours on shift 5	–0.52**	–0.56**	–0.65**	–0.52**	–0.43**	0.09	0.30*	0.58**	0.30*

Note: ** $p < 0.01$, * $p < 0.05$.

be seen from Figure 2 that ATCOs generally have a higher fatigue level during the late night and early morning. Previous research indicated that subjective fatigue varied in parallel with the circadian biological clock and night shift workers often have lower alertness levels than daytime workers due to a lower body temperature and circadian rhythm; and disturbed circadian rhythms have a negative impact on sleep quality, which in turn would result in ATCOs' increased chronic fatigue (Mulhall et al., 2019). On the fifth shift, it is a core night duty with only nine hours preceding rest for fatigue recovery (Figure 1). This work shift with sleep rhythm reserved in the long term could result in circadian dysrhythmia, and thus ATCOs' bodies internal rhythms would be out of synchrony with the day–night cycle. Due to ATCOs' irregular shifts and starting hours, disturbed circadian rhythm could increase difficulty in obtaining recovery sleep during rest days. Therefore, the fatigue level is the highest at the last working hour on the fifth shift and it might be due to the combined interaction effects of disturbed circadian rhythm by “shift days” scheduled in different period and resources depletion by accumulated “working hours” (Figure 3 and Table 1).

The daily quantity of sleep required varies individually, but on average it is 8 h. According to ATCO's current roster, there are only 9 h available for ATCOs having a rest and recovery from workload and stress between shift-4 and shift-5 (Figure 1). However, the available sleeping hours in these 9 h interval between shift-4 and shift-5 must consider commuting time, showering, eating, and relaxing before getting sleep. Therefore, the average preceding sleep hours on the fifth shift is only 4.88 h (Table 1), which is much less than the generally required eight sleeping hours daily. Pearson correlation analysis revealed that the preceding sleeping hours are significantly correlated with the fatigue levels on the fifth shift, $r = 0.43$, $p < 0.01$ (Table 3 and Figure 4). ATCOs suffered from fatigue due to the highly mental and physically demanding nature of work while performing night shift on

the last workday with insufficient sleep. Moreover, the drive for sleep varies on a 24-h cycle under the influence of the circadian biological clock, which also dictates the preference for sleep at night (Signal et al., 2003). ATCOs may prefer longer time off between two shift cycles by squeezing a core night-shift (on the fifth shift) into the last workday, which disturbed their circadian rhythm. Thus, a normal break will not have the same recovery effect, as the time of the day for recharging is more important than the duration of the break itself (Cabon et al., 2012). The irrationality of the fifth shift causing sleep deprivation would result in increased chronic fatigue and negatively influence ATCOs' vigilance and task performance, and thus increase the risks of aviation accident. Therefore, the working hours of the fifth shift should be revised to allow sufficient time for ATCOs to recharge and recover from accumulated fatigue. Furthermore, fatigue risk management must ensure appropriate rest time to maintain a healthy balance between matching resources and demands at work (De Jonge et al., 2019). Both shifts of work and duration of work are critical determinants of operators' fatigue levels in the high consequent industries (Sallinen & Kecklund, 2010).

3 | STUDY 2: EVALUATING THE EFFECTIVENESS ON COHERENCE TRAINING FOR FATIGUE INTERVENTION

The purpose of study 2 was to elevate the effectiveness of psychophysiological coherence training to mitigate ATCOs' fatigue. It is well known that circadian rhythm disorders associated with shift workers often deteriorate performance (Sato et al., 2020). A fatigued operator will suffer from slower information processing and likely commit more errors, as fatigue can reduce ATCO's resilience due to depletion on cognitive resources (Frone & Tidwell, 2015). Scientific interest in psychophysiological coherence has expanded the field from investigating risks associated with fatigue to increasing

self-regulation by training. Providing biofeedback measurements would promote the intervention of psychophysiological resilience which is associated with improved physiological coherence, and psychological functioning. The state of coherence can be measured by heart-rate variability (HRV) analysis wherein a person's heart-rhythm pattern becomes more ordered and coherent state is correlated with a general sense of wellbeing and improvements in cognitive and physical performance (McCraty & Tomasino, 2006). Psychophysiological resilience can increase the ability of individuals to resist and recover from negative experiences such as stress and fatigue (Rutter, 2007). The HRV measurement reflects the physiological changes in the human body using a noninvasive measure method (Durantin et al., 2014).

The parameters of cardiac rhythm including basal characteristics, time domain, frequency domain, and nonlinearity are proved to be associated with fatigue and perceived workload (Segerstrom & Nes, 2007; Tarvainen et al., 2014). HRV is a commonly used for assessing the functioning of cardiac autonomic regulation which is related to cardiovascular research and mental states (Stein et al., 1994). Low HRV is associated with lower resilience (Geisler et al., 2013), lower mental, and social flexibility (Williams et al., 2015) and was found to be a marker for fatigue (Volker et al., 2016). Evidence suggests that when the heart transmits a coherent signal to the brain, the mental function and self-regulation abilities are facilitated to produce emotional stability and improved cognitive acuity and task performance. Psychophysiological coherence is associated with a well-established relationship between enhanced cognitive function and lessened stress as well as fatigue (Bradley et al., 2010). The development of fatigue resilience is considered as a dynamic process which could be learned at any period of life by training. Training on psychophysiological coherence refers to self-regulation techniques that can be applied to improve an operator's resilience, performance, health, and well-being. Furthermore, research has demonstrated that the Quick Coherence Technique (QCT) resulted in significant improvements in the ability to self-regulate along with a wide range of cognitive functions (Ginsberg et al., 2010). Skill acquisition is facilitated using heart rhythm biofeedback and breathing techniques, which may be able to develop an effective intervention for increasing attentional control and psychophysiological coherence (Kim et al., 2019). This research is to examine the efficacy of heart rate variability biofeedback for ATCOs and to provide scientific evidence in developing fatigue risk management for ANSPs.

3.1 | Method

3.1.1 | Participants

Thirty-four volunteers with ATCO's license from a European Air Navigation Services provider participated in this research. The ages of the participants ranged from 23 to 58

years of age ($M = 41.21$, $SD = 7.49$). The collected data were gathered from human subjects; therefore, the research proposal was submitted to the Research Ethics committee for ethical approval in advance of data collection. As stated in the consent form, participants have the right to terminate the experiment at any stage and to withdraw their provided data at any moment even after the data collection. Data files will be organized in folders named after the sample location with the file name structured by date and sample numbers. All collected data are only available to the research team and be managed in accordance with the United Kingdom Ethical Code and the General Data Protection Regulation (GDPR).

3.1.2 | Apparatus and technique

The research apparatus is an Inner Balance device equipped with an ear sensor which can gather the Inter Beat Interval (IBI) parameters. Using the Inner Balance device together with QCT can increase psychophysiological resilience in minutes with simple but powerful breathing techniques. There are two simple steps, free frame, and heart-focused breathing techniques on QCT, using Inner Balance biofeedback to achieve psychophysiological resilience. The ear sensor of Inner Balance (Figure 5A) can connect with Bluetooth and export HRV data to other mobile devices through apps and was paced at a rhythm of 6 breaths per minute (0.1 Hz) while breathing. The QCT involves the use of biofeedback to control and visualize HRV based on moment-to-moment change in heart rate. Cardiac coherence is the coupling and synchronization of the rhythm of breathing to the rhythm of the heart (Trousselard et al., 2015).

New technologies now allow HRV measurement and analysis in the operational and research settings in a convenient way. This research is applying Kubios software to analyze participants' HRV time-domain parameters including mean RR, SDNN, pNN₅₀, mean HR, min HR, max HR, and coherence by HRV analysis heart-rhythm pattern at a frequency of around 0.1 hertz. Mean RR is the average time of inter-beat intervals between all successive heartbeats; SDNN is the standard deviation of RR intervals; pNN₅₀ is the percentage of successive RR intervals that differ by more than 50 ms; mean HR is the average heart rate in beats per minute during the whole respiratory cycle; min HR and max HR are the lowest and highest heart rate during the whole respiratory cycle (Malik, 1996).

3.1.3 | Research design

Participant was briefed that the trials involved three stages on HRV data collections, pretraining, posttraining, and on working position. Each participant carried out the same procedures as follows: (1) briefing the psychophysiological coherence training using Inner Balance device and research aims (5 min); (2) providing signed consent form with demographic

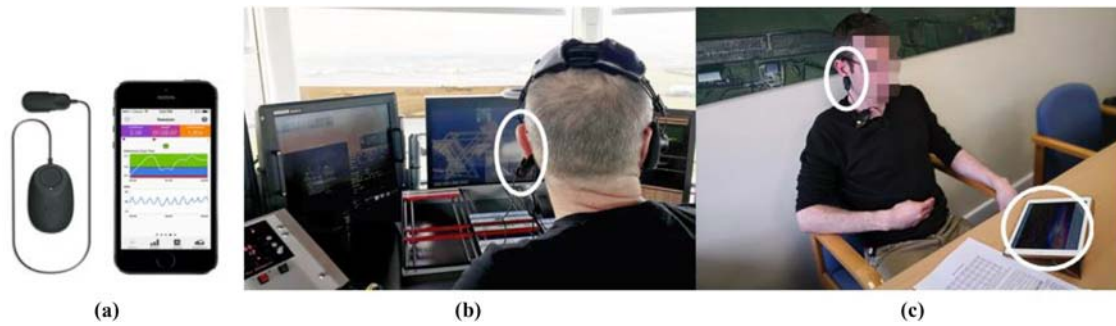


Fig 5 Inner Balance connected with a visual breath-pacer device for HRV data collection (A); ATCO on controller working position wearing ear sensor (shown as oval) connected with Inner Balance for HRV data collection in real time operations (B); ATCO practice Quick Coherence Technique based on biofeedback visual breath-pacer (iPad) connected with Inner Balance (C)

variables (5 min); (3) collect pretraining ATCO's HRV data by wearing Inner Balance on the controller working position while he/she was on duty (Figure 5B) (5 min); (4) collect ATCO's HRV data while he/she is relaxing in a quiet room as a baseline (5 min); (5) ATCO practice QCT based on biofeedback visual breath-pacer connected with Inner Balance device (Figure 5C) (30 min). Participants were instructed to activate a positive feeling by freeze-frame and practice 1-min with six-breath pattern of breathing technique. A visual breath-pacer is used to facilitate the consistency of the freeze-frame breathing on the device connected with Inner Balance. Participant's compliance with QCT was closely monitored by experimenter to ensure sufficient deep breathing and synchronization with the breath pacer in the training session; (6) collecting posttraining HRV data (5 min); (7) conduct debriefing and collect ATCO's feedbacks (5 min). The process of coherence training and data collection took approximately 60 min for each participant.

3.2 | Results

3.2.1 | Sample characteristics

One-way repeated measure ANOVA is applied to investigate the differences of six HRV parameters (mean RR, SDNN, pNN50, mean HR, min HR, and max HR) as well as ATCOs' coherence among three sections (1: on working position, 2: baseline on rest, and 3: after QCT). There is no outlier observed by boxplots, and the assumption of normality is verified by Q-Q plots. According to the Mauchly's test, the homogeneity of covariance assumption was violated in variables of mean RR ($\chi^2 = 40.05, p < 0.001, \epsilon = 0.58$), mean HR ($\chi^2 = 32.20, p < 0.001, \epsilon = 0.61$), and coherence ($\chi^2 = 10.70, p < 0.01, \epsilon = 0.81$). Therefore, the results of multivariate test were adopted to those variables. Both mean RR and mean HR variables the estimated epsilon (ϵ) by Mauchly's test are less than 0.75, the Greenhouse-Geisser correction was applied to modify the degrees of freedom. The Huynh-Feldt correction is used for coherence variable as its estimated ϵ is greater than 0.75. The post hoc pairwise comparisons were performed by Bonferroni, and effect sizes of samples were quantified by

Table 4 Means and standard deviations of ATCO's HRV parameters and coherence among three sections

Variables (unit)	Section	N	M	SD
Mean RR (ms)	Work position	34	796.20	99.70
	Baseline		814.53	105.54
	QCT		922.65	105.10
SDNN (ms)	Work position	34	85.10	56.19
	Baseline		71.15	39.829
	QCT		101.43	46.449
pNN ₅₀ (%)	Work position	34	35.93	25.89
	Baseline		34.30	21.26
	QCT		48.46	16.60
Mean HR (bpm)	Work position	34	76.48	9.31
	Baseline		74.91	9.98
	QCT		65.85	7.45
Min HR (bpm)	Work position	34	59.58	10.09
	Baseline		60.43	8.50
	QCT		52.75	6.40
Max HR (bpm)	Work position	34	99.03	18.54
	Baseline		95.92	17.18
	QCT		93.57	14.77
Coherence	Work position	34	27.01	6.51
	Baseline		25.74	5.22
	QCT		70.56	9.19

partial eta square (η_p^2). The descriptive statistics are shown as Table 4.

3.2.2 | QCT intervention moderating ATCOs' HRV parameters and coherence

The results of one-way repeated measures ANOVA indicated that there is a significant difference on ATCOs' mean RR parameter among three sections, $F(1.17, 38.51) = 19.94, p < 0.001, \eta_p^2 = 0.38$ (Figure 6A). Furthermore, post hoc pairwise Bonferroni comparison revealed that the mean RR

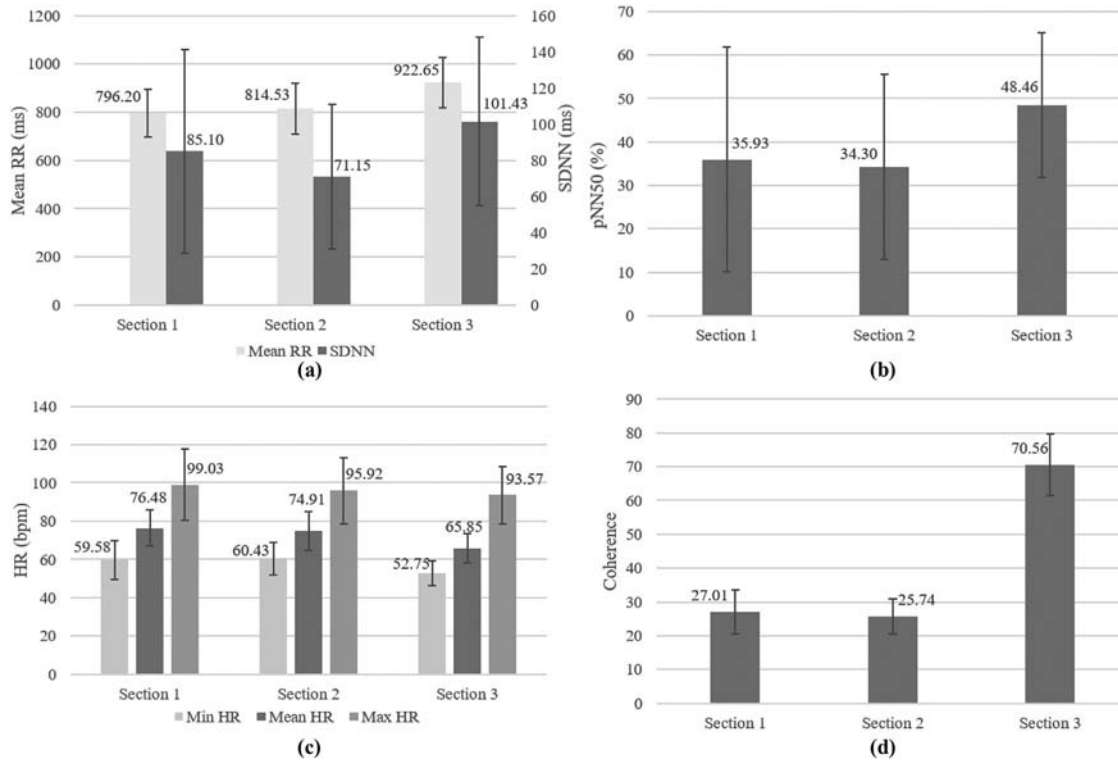


Fig 6 The differences of mean RR (A), pNN₅₀ (B), min and max HR, and mean HR (C), as well as coherence (D) among three sections

after QCT ($M = 922.65$, $SD = 105.10$) is significantly higher ($p < 0.01$) than on working position ($M = 796.20$, $SD = 99.70$) and baseline ($M = 814.53$, $SD = 105.54$). There is no significant difference of SDNN among three sections, $p = 0.072$. There is a significant difference on pNN₅₀ among three sections, $F(2, 66) = 3.42$, $p < 0.05$, $\eta_p^2 = 0.09$ (Figure 6B). Furthermore, post hoc pairwise Bonferroni comparison revealed that the pNN₅₀ after QCT ($M = 48.46$, $SD = 16.60$) is significantly higher ($p < 0.05$) than baseline ($M = 34.30$, $SD = 21.26$). ATCOs' mean HR among three sections is significantly different, $F(1.22, 40.38) = 21.55$, $p < 0.001$, $\eta_p^2 = 0.40$ (Figure 6C). Furthermore, post hoc pairwise Bonferroni comparison revealed that the mean HR after QCT ($M = 65.85$, $SD = 7.45$) is significantly lower ($p < 0.01$) than on working position ($M = 76.48$, $SD = 9.31$) and baseline ($M = 74.91$, $SD = 9.98$). There is a significant difference on min HR among three sections, $F(2, 66) = 7.70$, $p < 0.01$, $\eta_p^2 = 0.19$ (Figure 6C). Furthermore, post hoc pairwise Bonferroni comparison revealed that the min HR after QCT ($M = 52.75$, $SD = 6.40$) is significantly lower ($p < 0.01$) than on working position ($M = 59.58$, $SD = 10.09$) and baseline ($M = 60.43$, $SD = 8.50$). There is no significant difference of max HR parameter among three sections, $p = 0.381$. ATCOs' coherence among three sections is significantly different, $F(1.62, 53.47) = 808.51$, $p < 0.001$, $\eta_p^2 = 0.96$ (Figure 6D). Furthermore, post hoc pairwise Bonferroni comparison revealed that the ATCOs' coherence after QCT ($M = 70.56$, $SD = 9.19$) is significantly higher ($p < 0.01$) than coherence on working position ($M = 27.01$, $SD = 6.51$) and baseline ($M = 25.74$, $SD = 5.22$).

3.3 | Discussion

The results of one-way repeated measures ANOVA showed that the QCT training could significantly increase ATCOs' Mean RR and pNN₅₀ (Figure 6A,B). Mean RR interval is the average of inter-beat interval between all successive heartbeats, which has been proved to be lower under high stress and mental workload (Castaldo et al., 2015). The significant decreases of pNN₅₀ could reveal the accumulated mental and physical workload due to the cardiovascular regulation effects (Taelman et al., 2011). The pNN₅₀ is closely correlated with parasympathetic nervous system activity which facilitates ATCOs' relaxation and boosts coherence. Furthermore, both min HR and mean HR after QCT training are significantly lower than pretraining session (Figure 6C). Previous research suggested that an increase in workload would result in an increase of HR, whereas HRV decreased (Lei & Roetting, 2011); and HR is able to reflect the stepwise pattern of increase in cognitive loads and was sensitive to change in perceived workload (Mehler et al., 2012). The min HR after QCT training is significantly lower than on pretraining and even at rest time (Figure 6C). This finding indicates that the coherence training can provide ATCOs a more relaxing and flexible state both mentally and physically, and thus improve their resilience for further complicated tasks and mental challenges. Therefore, the increased coherence (Figure 6D), mean RR and pNN₅₀, as well as the decreased min HR and mean HR after QCT training indicated ATCOs' better resilience and effective recovery from accumulated fatigue and

workloads as a result of rotating shifts and accrued working hours. Practicing QCT resulted in significant improvements in self-regulation along with a wide range of cognitive functions (McCraty & Zayas, 2014).

Coherence is the state when the heart, mind, and emotions are in energetic alignment and synchronization. Gaining coherence is a strategy to build individual resilience, and recovering and accumulating more energy for positive outcomes. The QCT training program can increase the sense of coherence contributing to decreased work stress and fatigue, as well as improved resilience (Foureur et al., 2013). Coherence is the hallmark of applying biofeedback on QCT training program, which serves as a concise but global indicator of fatigue resilience level, as well as reflecting cognitive function. In the current study, when QCT improved ATCO's HRV status (mean RR and pNN₅₀ increased, min HR and mean HR decreased), the coherence level showed a significant increase from 27.01 to 70.56 (Figure 6D). Furthermore, Pearson correlation analysis showed that coherence is negatively correlated to mean HR ($r = -0.65, p < 0.001$) and positively correlated to mean RR ($r = 0.65, p < 0.001$). These findings revealed that the coherence could be a comprehensive index of ATCO's overall HRV status, as well as the resilience and fatigue level. Therefore, from the perspective of stress management proposed by EUROCONTROL (2020), the application of the QCT training program on both working position and during rest time could be an effective method to mitigate ATCO's accumulated perceived workload, as well as providing a quick recharge mental/physical resources and resilience from fatigue.

4 | GENERAL DISCUSSION

ATCO fatigue levels significantly deteriorated from the first shift to the last shift and the first working hour to the eighth working hour. Particularly, the sixth, seventh and eighth working hours indicated much worse fatigue levels between shift-4 and shift-5. This is a safety concern as the fatigue recuperation time of only 9 h cannot provide ATCOs sufficient sleep to maintain the high mental demand of air traffic services. Sleep loss and the resultant fatigue are both acute and cumulative and can increase the potential risk associated with sleepiness, tension, confusion, and decreased vigor while on controller working position. Research demonstrated that sleep deprivation and time since waking show impairments in performance and increased risk of incidents and accidents (EUROCONTROL, 2018; Williamson et al., 2011). Sleep loss on a single night can produce measurable increases in fatigue and resulting performance deterioration on a variety of tasks both in the lab and in real-world settings. The evidence of fatigue and declined performance is also robust particularly on tasks requiring ongoing vigilance and decision making (Tsai et al., 2007). ATCOs' performance impairments due to circadian dys-rhythm fatigue are observed in providing air traffic services that required continuous attention, especially over long durations on the rotating shifts on

this research. ATCOs' performances are susceptible to deterioration on rotating shifts due to circadian rhythm disorders which may also introduce fatigue in rested individuals. The phenomenon can be found on shift 2 and shift 4 in which ATCOs had maintained most sufficient sleep time before the shifts, but ATCOs still suffered from high levels of fatigue. Furthermore, ATCOs' fatigue levels from shift 1 to shift 4 were converging at the sixth working hour then significantly increasing in the seventh hour with the highest fatigue level at the eighth working hour. The fatigue level continuously increasing between the sixth hour and seventh hours can be understood as the effects of ATCO's cognitive resource depletion due to the long duration of work and accumulated mental and physical fatigue. EUROCONTROL (2004) proposed that working schedules and an awareness of the specific requirements in terms of sleep, pause, and relaxation periods are important tools to combat stress. It would be beneficial for ATCO's fatigue recovery for a short break to be added around the sixth working hour. Additionally, ATCOs are generally in a fatigue level at the sixth working hour from shift 1 to shift 4, taking a short break for QCT at this specific time could be more efficient and effective for roster arrangement and fatigue risk management. The dangers associated with fatigue are compounded by the fact that fatigued individuals are typically unaware of how severely their performance has deteriorated and thus may believe that they are safe to perform their duty when they are not (Banks & Dinges, 2007; Durmer & Dinges, 2005). Therefore, it is critical to provide an effective fatigue intervention to mitigate ATCOs' fatigue and is a mandatory regulation by the ICAO.

Biofeedback from HRV could provide information about the adaptability of autonomic nervous system on individual suffering from prolonged and accumulated stress and fatigue (Boissoneault et al., 2019). QCT training program is an effective strategy for fatigue risk management through which ATCOs can learn how to recharge their energy to recuperate the depleted resources and recover from fatigue and work stress. The visual breath-pacer biofeedback device enables ATCOs to precisely practice QCT which can increase the synchronization between sympathetic nervous system and parasympathetic nervous systems and enhance both mental and physical fatigue resilience. With consistent practice, QCT facilitates the cognitive functions to promote physiological efficiency, mental acuity, and emotional stability. An optimal HRV level after a QCT program reflects an inherent self-regulatory capacity, adaptability, resilience, and a wide range of cognitive functions (McCraty & Zayas, 2014). Furthermore, the pattern of ATCOs' coherence scores after QCT is significantly higher than on the rest state as the baseline. This finding may indicate that practicing QCT while on break can be more efficient in recharging ATCOs' cognitive energy than just relaxation on break. Given the fatigue risk management strategy on the rotating roster, it would be beneficial for recharging cognitive resources and improving resilience to set an extra short break and implementing a QCT session for ATCOs at the sixth working hour in each shift. Moreover, compared to various complicated physiological

parameters and strict conditions of traditional HRV measurement, psychophysiological coherence could be a simple and quick indicator of biofeedback for assessing general psychophysiological states and developing fatigue intervention. The visual-pacer biofeedback device allows the real-time monitoring and recording of ATCO's HRV parameters as well as coherence level by a convenient tiny ear sensor. The combination of QCT program and biofeedback device can provide air navigation service providers new insights and effective moderation on ATCO fatigue.

The current two-studies demonstrated a scientific approach to fatigue analysis and fatigue risk mitigation in air traffic services domain. This research offers particular insights into the fluctuation of ATCOs' fatigue level and the influence of a number of factors related to circadian rhythm and resources depletion impact on fatigue levels on study 1; and provides psychophysiological coherence training to increase ATCOs' fatigue resilience and mitigate negative impacts of fatigue on study 2, this research also irradiates other avenues for future research regarding fatigue risk management in high-consequence industries. In future research, frequency-domain and nonlinear HRV parameters are required to assess ATCO's fatigue status and contribute to develop a psychophysiological measurement model on cognitive functions. In addition, researchers could examine ATCOs' interpersonal physiological coherence correlated with psychosocial constructs in the working station. Furthermore, individual differences and preferences on shift works could affect ATCO's perception on fatigue, which require further investigation for setting the optimal roster and developing fatigue risk management by ICAO's new requirements. There are limitations in the process of data collection. ATCOs' fatigue levels on each working hour were rated subjectively by the retrieval approach after their tasks had been completed. The nature of recovering information held in the ATCO's working memory for a considerable period might affect their responses on subjective fatigue assessment. Moreover, current research only analyzed time-domain parameters of HRV data in a short term. There are still frequency-domain and nonlinear measurements on HRV data related to the dynamic activities of cognitive functions which could provide equally important information on developing QCT for fatigue risk management. To counter this issue, authors would like to propose that future research should analyze and compare all parameters related to biofeedback interventions to explore the optimization for developing ATCOs' fatigue risk management.

5 | CONCLUSIONS

This research based on meticulous analysis provides evidence on the fluctuations of ATCO fatigue levels over a 24-h basis while they followed their operational roster and provides new insights into fatigue risk mitigation using psychophysiological coherence intervention. First, the mixed effects of resource depletion and circadian rhythm disorder associated with ATCO fatigue caused by the five-shift rotating roster

were identified, especially the challenging 9 h fatigue recuperation interval between shift-4 and shift-5. Second, the evidence suggested that ATCOs' fatigue levels vary with the ATCOs' preceding sleep hours and the duration on working position. Third, a simple QCT using a biofeedback breathing pacer can be an effective intervention to mitigate ATCO fatigue by synchronizing the sympathetic nervous system and the parasympathetic nervous systems to increase psychophysiological coherence and cognitive function. Moreover, an extra short break to permit ATCOs to practice QCT at the sixth working hour can substantially recharge cognitive resources and increase mental and physical resilience to fatigue. In summary, this research provides empirical evidence of ATCOs' accumulated fatigue as a result of sleep deprivation, resource depletion, and circadian rhythm disorder which could have a negative impact on task performance and aviation safety. An objective biofeedback-based methodology can moderate ATCO fatigue by practicing the QCT. Air Navigation Services providers can develop efficient fatigue risk management systems based on scientific approaches to improving aviation safety and ATCOs' mental and physical health.

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CONFLICT OF INTEREST

The authors declared that they have no conflict of interest.

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