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ORIGINAL RESEARCH

Cognitive function following exposure to contaminated air on commercial aircraft: A case series of 27 pilots seen for clinical purposes

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Abstract
Background. Cabin air on commercial aircraft is sometimes contaminated with hydraulic fluids, synthetic jet engine oils and combusted or pyrolized materials. The incidence of contaminated air events is hard to quantify as commercial aircraft do not have air quality monitoring systems on board. In the UK, around 350 aircrew have advised their union that they may be suffering physical and psychological ill health following exposure to contaminated air.
Design. This paper presents a case series of 27 pilots referred for psychological assessment. The general aim of the assessment was to determine whether pilots show evidence of cognitive impairment and whether this relates to exposure history.
Materials and method. All pilots underwent neuropsychological and adult mental health assessment, undertaken by 12 examiners, instructed to search for alternative explanations other than exposure to toxic fumes for any symptoms reported.
Results. Pilots reported alarming cognitive failures at work such as being unable to retain or confusing numerical information from Air Traffic Control. Nine pilots were excluded from further analysis because they had a medical or psychiatric condition which might otherwise explain these difficulties. In the remaining 18 pilots, language, perceptual skills and general intellectual ability were preserved, but performance on tests of psychomotor speed, attention and executive functioning was below expected levels.
Conclusions. The cognitive deficits identified in this cohort of pilots cannot be attributed to factors such as mood disorder or malingering. However, the evidence available in this study does not enable firm conclusions to be drawn regarding a causal link with contaminated air; the cohort of pilots was self-selected and only crude indices of exposure were available. Further research is warranted given the scientific uncertainty regarding the health effects of inhalation of heated or pyrolized engine oil.

Key words: *Aviation air quality, cognitive impairment, memory, occupational exposure, organophosphates, pilots*

Introduction

To enable passengers and crews to live in a reduced pressure environment, aircraft cabins are pressurized and the air supply to the passenger cabin and cockpit is supplied from the

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engines or auxiliary power unit. This air is unfiltered and known as 'bleed air' and is sometimes contaminated with hydraulic fluids, synthetic jet engine oils and/or the compounds released when these fluids and/or oils are heated or pyrolized (for example, carbon monoxide, phosphorus oxides, aldehydes). When the 'bleed air' becomes contaminated in this way it is referred to as a 'contaminated air' event. Contaminated air may contain a large number of chemicals which can cause irritation, skin sensitization and neurotoxicity such as the organophosphate tricresyl phosphate (TCP) [1–3]. It is recognized that all aircraft are subject to engine oil leaks occasionally but certain types of aircraft record statistically more events than others. These include the BAe 146, A320 and Boeing 757 [4].

The incidence of contaminated air events on commercial aircraft is difficult to quantify as commercial aircraft do not have air quality monitoring systems on board. Under-reporting of contaminated air events is common amongst aircrew due to lack of awareness, commercial pressure and fears over job security if crew complain about working conditions and many crews see contaminated air as a normal, everyday occurrence. A recent survey by the British Airline Pilots Association (BALPA) found that only 61 out of 1667 contaminated air events (that is, only 3.66%) were recorded on the UK Civil Aviation Authority (CAA) database [5].

No monitoring has ever been successfully undertaken during a contaminated air event [6]. Therefore, the nature of the contaminants within the cabin air and the levels of exposure to passengers and crews during a contaminated air event are unknown. The material data safety sheets for jet engine oils BP 2380 (widely used in BAe 146 aircraft) and Exxon Mobil Jet Oil II (widely used in Boeing 757 aircraft) states that TCP is present in the oil and warn that toxic and harmful fumes/vapours/mists may be evolved on burning or exposure to heat and that exposure to thermal decomposition products in an enclosed space may cause headache, nausea, eye, nose and throat irritation. One study found the organophosphate tricresylphosphate (TCP) on the walls of BAe 146 aircraft, a BAe 146 pilots' trousers, Boeing 757 dust and HEPA filters [7].

Flight attendants, flight crew and some passengers around the world have been reporting ill health following contaminated air events for many years [3,5,8], but it is only recently that this issue has received attention in the UK. The immediate effects of exposure to contaminated air have been well documented and include eye irritation, respiratory problems, headache, skin problems, nausea, vertigo, loss of balance, dizziness, fatigue and cognitive impairment (disorientation, confusion and memory problems). These symptoms show a close temporal relationship with exposure and usually recede after cessation of exposure [1,5,9].

A number of individuals report persistent, chronic ill health lasting months or years after exposure, including lack of coordination, nausea/vomiting, diarrhoea, respiratory problems, chest pains, severe headaches, lightheadedness, dizziness, weakness and fatigue, parasthesias, tremors, increased heart rate, palpitations, irritation of ear, nose and throat, muscle weakness/pain, joint pain, salivation, skin itching, rashes, blisters, hair loss, signs of immunosuppression and chemical sensitivity [3,10–12]. Persistent cognitive impairment has also been reported involving memory problems, reduced information processing speed, reaction time and fine motor skills [13]. Work incapacity may be as high as 35% [10]. A debate is ongoing in the UK and US about causation, diagnosis and treatment of long-term effects.

This paper presents a case series of 27 commercial airline pilots who requested or were referred by other specialists for neuropsychological assessment. The pilots had concerns about their health and a number suggested their symptoms might be related to exposure to contaminated air on commercial aircraft. All pilots underwent neuropsychological and adult mental health assessment and their medical records were reviewed to determine whether they had a previous medical or psychiatric history which might otherwise account for their symptoms.

Method

Basis for project

Around 350 UK pilots have advised their union that they may be suffering health effects from exposure to contaminated air. The pilots union maintains a database of these individuals. This paper presents a case series of 27 aircrew who underwent psychological assessment for clinical purposes. The general aims of this case study were:

(1) To establish whether aircrew with a history of exposure to contaminated air on commercial aircraft show evidence of cognitive impairment.
(2) To examine the nature and extent of any cognitive deficits identified.
(3) To determine whether the pattern of cognitive deficit relates to exposure history.

Subjects

The subjects for this project were a self-selected sample of 27 commercial airline pilots who voluntarily underwent neuropsychological assessment and adult mental health assessment. All bar one of the aircrew involved in this audit were current or former pilots on the Boeing 757 or BAe 146 aircraft types.

Seven pilots were referred by either a general medical practitioner or a medical specialist (consultant neurologist or consultant psychiatrist) for an opinion regarding their cognitive functioning. The remaining 20 aircrew referred themselves directly (self-referral) and were retired, suspended and working pilots who fly/flew the BAe146 and Boeing 757 aircraft, who had reported exposure to contaminated air to union officials.

Ethics approval

All pilots were asked if their results from psychometric testing could be entered into a group analysis and all pilots gave written consent for this. Ethical approval for this work was granted by the joint UCL/UCLH committee on the Ethics of Human Research, Committee A.

Clinical interview

A clinical interview collected information, as outlined in Table I. Whenever possible, a relative/carer was interviewed as well to obtain corroborating evidence.

In addition, a complete set of each individual's general medical notes and any relevant hospital records were reviewed by the author to search for alternative explanations for any symptoms or deficits identified during the assessment.

Neuropsychological assessment

Subjects underwent a detailed neuropsychological assessment which lasted ~3 hours. After a short break they undertook a clinical interview and mental health assessment which lasted

Table I. Information collected during clinical interview.

Developmental and social history
Educational and occupational background
Past medical and psychiatric history; alcohol, drug and medication use
Recent stressful life events (for example, bereavement, divorce)
Exposure history. Pilots were asked to bring details of their career history including

- detailed records of flying hours (from their log books)
- the year they began flying
- which aircraft they had flown over the course of their career
- how long they had spent flying each aircraft type
- whether they thought they had ever experienced exposure to contaminated air, if so, did they suffer from any physical or psychological symptoms
- how long did the symptoms persist and did they recover
- did they report the incident(s) to any authorities
- were incident(s) investigated by engineers?
- did they have any long-term/persistent health problems which they attribute to exposure to contaminated air?
- had they consulted any doctors about their symptoms?
- what diagnoses have been given?

Onset of physical/psychological problems and their temporal relationship with exposure, plus their evolution over time
The nature of any medical treatment provided
Current symptoms/problems (physical, emotional, cognitive)
Impact on daily life
Mood state

~2 hours. Twelve examiners were involved in assessing aircrew; all examiners were blind to exposure status.

Psychometric assessment

Psychometric testing was carried out first to ensure the examiners were blind to the precise exposure status of the aircrew they were testing. Examiners were only given basic demographic information such as the name and age of the study participant they were seeing and they were aware that the pilots had been referred because they believed their health to have been affected by exposure to contaminated air. All examiners were instructed to search for explanations other than exposure to toxic fumes, for any symptoms or deficits identified during assessment. In particular they were asked to consider the possibility that symptoms might be secondary to excessive alcohol consumption or substance abuse, previous neurological injury, medical or psychiatric history, lifestyle factors, malingering, mood disorder, psychosomatic disorder, stressful life events or attribution error. In addition, examiners were instructed to ask subjects if they had been examined by a Consultant Neurologist to exclude other potential explanations for their symptoms and to report what diagnoses they had been given by any other medical experts they might have seen.

Only well known, reliable and clinically sensitive measures were selected for inclusion in the Psychometric test battery [14]. Tests were selected which would assess a broad range of cognitive functions including premorbid and current IQ, language skills, memory functioning (verbal and visual), information-processing speed, executive function and visuo-perceptual ability. A test of malingering was also included in the battery. Finally, emotional state at the time of testing was assessed using the Hospital Anxiety and Depression Scale (see Table II).

Table II. Psychometric battery.

Premorbid and current IQ
Wechsler Adult Reading Test (WTAR) [21]
Wechsler Adult Intelligence Scale–III (WAIS-III) [22]
Memory
Adult Memory and Information Processing Battery (AMIPB) [23]
Information Processing Battery and Psychomotor speed
Adult Memory and Information Processing Battery
Trail Making A
Language
Graded Naming [24]
Verbal Fluency (FAS) [25]
Semantic fluency (Animals)
Malingering test
Rey 15 item
Mental flexibility
STROOP [26]
Trail Making B
Perception
Benton Line Orientation [27]
Benton Face Recognition (short form)
Mood questionnaires
Hospital Anxiety and Depression Scale [28]
Beck Depression Inventory-II
Beck Anxiety Inventory
Life Events Checklist [29]

Descriptive information is provided for all 27 pilots regarding exposure history, physical symptoms associated with exposure and the results of various medical tests aimed at establishing the aetiology of these complaints.

Nine individuals were found to have a medical or psychiatric history which might otherwise account for any cognitive deficits identified during assessment and these were excluded from the group analysis of cognitive function. The rationale for this exclusion process was to ensure the most conservative analyses of the data in order to reduce the risk of false positive results. Reasons for exclusion were: alcohol intake above 21 units/week (2 pilots); anxiety and/or depression (2 pilots); co-morbid neurodegenerative condition (2 pilots); neurological symptoms of unknown aetiology (1 pilot); and 'others' (2 pilots).

Results

Demographic and exposure information

Demographic information is shown in Table III.

Flying hours. Table IV shows the total number of hours and years that pilots had spent flying throughout their career history and the total number of hours they had flown specific aircraft types. None of the pilots who flew/fly the Boeing 757 had flown the BAe146 and contrariwise, but all pilots had flown other aircraft types during their career history. The sample was equally split with regard to aircraft type flown with nine pilots having flown the Boeing 757 and nine having flown the BAe 146.

Table III. Demographic characteristics of aircrew.

Characteristics	Pilots	
	whole sample (n=27)	reduced sample (n=18)
Gender	3 Female; 24 Male	2 Female; 16 Male
Mean age years (±SD: range)	49.4 (±8.2: 36–63)	48.4 (±8.8: 36–62)
Mean educational level (±SD: range)	13.2 (±2.3: 10–18)	13.2 (±2.3: 10–18)
Mean WAIS-III full scale IQ (±SD: range)	119.9 (±13.9: 88–155)	119.3 (±10.5: 103–139)
Working aircrew	13	9
Long-term sick leave or medical suspended?	5	4
Retired on ill health grounds	6	2
Retired for other reasons	3	3

Table IV. Flying time and hours on specific aircraft types (reduced sample).

	Lifetime flying (hours)	Lifetime flying (years)	Boeing 757 hours	BAe 146 hours
Mean	11 642	22	1978	2647
SD	5 349	10.7	2742	3052
Range	3 000–25 000	5.5–40	0–8000	0–8147

A flying hour is not the same as time in the aircraft environment as it does not include time in the cockpit prior to engine start or after engine shut down completing pre- and post-flight duties.

Official reporting of fume incidents. All of the pilots examined reported unpleasant, oily, chemical smells in the aircraft cabin which would increase in intensity under certain conditions.

Pilots who fly/flew the BAe 146 describe the cabin as having a distinctive and unpleasant oily, chemical smell, the intensity of which would increase under the following conditions: (1) when the air conditioning system is turned on; (2) during 'pack burns', an operational procedure in which the aircraft air-conditioning system is operated at full heat so as to volatize hydrocarbons from the air conditioning system into the aircraft cabin whilst it is empty (although crew were sometimes present setting up the aircraft for its next flight [15,16]. Pack burns were reported to be performed regularly to remove oil contamination of the ductings and often caused visible fumes in the aircraft cabin which crews were exposed to (3) during take off, climb, descent and landing.

Pilots who fly/flew the Boeing 757 describe the cabin as having a distinctive and unpleasant oily, chemical smell, the intensity of which would vary depending on phase of flight and power settings on the engines.

Ten pilots stated that they had never formally reported contaminated air for the following reasons: (1) they assumed the distinctive smell in the cabin was part of the normal working environment and not something to be unduly concerned about; (2) fears over job security if contaminated air events were reported. Two pilots were threatened by senior colleagues when they suggested reporting an event; (3) a belief that the company would not act on the report; (4) not wishing to be delayed at work completing the necessary paperwork; and (5) not attributing symptoms of ill health to contaminated air. The remaining 17 pilots had reported a contaminated air event at some point during their career history.

Symptoms provoked by exposure and the development of chronic ill health

Acute symptoms. Thirteen pilots describe one or more of the following acute symptoms which develop immediately after exposure to contaminated air; flu-like symptoms, watering eyes, sore nose, throat, nasal congestion, breathing difficulties, headache, nausea, gastrointestinal problems, dizziness, fatigue, cognitive impairment (that is inability to complete basic tasks such as mental arithmetic or to follow instructions in the correct sequence). A number of pilots describe a metallic taste in the mouth following exposure. These symptoms usually resolve on cessation of exposure.

The cognitive impairment reported by pilots was alarming, bearing in mind the nature of the symptom and the consequences of an adverse outcome: being unable to retain numerical coordinates provided by Air Traffic Control regarding height, altitude, speed; mixing up the numerical coordinates provided by Air Traffic Control; completing tasks in the incorrect sequence; being able to hear Air Traffic Control or colleagues talking to them, but being unable to respond; feeling intoxicated; feeling unable to make decisions or problem-solve; losing track of conversations; word-finding difficulties; being easily distracted and unable to return to the task in hand; being unable to recall important matters such as whether the undercarriage had been raised or lowered. Several pilots reported being unaware of the extent of their impairment until it was pointed out to them by colleagues. Others found it necessary to request assistance from colleagues to complete their duties.

Long-term symptoms. All bar one pilot reported the development of more persistent, chronic health problems over time including fatigue, sleep difficulties, fluctuating gastro-intestinal problems, numbness and tingling in fingers and toes, memory and word-finding difficulties.

Two of the BAe 146 pilots reported feeling so fatigued at work that they had micro-sleeps whilst flying aircraft, that is they fell asleep whilst in control of the aircraft. All of the pilots who complained of fatigue described it as being intense and overwhelming and quite unlike fatigue which is precipitated by exercise or sleep deprivation. They also report that this chronic fatigue persists even after sleep/rest. Nine continued to work, one pilot was on long-term sick leave, two have retired on ill health grounds and three have retired for personal choice.

In most cases long-term symptoms develop gradually or after a major fume event, but three 757 pilots describe a marked deterioration in health following a viral illness which left them with disabling levels of fatigue and an inability to work. One of these pilots has fully recovered (though he has not returned to work for other reasons) but the others have not and have ceased flying. None of these three pilots formally reported fume events, though they did consult their GP about recurrent flu-like symptoms in the years preceding the sudden development of chronic ill health.

Neuropsychological functioning

Pilots underwent an extensive battery of more than 30 neuropsychological tests. There was no evidence of global intellectual decline or impairment, language or perceptual deficits in this cohort. Indeed, pilots were intact on the vast majority of tests. However, there was evidence of under-functioning on tests associated with psychomotor speed, executive functioning and attention.

Intellectual functioning. The average level of intelligence was on the border of the high average/superior range for the general population (mean full scale IQ was 119, SD ± 10.5).

Scores ranged from being average to very superior (IQ score range 103–139). None were below average.

With regard to WAIS-III sub-tests, 61% of the cohort obtained scores on a test of visual sequencing and psychomotor speed (digit symbol) which were statistically significantly different from their mean performance on other sub-tests within the WAIS-III. This means the likelihood of obtaining such a difference by chance is very low. Fifty per cent of the cohort obtained scores on a test of working memory/attention (digit span) which were statistically significantly different from their mean performance on other sub-tests within the WAIS-III; and 33% of the cohort obtained scores on another test of visual sequencing (picture arrangement) which were statistically significantly different from their mean performance on other sub-tests within the WAIS-III. Table V illustrates these findings, along with those of the only other neuropsychological study in this area [13]. The prevalence or frequency of most of the observed differences (that is two thirds) are rare in the standardization sample (that is less than 10% of the standardization sample would show differences of this magnitude).

To summarize, deviations in sub-test scores of this magnitude are unexpected. Not only are there a large number of participants who show deviations in sub-test scores, the deviations are apparent on the same sub-tests.

Executive functioning—mental flexibility. Fifty per cent and 39% of pilots obtained scores below the 50th percentile on tests of attention/mental flexibility (Stroop and Trails B) and 44% obtained low scores on a test of semantic fluency. These tests are all associated with executive functioning.

Information processing speed. Fifty per cent of pilots obtained scores below the 50th percentile on tests of mental information processing speed and 33% had a higher than

Table V. Psychometric test results.

	Percentage impairments	
Tests	Present study	Coxon study [13]
Visual Sequencing		
Digit Symbol	61%	87.5%
Picture Arrangement	33%	62.5%
Memory (verbal)		
Digit Span (working memory)	55%	50%
Story Recall	78%	87% impaired on verbal recall
List Learning	55%	
Memory (visual)		
Figure Recall	5%	50% impaired on visual recall
Design Learning	16%	
Executive (Frontal Lob) Function		
Stroop	50%	*
Trails B	39%	37.5%
Semantic Fluency	44%	
Information Processing Speed		
Mental Speed	50%	*
Motor Speed	17%	*
Increased Error Rate	33%	*

* comparable data not available.

average error rate on this test. In contrast, motor speed is relatively well preserved with only three pilots obtaining weak scores on this test.

Memory. All but two pilots were of high average to very superior intelligence, yet 78% obtained scores in the average or low average range on some aspect of a story recall test, 33% obtaining scores 1–2 SD below the mean. Fifty per cent obtained scores in the average range on a list learning task, 28% obtained scores 1–2 SD below the mean on this test.

In contrast, visual memory seemed to be relatively well preserved with only two pilots showing a weakness in this area.

Malingering test. None of the pilots included in the group analyses failed the malingering test.

Mood questionnaires. Any pilot with elevated scores on the Hospital Anxiety and Depression Scale or Beck Inventories underwent a structured interview to determine whether they met DSM-IV criteria for Major Depression or Anxiety Disorder. None of the pilots included in the group analysis met DSM-IV criteria for a diagnosis of anxiety or depression.

Statistical analyses

Comparison with a control group. As was mentioned at the beginning of this report this is not a research study, but an audit of a case series of aircrew examined during the course of clinical practice. Funding was not available to recruit a suitable, matched control group. However, the author has data on 22 healthy, non-exposed individuals, recruited from local job centres within London and newspaper advertisements, who completed the same psychometric test battery as the pilots, although matched to the sample of pilots in terms of gender, age and years spent in education, level of intelligence differed between the groups. The mean Wechsler Adult Intelligence Scale Full Scale IQ in the control group was at the top of the average range, whilst the average full scale IQ in the pilot cohort was at the top of the high average range (see Table VI).

As the two groups are not well matched in terms of IQ, statistical tests of differences in mean are less informative than tests of profile. In other words, while the pilot group had a higher overall mean, impairments in psychological performance might be indicated by a different pattern of performance across sub-tests. This was tested using profile analysis. Bonferroni corrections were applied to control for Type 1 errors. The analysis confirmed an overall difference in mean between the two groups ($F(1,39)=10.48$, $p=0.002$), but more importantly showed a difference in the sub-test profiles of the two groups ($F(9,31)=2.81$, $p=0.016$; see Figure 1). There was much greater variability in performance across the sub-tests amongst the pilots and this was primarily due to weaker scores on tests of digit span (working memory), similarities and picture arrangement (executive function) and digit symbol relative to performance on other intellectual sub-tests.

Table VI. Characteristics of pilots and controls.

Characteristics	Pilots ($n=18$)	Controls ($n=22$)
Mean age (SD) in years	48 (8.8)	46 (10.9)
Mean educational level (SD)	13 (2.3)	12 (2.1)
Mean WAIS-R full scale IQ	119 (10.5)	109 (12.3)

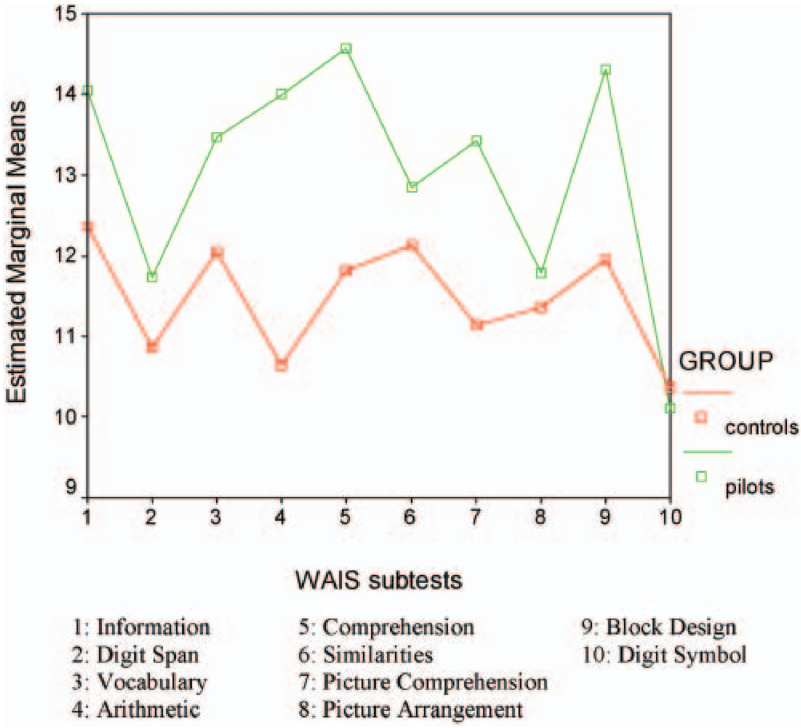

Figure 1. WAIS performance profiles.

Correlations between exposure history (flying hours) and cognitive function. Pearson Product Moment Correlations (or Spearman when appropriate) were used to establish whether there is a relationship between cognitive function and exposure history. It was predicted that performance will worsen with increased exposure; therefore, due to the unidirectional nature of the hypothesis, one-tailed test of significance was used. The number of variables entered into the analysis was kept to a minimum to reduce the risk of Type 1 errors occurring as a result of multiple comparisons. Partial correlations were also performed to control for the potentially confounding effects of age which was associated with both flying hours/years and performance on psychometric tests (see Table VII).

Significant correlations were observed between total number of years spent flying and lowered scores on the following tests: picture arrangement (visual sequencing), the Stroop test of mental flexibility, the trails B test of mental flexibility and a test of verbal memory ($r=-0.442$, $p<0.05$; $\rho=-0.414$, $p<0.05$; $r=0.544$, $p<0.01$; $r=-0.422$, $p<0.05$).

Significant correlations were observed between total number of hours spent flying and lowered scores on the following tests: picture arrangement (visual sequencing), semantic fluency, the trails B test of mental flexibility and three different tests of verbal memory ($r=-0.448$, $p<0.05$; $r=-0.400$, $p<0.05$; $r=0.453$, $p<0.05$; $r=-0.415$, $p<0.05$; $r=-0.530$, $p<0.05$; $r=-0.462$, $p<0.05$).

Lowered scores on tests of semantic fluency, mental flexibility (trails B and Stroop) and mental speed correlated with hours on the BAe 146 ($r=-0.463$, $p<0.05$; $r=0.817$, $p<0.01$; $\rho=-0.557$, $p<0.01$; $r=-0.651$, $p<0.01$). Correlations with hours on the Boeing 757 aircraft were counter-intuitive and indicated improved performance on tests of mental flexibility and mental speed were associated with this variable ($r=-0.565$, $p<0.01$;

Table VII. Correlations between exposure indices and psychometric tests.

Psychometric test	Total flying years	Total flying hours	Hours on Boeing 757	Hours on BAe 146	Number of months since last flight
Digit Span	ns	ns	ns	ns	ns
Picture Arr.	−0.442*	−0.448*	ns	ns	ns
Digit Symbol	ns	ns	ns	ns	ns
Semantic Flu.	ns	−0.400*	ns	−0.463*	ns
Trail B	0.544**	0.453*	−0.565**	0.817**	ns
Stroop	−0.414*	ns	0.420*	−0.557**	ns
Story I	ns	ns	ns	ns	ns
Story D	ns	−0.415*	ns	ns	ns
List I	−0.422*	−0.530*	ns	ns	ns
List D	ns	−0.462*	ns	ns	ns
Mental Speed	ns	ns	0.667**	−0.651**	ns
Motor Speed	ns	ns	ns	ns	ns

* $p<0.05$; ** $p<0.01$.

$\rho=0.420$, $p<0.05$; $r=0.667$, $p<0.01$). Number of months since last flight did not correlate with any of the psychometric data.

Partial correlations were performed to control for the potentially confounding effects of age and all of the observed correlations between hours/years spent flying and performance on psychometric tests were lost. Significant, but counter-intuitive correlations remained between hours spent flying the Boeing 757 aircraft type, mental flexibility and mental speed ($r=-0.4806$, $p<0.03$; $r=0.6293$, $p<0.003$). Significant correlations in the predicted direction remained between the number of hours spent flying the BAe146 aircraft type, mental speed and two tests of mental flexibility ($r=-0.6061$, $p<0.005$; $r=0.7867$, $p<0.0001$; $r=-0.4705$, $p<0.03$).

Discussion and conclusions

This paper presents a case series of 27 pilots who underwent neuropsychological assessment at University College London. To reduce the risk of false positive results, nine pilots with a medical or psychiatric history which might otherwise accounted for any deficits or symptoms identified during assessment were excluded from group analyses of psychometric test data.

Pilots completed an extensive battery of more than 30 neuropsychological tests. There was no evidence of global intellectual decline, language or perceptual deficits in this cohort. Indeed, pilots were intact on the vast majority of tests. However, there was evidence of under-functioning on tests associated with psychomotor speed, executive functioning and attention. Indeed pilots exhibited a different, more variable pattern of performance across intellectual sub-tests than healthy controls (matched for age, gender and years of education but not IQ).

Statistical analyses were carried out to look at the relationship between exposure history and cognitive deficits. A number of significant correlations were observed between exposure variables and verbal memory, executive function and information processing speed. However, when the potentially confounding effects of age weres controlled for, some of these correlations became non-significant.

The exposure indices available in this study were crude and may not be reliable or valid measures of exposure to contaminated air. For example, the pilots in this study had flown a variety of aircraft types over their career history, some of which will not have suffered engine oil leaks, therefore total number of hours or years spent flying may not be a good index of exposure to contaminated air. Even hours spent flying the BAe 146 or Boeing 757 aircraft types may also fail to capture exposure adequately, as exposure will depend on whether a fault occurs in a particular aircraft and some aircraft may be maintained to a higher standard than others. Reporting rate is also unlikely to correlate highly with exposure as a number of factors influence whether aircrew report fume events. However, it may be the case that factors other than exposure to contaminated air are responsible for the cognitive deficits identified in this analysis. Alternative explanations might include medical or psychiatric background, mood disorder/emotional distress, malingering or the general lifestyle of pilots.

Mood disorder, malingering, chance factors

Examiners found little to substantiate the view that the deficits seen in pilots might be secondary to psychological distress, malingering or chance factors. None of the pilots included in the group analysis were suffering from mood disorder and none failed a test of malingering. Working pilots were highly motivated to perform well as they expressed concern that if deficits were identified, they might lose their licence to fly. Furthermore, the profile of deficits seen in this group of pilots is not consistent with malingering and is unlikely to have occurred by chance as pilots were intact on the vast majority of psychometric tests and, when deficits were identified, they were in specific cognitive domains (that is attention, executive function and information processing speed). Malingering and chance factors (for example, regression to the mean) would produce a more random profile of results [17–19]. The pattern of deficits observed in each pilot were similar and consistent and are likely to be real rather than a result of faking or chance factors.

Medical or psychiatric history

Another possibility is that the profile of cognitive deficits identified in this cohort is due to some other medical condition. Although pilots with a medical or psychiatric history (including substance abuse) that might otherwise account for any deficits identified during testing were excluded from the group analysis, the abnormalities detected may be multifactorial so that no obvious, single alternative cause can be established.

The general lifestyle of pilots

Another possibility is that the profile of cognitive deficits identified in this cohort relates to some lifestyle factor, specific to pilots, for example, exposure to radiation, shift working, time changes and jet lag, reduced pressure environment, poor diet, dehydration and humidity. This is considered to be an unlikely explanation for the deficits observed in this cohort, as 50% of the cohort were suspended from or had retired from flying and were no longer subject to these lifestyle factors. Furthermore, the Boeing 757 and BAe 146 aircraft are classified as short haul aircraft. As such they are subject to less radiation and pressurization than long-haul aircraft and pilots are subjected to fewer time zone changes than long haul pilots. However, the best way to confirm whether medical or lifestyle factors are relevant would be to carry out an epidemiological survey of all UK pilots looking at the incidence, prevalence and severity of physical and psychological symptoms and what if any relationship exists between medical history, the type of aircraft flown and shift patterns pilots are assigned to.

Comparisons with previous research on aircrew exposed to engine oil emissions

General symptoms. With regard to general symptoms, the first paper found concerning ill health following exposure to contaminated air was published by Montgomery et al. [8] in 1977. The paper describes a 34 year old military navigator in a Lockheed C-130 Hercules transport aircraft who experienced acute intoxication following inhalation of vaporized or aerosol synthetic lubricating oil from a contaminated air supply. He reported a gradual onset of headache, nausea, dizziness, vomiting, incoordination and lethargy. By the time the plane could be landed he had difficulty standing. The authors conclude that 'further investigation into the potential hazards from inhalation of synthetic oil fumes … is definitely warranted'.

Since then a number of papers have been published which describe acute and chronic symptoms of ill health following reported exposure to contaminated air. The term 'Aerotoxic Syndrome' was proposed by Balouet and Winder [20] in 1999 to describe the association of symptoms observed among aircrew exposed to contaminated air.

The symptoms reported in these papers have much in common with those reported by the pilots we examined. For example, in 2002 Winder et al. [3] published the results of a health survey of 68 Australian and US aircrew who flew the BAe 146 and A320 aircraft types: 88% reported the following symptoms occurred after exposure to contaminated air: irritation of eye, nose and throat and respiratory system, gastro-intestinal problems and cognitive impairment. Eighty-two per cent reported that these symptoms persisted for 1 month after exposure and 74% reported symptoms persisted for up to 6 months following exposure.

In 2002, Cox and Michaelis [9] published the results of a health survey of 21 Australian BAe 146 aircrew who reported increased cold-like symptoms, running nose and watery eyes, headaches, skin irritation, fatigue and cognitive impairment, which they associated with flying this particular aircraft type. Forty-seven pe cent thought their symptoms were associated with exposure to contaminated air whilst 37% thought their symptoms were a normal part of working on this particular aircraft type.

In 2003, Michaelis [5] published the findings of a survey of 106 British Boeing 757 pilots who reported a similar constellation of symptoms which they associated with flying the Boeing 757 aircraft type because symptoms increased whilst on duty and improved after duty or on days off work.

A 2005 survey by Harper [10] of 60 commercial aircrew found a close temporal relationship between exposure to fumes and the onset of ill health. Symptoms occurred during flight and a number of people were usually affected concurrently; 45% of symptoms reported were neurological, 22% respiratory, 14% fatigue, 10% gastrointestinal, 5% skin and 3% musculoskeletal. Abnormalities detected during medical investigations include reduction in small airway function, diffusing capacity and gas exchange, nasal and vocal cord polyps, neuropathies, cognitive impairment, abnormal brain scans and evoked potentials.

Cognitive function. With regard to cognitive function, a research team in the US found radiological evidence of organic brain damage in crew complaining of ill health following exposure to contaminated air. Heuser et al. [11] examined 26 North American flight attendants who presented with a range of disabling physical complaints which had not been thoroughly investigated and had often been trivialized by physicians. Each flight attendant had a neurological examination and a neuropsychological assessment and 12 subjects underwent neuroimaging (PET scans). Neurological abnormalities were detected in 15 flight attendants. Many had impaired balance and coordination and some had developed a movement disorder (postural bilateral tremor). All showed evidence of cognitive impairment. Abnormalities were found in all of the crew who had PET scans, involving imbalance of function between cortical (decrease) and subcortical (increase) areas, frontal (decrease) and occipital (increase) areas; and increased function in some limbic areas, especially the extended amygdale region. Heuser et al. concluded that aircrew, exposed to contaminated air, deserve more medical attention and sophisticated investigations (that is neuroimaging) than is routine and suggested a medical protocol is created which outlines the evaluations that flight personnel should undergo.

A pattern of cognitive deficits, similar to that seen in this study, was described by Coxon [13] in eight Australian aircrew exposed to oil emissions on the BAe 146. Reduced performance on tests of reaction time, information processing speed, fine motor skills and verbal memory were confirmed.

Limitations of this study

This study has several weaknesses, which should be considered when interpreting the results. Weaknesses include sample size, sample bias, limited indices of exposure and the lack of a matched control group.

The number of participants in this study was relatively small and they were a self-selected sample. Therefore, it is unclear how representative they are of the aviation industry as a whole; and the sample size may be too small for associations between indices of exposure and cognitive function, to be detected. It would have been useful to have a control group of pilots who have not been exposed to contaminated air to determine whether the profile of cognitive strengths and weaknesses observed in this cohort is common amongst pilots or related to lifestyle factors.

Limited indices of exposure were available to us other than pilot's self-report. Air quality monitoring systems need to be developed and placed onboard aircraft to determine the incidence of contaminated air events and the nature of any contaminants involved.

Implications for future research

The above limitations make it impossible to establish or rule out a link between the abnormalities detected and exposure to contaminated air. In order to determine whether such a link exists, a large scale epidemiological survey should be undertaken to establish the prevalence of ill health (physical and psychological symptoms) amongst aircrew and relationship, if any, with working practices and exposure to contaminated air.

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References

1. Winder C, Balouet JC. Aircrew exposure to chemicals in aircraft: symptoms of irritation and toxicity. J Occup Health Safety Aust NZ 2001;17:471–483.
2. Winder C, Balouet JC. The toxicity of commercial jet oils. Environ Res A 2002;89:146–164.
3. Winder C, Fonteyn P, Balouet JC. Aerotoxic syndrome: a descriptive epidemiological survey of aircrew exposed to in-cabin airborne contaminants. J Occup Health Safety Aust NZ 2002;18:321–338.
4. Winder C, Michaelis S. Aircraft air quality malfunction incidents: causation, regulatory, reporting and rates. In: Hocking M, editor. Air quality in airplane cabins and similar enclosed spaces—the handbook of environmental chemistry. Berlin: Springer-Verlag GmbH; 2005. pp 211–228.
5. Michaelis S. A survey of health symptoms in BALPA Boeing 757 pilots. J Occup Health Safety Aust NZ 2003;19:253–261.
6. Winder C. Air monitoring studies for aircraft cabin contamination. Curr Topics Toxicol 2006;3:33–48.
7. van Netten C. Aircraft air quality incidents, symptoms, exposures and possible solutions. In: Winder C, editor. Proceedings of the BALPA air safety and cabin air quality international aero industry conference. New South Wales: British Airline Pilots Association/University of New South Wales; 2005. pp 245–255.
8. Montgomery MR, Weir T, Zieve FJ, Anders MW. Human intoxication following inhalation exposure to synthetic jet lubricating oil. Clin Toxicol 1977;11:423–426.
9. Cox L, Michaelis S. A survey of health symptoms in BAe 146 aircrew. J Occup Health Safety Aust NZ 2002;18:305–312.
10. Harper A. Illness related to cabin air: a survey of symptoms and treatment among commercial pilots and cabin crew. In: Winder C, editor. Proceedings of the BALPA air safety and cabin air quality international aero industry conference. New South Wales: British Airline Pilots Association/University of New South Wales; 2005. pp 43–51.
11. Heuser G, Aguilera O, Heuser S, Gordon R. Clinical evaluation of flight attendants after exposure to fumes in cabin air. In: Winder C, editor. Proceedings of the BALPA air safety and cabin air quality international aero industry conference. New South Wales: British Airline Pilots Association/University of New South Wales; 2005. pp 107–112.
12. Somers M. Assessing over thirty flight crew who have presented as a result of being unwell after exposure to fumes on the BAe 146 jets. In: Winder C, editor. Proceedings of the BALPA air safety and cabin air quality international aero industry conference. New South Wales: British Airline Pilots Association/University of New South Wales; 2005. pp 131–145.
13. Coxon L. Neuropsychological assessment of a group of BAe 146 aircraft crew members exposed to jet engine oil emissions. J Occup Health Safety Austd NZ 2002;18:313–319.
14. Spreen O, Strauss E. A compendium of neuropsychological tests. New York: Oxford University Press; 1991.
15. Fox RB. Air-quality testing aboard Ansett Airlines BAE 146 aircraft, August 1997. Houston: Allied Signal Aerospace Corporation; 1997.
16. Fox RB. Air quality and comfort measurement aboard a commuter aircraft and solutions to improve perceived occupant comfort levels. In: Nagda NL, editor. Air quality and comfort in airliner cabins, ASTM STP1393. West Conshohocken, PA: American Society for Testing and Materials; 2000.
17. Heaton RK, Smith HH, Lehman RAW, Vogt AT. Prospects for faking believable deficits on neuropsychological testing. J Consult Clin Psychol 1978;46:892–900.
18. Rogers R, Harrell EH, Liff CD. Feigning neuropsychological impairment: a critical review of methodological and clinical considerations. Clin Psychol Rev 1993;13:225–274.
19. Lezak MD. Neuropsychological assessment. Oxford: Oxford University Press; 1995.
20. Balouet JC, Winder C. Aerotoxic syndrome in air crew as a result of exposure to airborne contaminants in aircraft. American Society of Testing and Materials (ASTM) Symposium on Air Quality and Comfort in Airliner Cabins, New Orleans, USA; October 1999. pp 27–28.
21. Wechsler D. Wechsler test of adult reading. San Antonio, TX: The Psychological Corporation; 2001.

22. Wechsler D. Wechsler adult intelligence scale. San Antonio, TX: The Psychological Corporation; 1977.
23. Coughlan AK, Hollows SE. The adult memory and information processing battery: Test manual. Leeds: Coughlan; 1985.
24. McKenna P, Warrington EK. The graded naming test: Manual. Windsor: NFER-Nelson; 1983.
25. Borkowski JD, Benton AL, Spreen O. Word fluency and brain damage. Neuropsychologia 1967;5:135–140.
26. Trenerry MR, Crosson B, DeBoe J, Leber WR. STROOP neuropsychological screening test manual. New York: Psychological Assessment Resources; 1998.
27. Benton AL, Sivan AB, des Hamsher K, Varney NR, Spreen O. Contributions to neuropsychological assessment. Oxford: University Press; 1994.
28. Snaith RP, Zigmund AS. The hospital anxiety and depression scale: Manual. Windsor: NFER-Nelson; 1983.
29. Holmes TH, Rahe RH. The social readjustment rating scale. J Psychosom Res 1967;11:213–215.