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A Study of Environmental Factors That Affect the Physical and Mental Health of Airline Pilots: A Systematic Review With Metasynthesis

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by
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Approval Page

This applied dissertation was submitted by Deborah Donnelly under the direction of the persons listed below. It was submitted to the Abraham S. Fischler College of Education and approved in partial fulfillment of the requirements for the degree of Doctor of Education at Nova Southeastern University.

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Abstract

A Study of Environmental Factors That Affect the Physical and Mental Health of Airline Pilots: A Systematic Review With Metasynthesis. Deborah Donnelly, 2018: Applied Dissertation, Nova Southeastern University, Abraham S. Fischler College of Education. Keywords: systematic review, airline pilot health, aircraft environmental factors, airplanes exposures air quality

The purpose of the systematic review of the literature was to compile and synthesize the research that had been conducted on the environmental factors that affect airline pilot health during their cockpit exposure. The purpose was also to compile research on the effects of these environmental factors. This study added onto the scarce body of research on airline pilots and the environmental factors that affect their health.

This research included published sources that were found through searching electronic databases such as ERIC, ProQuest Central, PubMed, Federal Aviation Administration, and Nova Google Scholar. The study used qualitative studies, along with government publications and reports, dissertations, and conference proceedings. In addition, scholarly journals, dissertations, and peer-reviewed articles were analyzed and synthesized. Inclusion criteria in this study included research in the area of airline pilots, environmental factors, cockpit environment, airline pilot health, pilots' physical and mental health, chemical exposures to airline crew, radiation exposures to airline pilots and crew, occupational diseases in airline pilots, fatigue, and elevated cancer incidences among airline pilots. Exclusion criteria for this study were studies that included only military pilots and only flight attendants.

The systematic review of the literature compiled studies that subjects participated in, but this study did not directly include research participants. A systematic interpretive procedure was used to analyze the literature. A preliminary search indicated that there were no systematic reviews on the environmental factors that affected the physical and mental health of airline pilots. There was also little research that had been conducted inside the actual cockpit of commercial airlines and on the airline pilots in the cockpit setting.

Research findings indicated that the environmental effects of the cockpit that could affect pilot health were numerous and pilots were not made aware of many of these risks. The findings from this systematic review and metasynthesis suggested that, in order to optimize airline pilot health and performance, pilots must possess the knowledge regarding these environmental factors that affect the cockpit environment in which they spend hundreds of hours a year and learn the preventative measures that could be taken to minimize their risks.

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Chapter 1: Introduction

Statement of the Problem

The environmental factors that affect the physical and mental health of airline pilots have not been well-characterized. There are approximately 70,000 airline pilots in the United States and 140,000 worldwide (U.S. Department of Labor, 2015). The population breakdown is approximately 96% male and 4% female (Women in Aviation International, 2013). Aviation growth is projected to double air traffic over the next 20 years to over 7.8 billion passengers (International Air Transport Association, 2017). Studies of airline pilot health had not assessed all the environmental factors or had limitations in doing so. The environmental factors in the cockpit that affect airline pilot health include air quality, chemicals, carbon dioxide (CO2), circadian rhythm disruption, fatigue, low humidity, noise, ozone, pressurization, and radiation. Each of these factors can contribute to various occupational health issues (Space, Johnson, Rankin, & Nagda, 2000). Previous studies, including from the National Research Council (NRC, 2002), The Airliner Cabin Environment and the Health of Passengers and Crew, and Hinninghofen and Enck (2006), associated exposures to environmental conditions with adverse effects on the health of crew and passengers. There is concern about pilots not reporting their health conditions or symptoms for fear of losing their flying privileges or not being deemed fit to fly (Parker, Stepp, & Snyder, 2001). Although flying is safe, in 2016, the number of accidents and incidents was remarkably low in comparison to past years (European Aviation Safety Agency [EASA], 2017). Federal regulatory bodies are on a continuous mission to improve flight safety.

There have been numerous changes in the airline industry in the past decade that have further complicated the occupational health risks associated with the position of airline pilots. In December 2007, in the United States, the mandatory retirement age of airline pilots was increased from age 60 to age 65. This law was signed into effect to match the International Civil Aviation Organization law, which was passed in November 2006 (Federal Aviation Administration, [FAA], 2007). With the introduction of larger, long-haul jets such as the Airbus A380, flight times can be as long as 18 hours (Airbus, 2016). This introduces the opportunity to increase occupational exposures such as circadian rhythm disruption (Jackson & Earl, 2006), cosmic radiation, noise, vibration, air contaminants, low pressure and humidity, and gravitational forces (Space et al., 2000). The increase of polar routings, fuel conservation efforts, and pilot scheduling have all contributed to the increase in environmental exposures to pilots.

Another aspect of airline pilot health that warranted more investigation is pilot mental health. The environmental factors that are part of the cockpit environment also influence and can affect the mental health of the pilot. The Germanwings crash in March of 2015 brought this sensitive subject into the aviation and mental health discussions. Since 1976, eight airline crashes were attributed to pilot mental health and suicide. All were fatal and destroyed the aircraft (Flight Safety Foundation, 2015).

Today, airline pilots can have longer tenure than any other generation of pilots in history. Longer tenure also provides a greater chance of exposure to occupational hazards caused from being in the cockpit environment for prolonged times. Such exposures as radiation and noise can be estimated by tenure for research purposes (Hammer, Zeeb, Tventen, & Blettner, 2000). However, airline pilots do not have any information or access to their exposure levels or data such as noise, radiation, or air quality. The FAA oversees and governs all health and safety protection for airline pilots. In the United States, most employed workers are protected by the Occupational Safety and Health

Administration (OSHA, 2000) regulations; airline pilots are one of the few exceptions. There is a memorandum of understanding between the agencies that has been in effect since 1975 and was recently updated in 2000, which allows both agencies to work together to achieve worker protection (OSHA, 2000).

Flight crews have demonstrated increased rates of certain cancer types such as melanoma and breast cancer (Hammer, Blettner, & Zeeb, 2009). The altitudes at which commercial jet aircraft fly are from 29,000 feet to 42,000 feet and expose flight crews to cosmic radiation levels that are hypothesized to be a cancer risk factor (El Ghissassi et al., 2009).

Flight crews are considered by the International Commission on Radiological Protection (ICRP, 1991) to be exposed occupationally to cosmic radiation. In the United States, the FAA (1994) published an advisory circular that formally recognized that flight crew members are occupationally exposed to cosmic radiation. In 2006, the FAA cancelled this advisory circular and replaced it by a subsequent 2006 advisory circular. The FAA (2014) stated that "the likelihood of developing cancer because of occupational exposure to galactic cosmic radiation is a small addition to health risks experienced by the general population" (p. 6). In the United States, there are no official radiation dose limits for flight crews. The European Union member states do have regulations for flight crew radiation exposure. These require adjustment of flight schedules to ensure that no individual exceeds 6 milliSievert (mSv) per year and assessment of exposure when exposure is likely to be > 1 mSv per year (European Radiation Dosimetry Group, 1996).

The Federal Air Regulations in the United States provide provisions for air quality levels on board commercial aircraft. The detection and reporting of any type of contaminated air can be difficult because there is no way for flight crews to measure it, and all reporting is subjective. It has been determined from previous research that contaminated air events are underreported (Michaelis & Winder, 2005). Contaminants in the cockpit of airliners are an occupational hazard. Among these contaminants are engine oil and hydraulic fluids that contain toxic and hazardous materials, which can have short- and long-term health effects when exposed to (Hewstone, 1994). Many complaints from crew members on board commercial aircraft have included irritated eyes, sore throat, sinus pain, and stuffy nose (Spengler & Wilson, 2003). The exposure of these contaminants can lead to aerotoxic syndrome, which has diverse symptoms ranging from nausea and breathing difficulties for short-term exposure to chest pain, fatigue, memory impairment, and numbness for long-term exposure (Balouet, 2000). There have been numerous complaints from crew members and passengers regarding the air quality and safety on board commercial aircraft. Since 1986, this has prompted Congress to request the NRC to study the air quality on board commercial aircraft. The NRC (as cited in Spengler & Wilson, 2003) issued two reports of its findings. The first one was in 1986, and the second one was in 2002.

Circadian rhythm disruption is another flight crew exposure that has been linked to cancer risk (Straif et al., 2007). The typical flying schedule of international flight crews requires flying across multiple time zones and working while their body clock is on rest time (Grajewski, Nguyen, Whelan, Cole, & Hein, 2003).

Need for Systematic Review

The impact of the environmental factors that affect the physical and mental health of airline pilots is not fully known. Despite the importance of this problem and the negative health effects on pilots, research is limited. There have been no systematic reviews published on the overall environmental effects from the cockpit environment and how an airline pilot's health is compromised. A current systematic review of the literature can contribute to the overall health improvements for airline pilots and the environment in which they work.

Audience

The health and well-being of airline pilots is a primary concern for safety in the airline industry. The cockpit environment is a unique environment that provides exposures to the pilots while on duty. If these exposures are negatively affecting pilot health, the results may also affect the safety and performance of pilots. These effects are not limited to, but may include, fatigue, headaches, diminished cognitive processing, and cancer. This metasynthesis has consolidated recent research evidence from many studies and, by doing so, has made the pilots, their unions, the airlines, and the aircraft manufacturers aware of these environmental effects in the cockpit and how they may negatively affect pilot health and performance.

Airlines and unions worldwide are involved in efforts in improve the health and safety of their pilots. Using research and data, they may be able to make informed decisions on these matters. Despite the limitations of many of these studies, the objectives of developing research to educate the pilots and stakeholders of these environmental exposures are not going unnoticed. Recently, many airlines have started to acknowledge the danger of aerotoxic syndrome from the fumes that pilots and flight crews may be exposed to and have created checklists in the event that fumes are smelled (Spirit Airlines Flight Attendants Association, 2018). The information provided by this systematic review provides current aviation health researchers with an in-depth understanding of the types of research studies that were conducted in this area of pilot occupational health as well as aids future scholars with the ability to reference these studies in a consolidated manner.

Significance of Review

Scholarly significance. The existence of studies that addressed a singular environmental factor in the cockpit environment do exist; however, there is a lack of systematic research on the overall effects on airline pilot health and the environmental factors that affect them. This systematic review of the literature reviews the literature to enhance the limited research on airline pilot health and the environmental factors in the cockpit that affect them.

Practical significance. The systematic review of the literature has informed aircraft manufacturers, airlines, airline pilot unions, the FAA, aviation safety groups, aircraft engineers, airline industry leaders, government and regulatory stakeholders, and researchers of the health risks associated with working in the cockpit environment due to the environmental factors that airline pilots are exposed to during their careers on a daily basis. Research is needed to help air crew and airline management better assess the short-term and long-term medical effects of the exposure risks from the occupational environmental factors in the cockpit environment. This research could be used to improve safety and enhance the working environment for current and future airline pilots.

Purpose of the Study

The purpose of this study was to compile and synthesize the research on the cockpit environmental factors that affect airline pilot health. Pilot performance is affected by many physical and mental aspects of the job as well as external factors that may influence performance (Wu et al., 2016). The systematic review of the literature will add to the scarce body of knowledge regarding airline pilot health and the working environment in the airplane cockpit. A broader analysis will identify the health and safety factors that are affected by the occupational hazards encountered by flight crew. This research study will add to the body of knowledge on airline pilot occupational exposures and health effects through the process of synthesizing and evaluating the research evidence from individual studies. The purpose was to also compile research on the short- and long-term occupational health affects for airline pilots. This study will allow the stakeholders to make informed decisions regarding the exposures and safety of the cockpit environment with regard to pilot health effects.

Definition of Terms

The following definitions are presented for clarifying the terms used in the systematic review of the literature.

Aerotoxic syndrome. This refers to aviation exposure to contaminants and toxicity, along with their symptoms.

Air carriers. This refers to the commercial system of air transportation makeup of domestic and international certified and charter services.

Airline transport pilot. This is the certificate that is required for an individual to act as pilot-in-command for a scheduled airline.

Attention. This is a state of focused awareness on a subset of the available perceptual information (Harris, 2011). Attention is not a unitary phenomenon; it can be subdivided using a commonly described taxonomy that includes selective, sustained, and divided components as well as information-processing speed and supervisory or executive aspects (McCullagh, & Feinstein, 2011).

Aviation medical examiner. This is a physician designated by the FAA and given the authority to perform airman physical examinations for the issuance of second-and third-class medical and student pilot certificates; senior examiners perform first-class airman examinations (FAA, 2018).

Aviation psychologist. This is a person who is concerned with pilot performance and reducing flight crew error. Psychology applied to aviation is an integrative field involving knowledge of just about all areas in psychology, including perception, attention, and cognition. Other areas of focus include memory and decision-making skills, pilot selection, cockpit designs, human-computer interaction, human factors design, program management, and human performance research (Flach, Feufel, Reynolds, Parker, & Kellogg, 2017).

Cognitive deficit. This is defined as a decrease in functional problem-solving skills as measured by a standardized assessment tool (Rath, Hradil, Litke, & Diller, 2011).

Crew resource management. This refers to skills known as human factors in flight that include broad areas such as situational awareness, decision making, communication, team building and leadership, and workload management. It is a multidisciplinary concept that draws from behavioral and social sciences, engineering, physiology, and psychology to optimize human performance and reduce human error (Helmreich & Foushee, 1993; U.S. NRC, 2011).

Executive function. This is associated with the prefrontal cortex and is defined as the set of cognitive processes necessary to complete goal-oriented, complex tasks (Ahmed & Miller, 2011; Frye & Zelazo, 1998; Lezak, Howieson, Loring, & Cox, 2005).

FAA. This is an independent agency of the U.S. Government that is charged with controlling the use of U.S. airspace to obtain the maximum efficiency and safety.

Flight crew member. This is a pilot certified for the safe operation of an aircraft.

First-class medical certificate. Under Title 14 of the Code of Federal Regulations (14 CFR) Part 1 and the Guide for Aviation Medical Examiners (as cited in FAA, 2018), this is defined as a medical certificate as acceptable evidence of physical fitness on a form prescribed by the administrator. The primary goal of the airman medical certification program is to protect not only those who would exercise the privileges of a pilot certificate but also air travelers and the general public (FAA, 2018).

Long-term memory. This is memory processes associated with the preservation of information for retrieval at any later time (Harris, 2011).

Senior aviation medical examiner. This is an aviation medical examiner delegated with the additional authority to accept applications and perform physical examinations necessary to determine qualifications for the issuance of first-class FAA Airman Medical Certificates (FAA, 2018).

Short-term memory. This is memory processes associated with preservation of recent experiences and with retrieval of information from long-term memory; short-term memory is of limited capacity and stores information for only a short length of time without rehearsal (Harris, 2011).

Situational awareness. This is a pilot's awareness of operational conditions and contingencies that include factors such as monitoring, vigilance, planning, and distraction avoidance (Helmreich & Foushee, 1993).

Chapter 2: Literature Review

Introduction

This chapter includes a review of prior research on the environmental factors that occur in the cockpit environment and could affect an airline pilot's health. A qualitative approach was used to assess existing literature on environmental factors in the cockpit environment through a systematic review. The following evaluation demonstrates a relationship between the environmental factors in the cockpit and the health effects on airline pilots through the systematic review of previous research. This review addresses the research questions if the cockpit environment can be hazardous to the airline pilot's overall health and how these issues are being addressed. This chapter identifies any connection by performing a review of over 30 studies from peer-reviewed journals, government documents, and dissertations on the environmental factors of the cockpit and airline pilot health issues. The results of this review showed the need for continued research in the method of a systematic review and meta-analysis of experimental research.

Radiation Exposure

Meta-analyses (Buja et al., 2006) and reviews (Hammer et al., 2000) of cancer studies among commercial flight crew showed the excess of breast cancer and had used data available from pilots such as logbooks, flight hours, and equipment flown. These estimates did not directly address cosmic radiation exposures incurred from solar particle events (Grajewski et al., 2011). Pilots' flight exposure to radiation have increased due to several factors found by Grajewski et al. (2011). These factors included more frequent polar routing, changes in flight crew duty limits and contracts, and efforts to decrease fuel consumption. Pilots were found to be exposed to cosmic radiation at altitudes that were over 100 times of that found at sea level (Oksanen, 1998). A major health concern for major airline pilots is the increase in the associated risk of fatal cancer from occupational exposure to cosmic radiation. Grajewski et al. (2011) also concluded that their study suggested that "there is a highly exposed group of airline pilots who may be at increased risk for the health effects of cosmic radiation and chronic circadian rhythm disruption compared to other pilots" (p. 473).

Grajewski et al. (2011) used the actual pilot logbooks, company records, and flight history questionnaires to determine that these 83 male pilots flew a median of 14,959 block hours over 27.8 years and crossed 362 time zones. They were, then, able to provide an exposure profile of this group of U.S. airline pilots and an estimated median dose of 1.92 mSv from cosmic radiation. Airline flying and military flying were the highest sources of exposure for the pilots in this study. This study was the first published assessment using actual flight segments and flight history questionnaires to assess radiation dose exposure and circadian rhythm disruption. Previous studies used estimated cosmic radiation exposure from information such as aircraft flown, routes, altitudes, and estimated flight hours. This assessment provided a more detailed level of exposure through actual flight hours and less recall bias by using the actual flight logbooks from the pilots. The pilot logbooks were also compared with the official company flight records and demonstrated accuracy.

Two primary exposures for flight crew, which are hypothesized as cancer risk factors, are cosmic radiation exposure and circadian rhythm disruption (International Agency for Research on Cancer [IARC], 2000). Cosmic radiation can also generate secondary and tertiary radiation by interacting with atmospheric molecules at aircraft altitudes typically flown above 30,000 feet. These molecules include neutrons, which have been classified as a Group I carcinogen by the IARC (as cited in IARC, 2000; El Ghissassi et al., 2009). The galactic cosmic radiation in the earth's polar regions is 2.5-5.0 times more intense than those areas close to the equator region (Bartlett, 1997). Data on the effects of low-dose ionic radiation are not so readily available (Sinclair, 1985).

Flight crews are classified by the ICRP (2008) to be high-risk radiation workers because they are occupationally exposed to cosmic radiation on a daily basis. Radiation doses are measured using the Sievert. Effective dose limits are recommended by the ICRP (2008) of 20 mSv per year for radiation workers (over a 5-year period) with no more than 50 mSv in a single year and 1 mSv per year for nonradiation workers. The ICRP (2008) guideline for pregnant female radiation workers is a recommended dose limit of 1 mSv. This limit is recommended from the declaration of the pregnancy until the end of the gestation period (ICRP, 2008). The "European Council Directive" (1996) estimated that the risk of genetic defects to an unborn child would significantly increase if the flight crew member was exposed to an average of 5 mSv annually and flew until their 7th month of pregnancy. The risk of genetic defects was estimated to increase to be nine in 10,000, as opposed to 600 in 10,000. The European Union (as cited in "European Council Directive," 1996) placed limits on pregnant female crew members flight time in order to limit this exposure level and minimize the risk of birth defects. The average exposure for flight crew has ranged from annual estimates of 0.2 to greater than 7.0 mSv per year for flight crews that average 600-1000 flying hours per year (Friedberg, Snyder, Faulkner, Darden, & O'Brien, 1992).

The FAA does not regulate or monitor any specific radiation dose limits for flight crews in the United States. In the past, the FAA (1994) published recommendations for flight crews and that they should be educated and informed on the associated health risks associated with their radiation exposure. The European Union monitors flight crew radiation exposures and will monitor pilot schedules when their estimated dose is estimated to be greater than 1 mSv per year. They will also adjust schedules to ensure that no pilot exceeds 6 mSv per year (European Radiation Dosimetry Group, 1996). The options that are available to monitor flight crew radiation doses are limited to using dosimetry to monitor crew members and also to use a predictive software for the estimated flight radiation dose (McCall, 2000). The FAA (2018) developed a software program called the CARI-7, which can calculate the effective dose of galactic cosmic radiation for an individual based on flight segments and altitudes.

Okasanen (1998) used estimated annual cosmic radiation doses for flight crews based on flight profiles and altitudes. The study used saved flight data from Finnair for 500 pilots and 1,500 cabin crew members. The study utilized the data from June 1, 1994, to May 31, 1995. It used all the aircraft types flown at Finnair, which included the MD-11, DC-10, Airbus, and MD-80 aircraft. Okasanen utilized these data to estimate the annual cosmic radiation doses for the crew members.

The results showed that the longer haul MD-11 pilots and pilots DC-10 received an estimated radiation dose greater than the other fleets. Both of these fleet types are utilized on the long range, international flights averaging 8-10 hours. However, the MD-11 pilots received the highest dose of 2.11 mSv in lieu of the average of the other fleets at 1.65 mSv; even the DC-10 estimated dose was lower at 1.57 mSv. The MD-11 fleet crew members also flew the lowest number of hours when compared to all fleets. Okasanen explained this by the fact that the MD-11 aircraft can reach the cruise altitude faster than the DC-10, thus, exposing the crew members to greater cosmic radiation. The pilots with the lowest estimated radiation dose were the short haul DC-9 pilots who also cruised at the lowest flight altitudes and had an estimated radiation dose of 1.34 mSv. This study used only estimated radiation doses and did not account for flight operations that did not reach the highest flight levels on their routes due to external factors such as weather, traffic, or fuel efficiency. The results of this study may be higher than the actual radiation doses received due to these factors.

Bagshaw (2008) found no conclusive evidence that indicates airline pilots or crew members showed an increased probability in suffering from disease due to exposure of cosmic radiation. Bagshaw reviewed data available on cosmic radiation and aviation exposure. A British Airways flight crew mortality study, which was conducted by Irvine and Davies (1999), evaluated male pilots from 1952-1999. The study evaluated 6,209 male pilots and 1,153 male flight engineers who were employed at British Airways for at least 1 year during the study's time period. Irvine and Davies accounted for long haul in lieu of short haul pilots. The study used a Standardized Mortality Ration using England and Wales as the comparison. The study found that, over a 20-year career, the likelihood of developing cancer due to the cosmic radiation exposure was 0.4%, and, over a 30-year career, it was 0.6%.

This study hypothesized that 23.0% of the population in the western world will be exposed and die from some type of cancer, so the increase from being exposed to galactic cosmic radiation would not increase the overall death rate by a significant amount. However, the study did find that rates of melanoma were significantly raised in pilots in comparison to the general population and the absence in melanoma rates in the flight engineer population. This may be attributed to the nondirect sunlight exposure that the flight engineers received in comparison to the pilots. Irvine and Davies concluded that the flight deck crew had a longer life span than the general population and they did not demonstrate any patterns of death attributed to their occupation as flight crew members.

Bleed Air

Cabin air contamination by lubricants and hydraulics is a problem that has been a major issue affecting air quality in airplanes for several decades. It began in 1953 when the U.S. Aeromedical Association (as cited in Committee of Aviation Toxicology, Aeromedical Association, 1953) first expressed their concern about the risks associated with these contaminants. Heated engine oil and hydraulic fluid have the potential to contaminate the air supply inside the cockpit and cabin through aircraft design and operation (Kayser, 1953).

Contaminants present in cabin air include carbon monoxide, CO2, ozone, volatile and semivolatile organic compounds, and additional airborne particles (Day, 2015). Volatile and semivolatile organic compounds are a hazard to crewmembers because they are found in vapors in the cockpit and cabin air. These are chemical compounds that are components of engine oil, hydraulic fluids, and deicing fluids. By applying heat or reducing pressure, these compounds are volatized and form a vapor (Day, 2015).

Unfiltered bleed air on commercial aircraft has been the cause of numerous health issues reported by flight crews (Michaelis & Winder, 2005). Ventilation systems on commercial aircraft are supplied by bleed air. Recently, the only exception to this is the Boeing 787, which uses a bleed-free system with electrical compressors. These electric compressors use dedicated air inlets to direct the outside air into the cabin. The fuel efficiency is also increased by using the electric compressor in lieu of bleed air. Boeing (2011) estimated that fuel consumption can be reduced by 1% to 2%. This decision from Boeing (as cited in Harrington & Alaimo, 2016) to eliminate the use of bleed air in their newest aircraft model demonstrates to the industry that an alternative design is available.

Engine bleed air comes from the engine compressor sections, either the high pressure or low pressure. Bleed air is outside air cycled through the compressor stage of an engine. The temperatures in this stage can exceed 500 degrees Celsius (van Netten, 2000). Approximately one half of the air coming into the aircraft is recycled through the environmental control system (Spengler & Wilson, 2003). Noxious compounds are also produced when contaminants leak and are exposed to these high temperatures (Spengler & Wilson, 2003). Bleed air is used for air conditioning, including cabin and cockpit ventilation and pressurization. The bleed air can also come from the Auxiliary Power Unit, which is a small engine used primarily during ground operations for air conditioning operation. The exhaust that is drawn into the aircraft cabin and cockpit is the cause of the fumes from the Auxiliary Power Unit, along with oil leakage (van Netten, 1998). Jet engine oil and hydraulic fluids can contaminate the ventilation system and the cabin air because they contain various ingredients that may be toxic. They can leak through seals, maintenance, or operation (van Netten, 2000). According to Kayser (1953), this problem has been acknowledged since 1953 when the Committee on Aviation Toxicology of the Aero Medical Association stated that the potential for "toxic substances to arise in personnel compartments of an airplane (supplied with bleed air) from such sources as oil . . . and hydraulic fluids" (p. 1).

Jet engine oils can contain up to 3% tricresyl phosphate (TCP), including 0.01% of the neurotoxic ortho isomer, tricresylortho phosphate (TOCP), which has been linked to causing Organophosphate Induced Delayed Neuropathy (Hewstone, 1994). In hydraulic fluid, this isomer can be up to 1%. TOCP can also be hazardous to the skin and eyes, if contact is made directly. Inhaling TOCP above the recommended National Institute of Occupational Safety and Health concentration over 10 hours of 0.1 milligram per cubic meter of air can cause nervous system damage (as cited in Eaton & Klaasen, 2001).

TCP-mixed esters is a chemical that is added to jet engine oil and hydraulic fluid for its antiwear properties to increase load-bearing capabilities. Chemical analysis have confirmed the presence of TCPs at ambient and elevated temperatures (van Netten, 2000). Winder and Balouet (2002) stated that the mixture of compounds in commercial grade TCP is known to have neurotoxic effects. Symptoms of contamination include headaches, lack of concentration, confusion, vertigo, lethargy, and drowsiness (Eyer, 1995). These symptoms are typical of organophosphate-induced delayed neuotoxicity. The World Health Organization (as cited in Mackerer, Barth, Krueger, Chawla, & Roy, 1999) reported that over 60,000 people around the world have been poisoned from TCP, most prevalent from food exposure and occupational hazards. These symptoms are typical of Organophosphate Induced Delayed Neuropathy. More recently, chronic exposure to organophosphates has led to a distinct condition of Chronic Organophosphate Neuropsychological Disorder (Jamal, 1997). Individuals with single or short-term exposures, demonstrating symptoms leading to toxicity, may exhibit Chronic Organophosphate Neuropsychological Disorder as well as individuals with long-term, low-level, repeated exposure, sometimes exhibiting little or no symptoms of toxicity (Steeland, 1996). Additional long-term effects, which are defined as effects lasting longer than 1 year, can include multiple chemical sensitivity (Winder, 2000). Altitude also impacts the effects of exposure to these toxins. This is due to the fact that, as cabin altitude increases, the actual amount of oxygen in the air decreases. This lowered oxygen also changes sensitivity to toxic exposures (Winder & Balouet, 2002).

Centers (1992) also found the potential generation of an additional neurotoxin, trimethyl propane phosphate, that is produced in temperatures from 350-650 degrees Celsius from TCP and trimethylolpropane esters (van Netten, 2000). The results of these contaminants into the ventilation system of aircraft cabins have led to numerous air quality incidents that have been reported to the Aviation Safety Reporting System. The reports included symptoms of dizziness, nausea, confusion, disorientation, swollen lymph glands, headache, blurred vision, vomiting, and loss of energy. Cox and Michaelis (2002) reported on the symptoms of an Australian air crew flying the BAe 146 aircraft, which had a documented history of experiencing oil leaks and contaminating crew and passenger air supply. The pilots and flight crew experienced symptoms, including chronic fatigue; headaches; neuropsychological impairment; eye, skin, and upper airway irritation; and muscle and joint pain.

In 1998, van Netten conducted a study that involved five aircraft, including four BAe 146 aircraft, manufactured by British Aerospace, and one de Havilland Dash 8-100. Two BAe aircraft had a history of air quality issues from the previous days, and one BAe aircraft was equipped with a special charcoal filter, which was experimental. This study confirmed that the leaking oil seals was a leading cause of the air quality issues and adverse health effects (van Netten, 1998). This study also concluded from flight crew that there were short-term health effects associated with the air quality issues. These symptoms were found over a 4-month period and included sore throats, eye irritation, nasal congestion, and disorientation. The symptoms lasted 24 hours or less. This study was not able to show any long-term health effects, and no follow-up was conducted on the crew members after the 4 months (van Netten, 1998).

Muraswski and Supplee (2008) attempted to address the gap in reporting data available through data collection over an 18-month period by an industrial hygienist. The dates of the reports collected ranged from January 2006 through June 2007. The sources were limited as to where reports were filed regarding air contamination in the airlines. The data gathered for this study were from the following sources: FAA records of Service Difficulty Reports (SDR) and Incident Data System reports, flight attendant documented incidents through the representative labor union reports, and research articles through journals and newspapers. The results were also reviewed by a qualified airline mechanic to determine eligibility for this study. Their findings included 470 air supply contamination reports over an 18-month period in U.S. commercial airlines. This amount averaged 0.86 events per day and included 350 incidents that were officially reported to the FAA.

There is a lack of exposure data due to the fact that there are no commercial aircraft currently flying that have any form of detection system or monitoring the air quality for contaminants. There are also challenges in capturing these events because the irregularity of them, and there are sometimes low-level contamination that is difficult to detect. There are limited records of exposure data, which can estimate the frequency of air supply contamination events involving engine oil and hydraulic fluid (Murawski & Supplee, 2008). The airlines have not studied or assessed the impact of inhalation exposure on flight crews, despite the acute and chronic neurological symptoms that have been recognized (Abou-Donia, 2003). The aircraft manufacturers also claim that the levels of fume mist are experienced on an infrequent basis and are not harmful to crew or passengers (Aochido, 2002). The U.S. Congress had directed the FAA to commission the NRC to study the problem of air quality and the health effects of crew members and passengers on aircraft. This study was commissioned in 1986 and 2002 in which reports regarding air quality and health implications, including fumes from the breakdowns of oils and hydraulics, were published (NRC, 1986, 2002). Changes were made following the 2002 National Academy of Sciences report (as cited in NRC, 2002). These mandates by Congress to the FAA included monitoring ozone levels on a sample of flights to ensure the levels were within regulations, collecting information on pesticide exposures, measuring samples from ventilation ducts on aircraft that had reported air quality incidents, studying cabin pressure and altitude effects, and creating an air quality issue reporting system (NRC, 2002).

Resulting from the previous studies, the FAA created the National Center of Excellence for Airliner Cabin Environment Research (2004). In 2007, its name was changed to the National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment. This new group collaborated with airlines and government, academic, and industry organizations to bring the airline cabin environment experts together. The National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment has collaborated with the U.S. Air Force, the National Aeronautics and Space Administration, and the FAA (as cited in Hunter, Lekki, & Simon, 2014).

The FAA oversees the design of air conditioning systems, and, at the time of manufacture, they should allow crewmembers the ability to work and complete their tasks without any distress or fatigue. They are also designed to provide comfort to the passengers (FAA, 2018) and that the air be clean and uncontaminated of any dangerous concentrations of vapor or gases (FAA, 2018). There is also a lack of crew training and awareness of the symptoms and consequences of contaminated cabin air. There are reports and data to support the fact that contaminated air events are occurring and can potentially affect flight safety by causing short- and long-term adverse health consequences. Pilots are required to document any maintenance irregularity, which include smoke and fume events, in the aircraft logbook per FAA (2018) regulations. The FAA does not make these data available to the public.

In the United States, the FAA (2018) also requires all commercial airlines that operate under Part 121 or Part 135 to submit a report called a SDR for each time an aircraft mechanical problem causes smoke, fumes, or vapor to pass through or accumulate in the cockpit or passenger cabin during flight. The airlines must also submit a SDR report to the FAA if flight safety is or may be endangered due to any mechanical failure, malfunction, or defect (FAA, 2018) and also a Mechanical Interruption Summary Report for each time a flight has an unplanned destination change due to a mechanical malfunction. These are the mechanical difficulties that are not required to be reported under the regulations (FAA 2018). The U.S. airlines are also required to report to the FAA's Incident Data System any type of mechanical malfunction other than an aircraft accident that directly affects the safety of flight or has the possibility to affect the safety of flight (FAA, 2018). An additional report to the National Transportation Safety Board must be made immediately of an incident that results in any pilot or flight engineer not being able to perform their job function due to being injured or ill although the official definition of flight crewmember does not include flight attendants (FAA, 2018).

Further research into this area is recommended, along with implementing a monitoring system into the ventilation systems of commercial aircraft. Until an industry standard monitoring system is in place, it will be difficult to determine the levels of toxins that flight crews are exposed to through fume events and other sources (Harrington & Alaimo, 2016). To determine the exact risk of engine lubricant fumes in the aircraft cabin, more incident data, exposure studies, and toxicity studies are needed (Spengler &

Wilson, 2003). The National Academy of Sciences (as cited in NRC, 1986) also expressed the need for additional research in the area of aircraft cabin and cockpit air quality and stated that evidence exists that this area is in need of additional quality scientific studies to measure the quality of air inside the aircraft and the health effects due to short- and long-term exposures.

There have been technologies considered to help the contamination such as catalytic converters, disposable carbon absorbent filters, high temperature particulate filters, photocatalytic oxidation, and nonthermal plasma oxidation; however, none have been implemented to date (Bull & Yeomans, 2007). A continuous monitoring system to identify chemical compounds that are identified with cabin air contamination, providing immediate feedback to the crew, would also be a preventative measure (American Society of Heating, Refrigeration, and Air Conditioning Engineers [ASHRAE], Inc., 2007). Another way to eliminate the TCP exposure through engine oils would be to use lubricants that do not contain the antiwear agents that contain TCP. One, called Turbonycoil 600, has been developed by the French manufacturer NYCO. It is currently being tested to determine the toxicity of the alternative phosphate that it contains (Harrington & Alaimo, 2016). Improved filtration, disinfection, or advanced air cleaning may be difficult for all airlines to install due to cost. However, it may also be cost-effective if the results provided reduced maintenance costs over the long-term (Spengler & Wilson, 2003).

Ozone

Ozone exposure is a health concern for airline crew members and passengers. The aircraft cockpit and cabin is a unique environment where crew members are confined in an enclosed area for hours at a time while breathing a mix of recycled air and fresh air drawn in from the aircraft engines. At an airline's typical cruise altitude between 33,000 feet to 39,000 feet, which is in the upper troposphere, the risk of ozone exposure is high due to the high levels of ozone concentration at these altitudes. Ozone enters the inside of the cockpit and cabin from the outside, which results in elevated ozone levels being breathed in by crew and passengers. Weisel, Weschler, Mohan, Vallarino, and Spengler (2013) found that ozone levels that were measured on 52 transcontinental flights without catalytic converters between 2008 and 2010 exceeded 100 parts per billion (ppb). The newer aircraft with the catalytic converters installed had a reduced amount of ozone concentrations. The catalyst can convert 95% of the ozone entering into oxygen when it is new. The useful life of the catalyst is 12,000 flight hours where, at this time, it is only 60% efficient in converting the ozone into oxygen (Hunt, Reid, Space, & Tilton, 1995). There are still tens of thousands of aircraft flying where only approximately 10% of the fleets have the catalytic converters installed. These include the Boeing 757, 737, 767 series and MD-80 aircraft. The only fleet that is currently at 100% equipped with the catalytic converters is the Boeing 777 (Spengler & Wilson, 2003).

Chemical reactions associated with ozone and the human skin form by-products, which can be even more damaging than the ozone itself (Wisthaler et al., 2005). There are significant health concerns associated with ozone exposure as a chemical agent (U.S. Environmental Protection Agency [U.S. EPA], 2006). Among these health concerns are respiratory problems that include asthma, hyper-responsiveness, and inflammation (U.S. EPA, 2006). Ozone exposure is also linked to cardiovascular morbidity (U.S. EPA, 2006) and an increase in one's mortality risk (Bell, Peng, & Dominici, 2006). Detels et al. (1987, 1991) found that chronic exposure to ozone has been associated with lower lung function. Koren (1995) found that asthmatic symptoms have been exasperated by exposure to chronic ozone.

The FAA (2018) imposed regulations that limit the cabin ozone concentrations anytime above 32,000 feet to an ozone concentration of 250 ppb, sea level equivalent, or to 100 ppb during any 3-hour interval above 27,000 feet. The U.S. EPA's (1996) short-term National Ambient Air Quality Standard is 120 ppb. Various studies showed that ozone levels have exceeded the 100 pbb limit. Spenger, Ludwig, and Weker (2004) found that 20% of 106 flights that were measured exceeded this limit. After 1985, in response to the Federal Air Regulations that addressed the ozone concentrations, catalytic converters were installed into the environmental control systems of some aircraft and the newer models such as the Boeing 777 (Wiesel et al., 2013). There are significant limitations to measuring the ozone levels during flight, including expense and feasibility (Rai & Chen, 2012). Many studies utilized cabin mockups and simulations to study ozone levels and reactive chemistry (Wisthaler et al., 2005).

Rai and Chen (2012) developed a study that used a computational fluid dynamics model to simulate the distribution of ozone in an aircraft cabin mockup. This study simulated the ozone distribution in five different scenarios. These included an empty aircraft cabin, an aircraft cabin with seats, an aircraft cabin with soiled clothing, an aircraft cabin occupied with simple human geometry, and an aircraft cabin with detailed human geometry. Rai and Chen concluded that the ozone retention rates found were lower than the FAA recommended number, which indicated an increased risk from associated by-products.

Noise

Pilots are exposed to noise on a daily basis as part of their jobs. In addition to damaging hearing, research by Van Kempen et al. (2002) showed a possible connection between noise and hypertension. Hearing loss caused by possible relationships between noise and high blood pressure was also researched by Sokas et al. (1995). The variability of noise in the aircraft cockpit and the cabin and the full range of health effects are poorly understood. Inside the aircraft, the exposures are sustained for an extended period of time, up to 17 hours on some long-haul flights. The engine noise generated from the propulsion system and the airframe noise are the primary sources of aircraft noise, and the dominant source will vary depending on aircraft design (NRC, 2010). Aircraft cabin and cockpit noise were studied and included noise-induced hearing loss (Basner et al., 2013). Orsello, Moore, and Reese (2013) showed an increased prevalence of noise-induced hearing loss among military pilots. Although noise standards for aircraft certification have become more stringent, they have led to the development of engines with lower noise emissions (Martens, 2002).

Noise exposure has also been associated with numerous additional health problems, including affecting cognitive functioning, mental health, and cardiovascular effect in aviation occupations (Haskell, 1975; Munzel, Gori, Babisch, & Basner, 2014). Tomei et al. (2005) studied over 300 pilots in Italy and found that chronic exposure to noise was a risk factor for hypertension in pilots exposed to high noise levels. This association of noise exposure with fatigue and hearing loss could also have important implications for the safety of air travel. McNeely et al. (2014) studied flight attendant health effects and found a higher prevalence of sleep disorders, cardiovascular disease, depression, and fatigue compared to the general population. Some of these may be associated with environmental conditions in the aircraft cabin, including noise.

Occupational noise in the aircraft is not regulated and, therefore, not monitored or measured (OSHA, 2014). OSHA's general industry standards for noise exposure (as cited in FAA, 2014) specified a permissible exposure limit of 90 dB(A), a maximum of 115 dB(A) for continuous exposures of less than 15-min duration, and 140 dB(A) peak exposure limit for impulsive noise. Studies should be performed to document airline pilot noise exposures. Combining exposure assessment studies with health condition surveys would improve the level of understanding of the effects of noise exposures on airline pilot health and the development of interventions or preventions in the cockpit. Additional research is also needed on the additional health effects of noise, including cardiovascular effects. Noise exposure in the cockpit environment is poorly understood but may have important implications for the health and well-being of flight crews, especially in combination with other stresses, environmental conditions, or existing health conditions.

Pressurization

In a commercial aircraft, cabin pressure can change rapidly. This change takes the cockpit and cabin from an altitude of sea level up to 8,000 ft, which is standard on most commercial jet flights traveling at 37,000 feet. There are some health complications associated with this pressure change. As the pressure is reduced, the gas inside the body also expands. This causes minor discomfort, ranging from severe pain in the middle ear to infants and those traveling with colds or sinus infections (Spengler & Wilson, 2003).

CO2

Pilots are exposed to various air pollutants on the flight deck that can affect air quality (Beko, Allen, Weschler, Vallarino, & Spengler, 2015). CO2 is a by-product of metabolism (Nattie, 1999). CO2 levels are found to be elevated while the aircraft is on the ground boarding and before takeoff (Spengler & Wilson, 2003). This is due to lower ventilation rates while the aircraft engines are not running. In a study that was conducted in 2012, Spengler Vallerino, McNeely, Estephan, and Sumner researched domestic and international commercial airline flights and the cabin air quality. During 83 flights that were monitored, their study showed that CO_2 levels between 1,404 (+/- 297) parts per million (ppm) with a range of 492 ppm to 3,454 ppm.

Previous studies showed significant physiological effects at CO_2 levels higher than 1,000 ppm (Sechzer et al., 1960; Sliwka, Krasney, Simon, Schmidt, & Noth, 1996). These included increased heart rate, blood pressure, respiratory rate, and headaches. In 1999, Lee, Poon, Li, and Luk conducted a study that included 16 flights and found substantially higher concentrations of CO_2 during boarding and deplaning than during cruise. The mean reported CO_2 concentrations ranged from 629 to 1,097 ppm, and the maximum concentrations ranged from 1,347 ppm to 4,725 ppm. During boarding and deplaning, Lee et al. found typical concentrations to be between 2,000 ppm and 2,500 ppm. This could have been attributed to a low fresh air supply. In 2002, Lindgren and Norback found even greater effects, including higher CO_2 concentrations during boarding and noncruise flights. The range of CO_2 concentrations was from 694 ppm to 3,686 ppm during noncruise conditions. This was attributed to restricted air exchange (Lindgren & Norback, 2002). Thom, Bhopale, Hu, and Yang (2017) studied the response of mice to elevated levels of CO_2 and found that mice that were exposed to levels of CO_2 at 2,000 ppm for 2 hours exhibited vascular leak in brain and muscles. They concluded that these elevated levels of CO_2 could harm tissue and cause organ damage due to circulating proinflammatory microparticles.

Satish et al. (2012) evaluated CO_2 exposure on nine scales of decision-making performance, including basic activity, applied activity, focused activity, task orientation, initiative, information search, information usage, breadth of approach, and basic strategy.

In this study, 22 participants were exposed for 2.5 hours each to three different CO_2 levels. These levels were 600 ppm, 1,000 ppm, and 2,500 ppm. During this study, participants completed standardized tests that measured decision-making performance and cognitive functioning. At a CO_2 level of 1,000 ppm, Satish et al. found six of the nine scales showed statistically significant decrements in decision-making skills when compared to the 600 ppm concentration levels.

In the United States, the ventilation in aircraft is governed by the FAA and its regulations. Ventilation is the main component for controlling the concentration of CO_2 and other pollutants inside aircraft. The Federal Aviation Regulation (FAR; as cited in FAA, 2018) mandated that the cabin ventilation system must provide at least 0.55 lb of fresh air for each passenger per minute. This is equivalent to a steady CO_2 level of 1,460 ppm. In conjunction with this regulation is also a part of FAR, Part 25 (as cited in FAA, 2018) that specifies that crew members must be able to perform their duties without undue discomfort or fatigue. A 2002 NRC report suggested that these FARs may not be sufficient to protect the health and well-being of flight crew members and passengers. A recommendation from the 1986 NRC study was made to reduce the CO_2 standard from 30,000 ppm to 5,000 ppm. In addition to the FAA, the ASHRAE, Inc. (2007) issued a standard for specifying requirements for air quality within commercial aircraft. This ASHRAE, Inc. standard specified that, based on a steady state CO_2 level of 1,830 ppm, the minimum outside air ventilation rate is 3.5 L/s/p. The OSHA (2014) also specified a recommended exposure limit over 8 hours at 5,000 ppm. The National Institute of Occupational Safety and Health (1993) also had a recommended 8-hour exposure limit of 5,000 ppm.

The aircraft are manufactured to meet these initial standards; however, monitoring is rare, and these regulations are difficult to enforce. The FAA does not monitor or enforce these regulations because it certifies performance based on only the initial engineering design of the aircraft, which is designed to meet these standards. The CO2 concentrations that are in excess of FAA standards may be the result of operational factors for a particular flight. There are few studies that measured actual CO2 on board an aircraft in the cockpit during flight, and, therefore, more research is needed.

The EASA study from March 2017 measured flight deck air quality measurements from the cockpit of 69 commercial flights. The aircraft included eight Boeing 787 aircraft and 61 additional types of aircraft (EASA, 2017). A National Institute of Occupational Safety and Health (1993) survey had measured CO2 inflight levels, ranging from 874 ppm to 2,328 ppm, with the highest measurements exceeding 4,000 ppm for 5-min concentrations (Waters, Bloom, Grajewski, & Deddens, 2002).

Regulations

The FAA regulations with regard to air supply contamination are limited and are very difficult to enforce due to the fact that they are based upon interpretation. FAA (2018) implied that the air must be clean of contamination, including dangerous vapors or gasses, and stated that aircraft systems must be designed at time of manufacture to allow crew members the ability to work and complete their tasks without any distress or fatigue. They are also designed to provide passenger comfort (FAA, 2018). The regulations are subjective and are designed to require a clean air supply; however, there is no way to measure the air quality or contaminants in the aircraft. The FAA ventilation requirements depend on the date the aircraft manufacturer requests FAA approval. Therefore, older aircraft models may be in compliance although their aircraft do not meet current standards. They do meet the standards that were applicable at the time of their certification.

Additional Occupational Health Risks

In addition to the above cockpit exposures that can negatively affect pilot health, there are other factors that must be considered that are unique to the airline pilots' occupation. International pilots also experience frequent circadian rhythm disruption, and this also is a factor for cargo pilots who fly primarily on night flights (i.e., during their normal sleep hours; Grajewski et al., 2003).

Sancar et al. (2010) found that the molecular circadian clock also modulates cellular response to DNA repair. From studies on flight attendants, Straif et al. (2007) found that IARC has classified shift work that involves circadian rhythm disruption as Group 11A. This signifies that it is probably carcinogenic to humans (IARC, 2000).

Allen et al. (2013) found that exposure to flame retardant chemicals that are used in the materials inside aircraft, including seats and carpets, may contain known carcinogens such as tris(1, 3-dichloro-isopropyl)-phosphate. During November and December 2010, dust samples were collected on 19 aircraft, including aircraft manufactured by Boeing, Airbus, Embraer, McDonnell Douglas, and Canadair Regional. Samples were collected from the air vents and the airplane carpets. The study showed that most flame retardants, including tris(1, 3-dichloro-isopropyl)-phosphate, was found in 100% of all the dust samples (Allen et al., 2013). This is another area of crew member environmental health that needs to be researched for exposure and long-term health effects.

Research Questions

The following research questions were used to answer this meta-analysis:

1. How do the environmental conditions of the cockpit affect the pilot's health,

and what measures can be taken under the current regulations to improve these conditions?

2. How can airlines, aircraft manufacturers, and pilot unions benefit from additional research into the environmental factors that affect pilot health and make improvements?

Chapter 3: Methodology

Introduction

A systematic review and metasynthesis was conducted to identify and compile a review of prior research on the environmental factors that occur in the cockpit environment and can affect an airline pilot's health. Chapter 3 describes the methods and procedures that were used to guide this research study. The protocols of this study were to follow rigorous research methods and the guidelines by the Campbell Collaboration for systematic reviews and metasynthesis (as cited in LaForest, 2013). The purpose of a systematic review is to "find, evaluate, and synthesize the results of relevant research" (Campbell Collaboration, n.d.b, What is a systematic review section, para. 2). This systematic review of the literature identifies, evaluates, and synthesizes the environmental factors that affect the physical and mental health of airline pilots.

The research questions are as follows:

1. How do the environmental conditions of the cockpit affect the pilot's health, and what measures can be taken under the current regulations to improve these conditions?

2. How can airlines, aircraft manufacturers, and pilot unions benefit from additional research into the environmental factors that affect pilot health and make improvements?

The research questions presented were explored in a systematic review and metasynthesis of studies from 1994 to 2017. A systematic review and metasynthesis method was used for the following reasons:

1. According to Higgins and Green (2006), the systematic review method is a transparent process that limits bias and reduces chance effects, which lead to a more

reliable result.

2. A systematic review is approached with the same level of rigor as those who conduct primary research (Uttley, & Montgomery, 2017).

3. According to Maynard (2010), a well-defined process of a systematic review allows for the review to be replicated by other reviewers who want to add current studies as new data become available.

Erwin, Brotherson, and Summers (2011) discussed that qualitative research studies have multiplied in number in recent years and the metasynthesis offers an opportunity to bridge the knowledge base and contribute with deeper insights to the research. In addition, a systematic review requires a well-defined process for searching and selecting studies included in the review as well as for coding and analyzing data found in the studies.

During the empirical research, this systematic review has gone through a process of synthesizing, integrating, and interpreting selected sets of scholarly works related to the environmental effects found in the cockpit and how airline pilot health is affected. This study used the research methodology of a systematic review and metasynthesis (Campbell Collaboration, n.d.a; Saini & Shlonsky, 2012). The term *metasynthesis* refers to the synthesis of studies across multiple qualitative reports to create a new interpretation (Finfgeld, 2003; Saini & Shlonsky, 2012).

In addition to the guidance from the Campbell Collaboration (n.d.a), the Preferred Reporting Items for Systematic Reviews and Meta-Syntheses (PRISMA) Checklist (as cited in Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, 2010) was used as guidelines for this systematic review. The PRISMA Checklist is also used for critical appraisal of a published systematic review and as a basis for reporting systematic reviews of other types of research such as evaluations. The PRIMSA Checklist is an evidence-based, detailed list of items that provides guidance and clarity for conducting systematic reviews. The PRISMA Checklist can be found in Appendix A.

Study Protocol and Design

The Campbell Collaboration (n.d.a) stated that a systematic review requires a detailed protocol to uphold the standards of the Campbell Collaboration. The protocol of this systematic review includes the following components: informational sources, inclusion criteria, and exclusion criteria (LaForest, 2013). The Campbell Collaboration (n.d.a) also recommend the development of inclusion and exclusion criteria in the first step of development of a systematic review. The systematic review also composes the guidelines of participants, interventions, comparisons, outcomes, and study design. The procedures included gathering information sources, evaluating search strategies, studying selection processes, analyzing data-collection processes, and examining data-analyses procedures (LaForest, 2013).

Procedures

A systematic interpretive procedure was used to analyze the literature (LaForest, 2013). The researcher read and analyzed the studies to identify the (a) study design, (b) sample, (c) procedures, (d) data-collection methods, (e) data-analysis methods, (f) findings and conclusions, and (g) methodological quality (Zief, Lauver, & Maynard, 2006). The research findings were, then, analyzed for methodological quality (LaForest, 2013). The topic of this systematic review was reviewed for the relevance of the cockpit environmental factors that could affect an airline pilot's health.

Inclusion and Exclusion Criteria

The criteria of the Campbell Collaboration (n.d.b) for inclusion and exclusion criteria involve well-defined information to be specified in regard to the research studies being explored. These criteria guided the study and the type and quality of studies that were included in this systematic review.

Inclusion criteria. The protocol of this systematic review included studies guided by the specific research questions. The protocol of this study included research in the area of (a) cockpit environmental factors; (b) airline pilot health; (c) preventative measures for the cockpit environment; (d) regulations that govern the cockpit environment; (e) aircraft systems that affect the cockpit environment; (f) high-level radiation and its health effects; (g) ozone and its health effects; (h) bleed air and its health effects; (i) air quality in aircraft; (j) noise exposure and its health effects; (k) CO2 exposure and its health effects; (l) pressurization and altitude effects on health; (m) pilot medical certification; (n) cancer probability and airline pilots; (o) aerotoxic syndrome; (p) unpublished studies found in government reports, dissertations, and conference proceedings; (q) studies conducted between 1994 to 2016; and (r) studies found in published peer review journals. The protocol of this study included research synthesis in the area of cockpit environmental factors and how they could affect pilot health and effective strategies for improving and preventing these conditions.

Exclusion criteria. Studies that did not align with the research questions in this study were excluded (LaForest, 2013). The exclusion criteria studies were (a) conducted prior to 1990, (b) conducted with airline pilot participants with no indication of subgroup, and (c) conducted with pilots who were not airline pilots or flying transport category aircraft.

Information Sources

The following are informational sources that were used in this study:

1. Databases. This research included published and unpublished sources that were found through searching electronic databases (i.e., ERIC, ProQuest Central, Pub Med, Google Scholar, and the FAA).

2. Relevant journals. The systematic review also included relevant journals in the field of environmental studies, aviation, and medicine. These searches included the following journals: *Journal of Exposure Science and Environmental Epidemiology, Occupational Medicine, and Environmental Science and Technology*.

The Selection Process

The first step of the selection process was the analysis of the titles of the studies that were collected. The second step consisted of reading the abstract and introduction of the studies to identify the relevance of the research topic. Then, the following tools were used to analyze if the studies met criteria for the systematic review: the Critical Appraisal Skills Program (CASP) Assessment Tool, PRISMA, and the Data-Extraction Form (see Appendix B). Finally, the full text of studies that met the inclusion criteria was read and analyzed.

Participants

The participants in this systematic review were the participants from the individual studies that the review examined, synthesized, and evaluated (LaForest, 2013). The participants in these studies included current airline pilots, retired airline pilots, and former airline pilots. The focus of this systematic review of the literature was research on the topic of interest, and, as a consequence, no human subjects were participants in this study or affected by it.

Data-Collection Tools

The data-collection process included using a data-extraction form that was used to collect data from each individual study. This was completed after all studies were reviewed and the relevant studies were separated from those that were excluded. The data-extraction form included separate areas that recorded detailed information from each individual study. The form used a number system to organize and code the data. This form was modified from Sandelowski and Barroso (2007). The first number refers to a broad category of study (1 represents radiation, 2 represents bleed air, etc.). The second number refers to study design (1 represents qualitative). The third number refers to the source of the data (1 represents journal, 2 represents book, 3 represents thesis, 4 represents dissertation, 5 represents report, and 6 represents all other sources). The fourth number refers to the type of sampling (1 represents random, 2 represents convenience, 3 represents purposeful, and 4 represents not reported). The fifth number represents sample size (1 represents small, 2 represents medium, and 3 represents large; Stock, 1994).

The validity and quality of each study was also measured. The design features of each study and if they minimized biases were assessed. Also, the types of instruments the researchers used in each study and how they selected their participants and analyzed their data was evaluated. The data-extraction form was also used to evaluate the possibility of bias in original studies.

Data Analysis

In the qualitative data-analysis process of this systematic review, the transparent processes were used to analyze all relevant and appropriate studies that met the inclusion criteria. This process identified all electronic databases that were used in this search. The details for each individual study were described using text, tables, and appendices. The results showed the number of studies that were identified, screened, and found valid to be included in this systematic review. The results are displayed using the PRISMA

Flowchart Diagram (see Appendix C).

Data analysis included the following: (a) study design, (b) the number of participants in each study, (c) the duration of the study, (d) procedures, (e) findings, and (f) conclusions. An additional assessment of the studies and the methodological quality were conducted using the CASP Assessment Tool (Creative Commons Attribution, n.d.). The CASP Assessment Tool, as shown in Appendix D, is a checklist that checks the study quality by asking a number of questions regarding a study (Denzin, 2009).

Potential Research Bias

The presence of bias in each individual study was examined based on the possibility of different biases that could have been present. This was examined in each individual study by checking the reasons the study was conducted, the transparency in the relationship between the researcher and the participants, the funding of the study, and the disclosures of these facts.

Limitations

The limitations of this study included the number of other potential exposures that airline pilots had on and off the job. These other exposures may have been associated with the health effects examined in this study but were not comprehensively evaluated in this study. Fatigue and sleep issues can be results of circadian rhythm disruption, another effect of the profession (Goelzer, Hansen, & Sehrndt, 2001). Exposure to air pollution, sedentary lifestyle, stress, poor diet, sun exposure, and excessive alcohol consumption could also contribute to the health effects found from the environmental exposures. Not controlling for these risk factors could result in over- or underestimating effects.

The airline pilot population is mostly male. As such, the sample size for female airline pilots was relatively small or nonexistent. This resulted in a reduced ability to detect effects in females and decreased statistical power. Another limitation of this study was that it relied on many self-reported health symptoms of airline pilots that were not verified by a review of medical records. Use of tenure as a proxy for exposure could have also been inaccurate because this approach assumes airline pilot exposures were uniform over time among participants, which was not likely to be the case.

Self-selection could also be a potential source of bias. Airline pilots may be more motivated to participate in the studies if they have underlying health conditions or dissatisfaction with their work environment in comparison with those who are healthier or more satisfied with their work environment.

Delimitations

The systematic review and metasynthesis was the research method used in this study. A metasynthesis was used instead of a meta-analysis due to the fact that many of the studies relating to aviation and environmental health used qualitative research methods and narratives to assess findings in their research studies. During this process of the systematic review, the researcher’s goal was to interpret and synthesize the research. The findings were classified in categories and discussed regarding the differences and similarities within each category.

Chapter 4: Findings

Introduction

This study sought to examine, evaluate, and synthesize the research evidence on the environmental conditions in the cockpit and the health effects on airline pilots. The environmental conditions that were evaluated included radiation exposure, air quality, ozone, noise, and CO_2. The results of the data search, collection, and review process are first presented in this chapter. The findings from the current metasynthesis and systematic review are organized by answering each of the two research questions on which this study was based.

Search Process Results

During the initial phase of searching for previously conducted studies that met the inclusion criteria, the search process involved using a combination of the following key terms that were entered into databases: systematic review, metasynthesis, airline pilot health, aircraft environmental factors, airplane health, exposures, air quality, fatigue, radiation, aviation, aerotoxic syndrome, CO_2 exposure, and noise exposure. These databases included (a) ERIC, (b) ProQuest Central, (c) PubMed, (d) FAA, and (e) Google Scholar. After reviewing titles and abstracts, the search from the databases yielded a potential pool of 89 studies. Following this stage, the full copies of the studies were reviewed and screened using previously determined inclusion criteria. This process of checking the studies against the inclusion criteria led to the identification of 32 studies.

The second phase of the search involved a hand search from several relevant journals, including *Environmental Health* and *Aviation, Space, Environmental Medicine.* This search found an additional 12 studies. After the full copies of the studies were reviewed and screened for exclusion criteria, an additional seven studies were added to this review.

The third phase of this search included a search for government reports, professional organizations, and conference proceedings. This search yielded an additional 33 papers. After screening, a total of 10 papers met the inclusion criteria. The next stage of the search process included theses and dissertations, with 10 yielded in the results. After the screening process, one study met the inclusion criteria. From the identification of more than 100 studies, the results yielded 50 studies that met all the inclusion criteria and were included in this systematic review and meta-analysis.

A display of the information and specific details on the results of the search process, including the total number of potential studies, identifies the total number of excluded studies, and included studies can be found in Appendix C using the PRISMA Flowchart Diagram. Additionally, all journals and other sources (A-I only) are displayed in Appendix E, and all other journals and other sources (J-Z only) are displayed in Table 1. Appendix E and Table 1 also include the number of studies and the names of the authors of the individual studies. Table 2 contains the final coding template used in the study. All identified studies and specific characteristics of those studies included in this metasynthesis and systematic review can be found in Appendix E. The specific information for each study includes the (a) author, (b) study design, (c) sample characteristics, (d) data collection process, (e) data analysis process, and (f) findings.

Study Evaluation Process and Results

All individual studies were evaluated using the CASP Assessment Tool found in Appendix D. The next step of the study included evaluating all components of relevant studies for methodological quality using the CASP Assessment Tool. The evaluation process also involved screening the studies for bias and validity.

Table 1

Journals, Other Sources, J to Z, Number, and Authors of Studies

Journal name	*N*	Study authors
Journal of Applied Occupational and Environmental Hygiene	1	van Netten, 1998
Journal of Applied Physiology	2	Sechzer, Egbert, Linde, Cooper, Dripps, & Price, 1960; Thom, Bhopale, Hu, & Yang, 2017
Journal of ASTM International	1	Murawski & Supplee, (2008)
Journal of Exposure Science and Environmental Epidemiology	1	Allen, Sumner, Nishioka, Vallarino, Turner, Saltman & Spengler, (2013)
Journal of Occupational Health and Safety	1	Cox & Michaelis, (2002)
Journal of Women's Health	1	Buja, Mastrangelo, Perissinotto, Grigoletto, Frigo, Rausa & Dominici, (2006)
Lancet	2	El Ghissassi, Baan, Straif, Grosse, Secretan, Bouvard & Cogliano, 2009; Basner, Babisch, Davis, Brink, Clark, Janssen & Stansfeld, 2013
Occupational Medicine	1	Jackson & Earl, (2006)
Outside air treatment solutions for aircraft	1	Bull & Yeomans, (2007)
PloS One	1	Beko, Allen, Weschler, Vallarino & Spengler, (2015)
Proceedings of the Institution of Mechanical Engineers	1	Spengler & Wilson, (2003)
Radiation and Environmental Biophysical	2	Hammer, Zeeb, Tventen, & Blettner, 2000; Hammer, Blettner & Zeeb, 2009
Radiation exposure of air carrier crewmembers II	1	Friedberg, Snyder, Faulkner Darden & O'Brien, (1992)
Travel Medicine and Infectious Disease	1	Bagshaw, (2008)

Table 2

Final Coding Template

Code	Category	Subcategories
1.0	Radiation studies	1.1 Estimates of measure-ments of radiation doses, using flight data 1.2 Estimates of radiation doses using flight information and pilot logbooks
2.0	Bleed air studies	
3.0	Ozone studies	1.1 Ozone studies measured in flight 1.2 Simulated ozone studies
4.0	Noise studies	
5.0	Carbon dioxide studies	

The potential biases that were examined included financial benefits received as a result of conducting the study or researcher and participant relationship. The components that were evaluated included (a) study design, (b) purpose, (c) sample characteristics, (d) data-collection methods, (e) data-analysis methods, and (f) findings. The results of this appraisal can be found in the last column of the Systematic Review of Studies Table in Appendix F. No studies were excluded based on the appraisal and evaluation status because all studies received scores of 9 or 10 points on a 10-point scale.

Data Synthesis Process

After evaluating the quality of the studies, the next step in this study used a process that involved a multistep iterative process of coding extracted data from the studies to build a conceptual framework and to form broad categories. After several reviews of the data, the broad categories were identified to synthesize the data and included radiation studies, ozone studies, air quality studies, CO2 studies, and noise studies.

Research Questions

The findings in this section are organized by answering each research question. The research questions that this study sought to answer were, How do the environmental conditions of the cockpit affect the pilot's health?, and What measures can be taken under the current regulations to improve these conditions? The findings that answer these research questions are found in the next section.

Radiation Studies

A group of studies focused on radiation studies and the effect of exposure on crew members. These studies were also divided into the following two areas: estimates of radiation doses using pilot logbooks and company records and radiation effects and estimates of in-flight radiation doses using actual flight profiles and pilot logbooks.

Researchers in eight studies and reports provided evidence to support the fact that flight crew members were exposed to higher levels of radiation than the general public and that this exposure had various health effects, including higher levels of specific types of cancers (El Ghissassi et al., 2009; FAA, 1994, 2014; Friedberg et al., 1992; Grajewski, et al., 2011; Hammer et al., 2000). Oksanen (1998) specifically used actual flight profiles and pilot logbooks to estimate the radiation doses the pilots were exposed to and found this method to be even more accurate in calculating the estimated radiation dose for crew members.

The components that the researchers were using in these seven studies to estimate the radiation doses for crew members included flight altitude, flight duration and distance, flight routing (polar vs. nonpolar), and solar flare activity. Oksanen (1998) also included the actual flight times from pilot logbooks to obtain a more accurate estimate of exposures. Friedberg et al. (1992) found that their estimates would give a crew member that worked an average of 900 block hours per year an average exposure between 0.21 and 7.2 mSv. Although this is far less than the ICRP (2008) recommendations of 20 mSv per year over a 5-year average for nonpregnant, high-risk radiation workers, it would far exceed the 2 mSv annual recommended exposure for pregnant females. Bagshaw (2007) found that average long-haul pilots are exposed to an estimated dose of 4 to 5 mSv annually and short-haul pilots are exposed to an estimated dose of 1 to 2 mSv annually. These estimated doses were measured using computer-modeling programs.

In the United States, flight crew members are not monitored for their exposure rates. In many countries in Europe, including Finland, the law imposes a maximum annual dose limit of 6 mSv for flight crews as exposed radiation workers (Oksanen, 1998). Any estimated dose greater than 1 mSv in Europe requires crew members to be monitored for their radiation dose. Pregnant crew members may easily exceed the ICRP guideline of 1 mSv per year (as cited in Grajewski et al., 2011). Aviation crew members are the fourth most exposed group of occupational radiation workers (FAA, 2014), and the FAA (2014) provided crew members with informational data for exposure health hazards and variables. The FAA (2014) developed a computer software program to estimate effective dose for a given flight using the flight profile and date.

Individuals exposed to ionizing radiation are believed to have higher rates of cancer, genetic defects for fetuses, and additional health effects. Ionizing radiation affects the DNA by causing changes in the cell chemicals and proteins (FAA, 2014). El

Ghissassi et al. (2009) found that the solar radiation exposure has a causal association with skin cancer, and the IARC (2000) classified ultraviolet radiation as a Group 1 carcinogenic, which is carcinogenic to humans. In another study, Hammer et al. (2009) found that, among flight crew cohort studies, they were at a significantly elevated risk of developing melanoma.

The study also showed that male pilots were at a 50% risk increase of developing prostate cancer, and this number increased with the number of international, long duration flights. In a similar finding, Irvine and Davies (1999) found that male pilots had a statistically significant elevation in melanoma rates in comparison to the general population. Buja et al. (2006) also found that female flight attendants had a significant excess of melanoma and breast carcinoma in comparison with the general population.

McNeely et al. (2014) found that flight attendants had a 34% increase in reproductive cancers in comparison to the general population. These cancers included breast, uterus, and ovarian. Oksanen (1998) stated that “exposure to radiation creates a risk to individual health, to unborn child, and an increase in susceptibility to genetic defects” (p. 624). Likewise, Friedberg et al. (1992) found that a child conceived after exposure to ionizing radiation was at a higher risk of developing radiation-induced genetic defects, including mental retardation and childhood cancer. The variables included the stage of development of the fetus and dose of exposure at the time or times exposed. Hammer et al. (2009) found that the cancer risk of flight crew could also be affected by additional occupational risk factors, including electromagnetic fields from cockpit instruments, jet engine exhaust and fumes, circadian rhythm disruption, and air quality.

Crew members could minimize their exposure by flying flights close to the equator (nonpolar routing), lower altitude, shorter duration, and monitoring solar flare activity (FAA, 2014). Oksanen (1998) found that the lowest levels of cosmic radiation were found in the DC-9 pilots (i.e., 1.34 mSv), who flew the shortest flight durations and the lowest altitudes of all Finnair flights during a 12-month period. It is also suggested that crew members actively monitored their flights for estimated dose and solar flare activity, especially if they were or may have been pregnant.

Bleed Air Studies

Abou-Donia (2003), Allen et al. (2013), Centers (1992), Cox and Michaelis (2002), Day (2015), Lee et al. (1999), Lindgren and Norback (2002), Murawski and Supplee (2008), Spengler and Wilson (2003), Spengler et al. (2012), Spirit Airlines Flight Attendants Association (2018), van Netten (1998), Waters et al. (2002), and Winder and Balouet (2002) provided evidence of the effect of bleed air leaks affecting pilot health and performance. Findings from these studies included the minimal presence of volatile organic compounds (VOCs) from contaminated bleed air and also the health effects and symptoms that exposure to these chemical compounds could induce.

Spengler and Wilson (2003) reported that engine oils and hydraulic fluids can enter into the air inside the aircraft if seals are broken or leak. These fluids include organ-phosphate additives. Typically, jet oils are formulated with approximately 3% TCP; this is used as an antiwear additive to enhance load bearing and has flame retardant properties (Winder & Balouet, 2002). When pyrolysis occurs, these compounds may form a highly toxic isomer called TOCP. The effects from this exposure may not be immediate and may not be noticed until over a week later. Although the catastrophic failure of oil seals is relatively uncommon, minor leaks in oil seals can occur more frequently, and chronic low-level exposures are possible.

In another study, Spengler et al. (2012) measured the level of VOCs on 83 flights and found 64 VOCs in aircraft cabins. The TCP isomer, TMCP was only found in one sample. Spengler et al. (2012) sampled 63 flights for TCP levels, and it was detected in only one sample. The sporadic occurrences of air quality events make them difficult to detect and measure. Day (2015) stated that "the likelihood of randomly selecting a flight on which to collect air samples during an air quality event is indeed extremely low" (p. 5). Waters et al. (2002) sampled 36 commercial aircraft segments on 11 different aircraft and found general contaminant levels low and not atypical for indoor environments. Lee et al. (1999) sampled the air quality on 16 flights on one airline from June 1996 to August 1997. They concluded that the air quality was within the relevant standards. It should be noted that the average age of the aircraft was less than 2 years. Lindgren and Norback (2002) also reported in their study that contaminant values were below the recommended values.

In contrast, Murawski and Supplee (2008) found that there were 470 air contamination reports in U.S. commercial aviation over an 18-month period from January 2006 to June 2007. There were 350 of these events that were official reports that were filed with the FAA on 47 different aircraft types. Cox and Michaelis (2000) surveyed 21 crewmembers who operate on the BAe 146 aircraft, which had several documented cases of fume events and found that the crew experienced high rates of symptoms. These symptoms included headaches, eye and skin irritation, respiratory irritation, joint and muscle pain, and neurological impairment. Spengler and Wilson (2003) noted that the current air monitoring studies had not been extensive enough to capture the fume events where oil and hydraulic mixtures have entered the cabin and cockpit circulated air. The findings indicated that self-reporting of the fume events by passengers and crew provided a more accurate description of the event in contrast to random air quality testing performed during a few randomized flights.

Day (2015) described the potential health risks related to exposure of contaminants that are generated during a fume event inside the aircraft. These symptoms ranged from eye and nose irritation, confusion, dizziness, headaches, and cognitive impairments. If exposed at higher levels, damage to liver and kidneys could result. van Netten (1998) found the health complaints of flight crews on the BAe-146 aircraft who were exposed during fume events and admitted to the hospital, in some cases, to be consistent with upper respiratory irritation, fatigue, dizziness, cognitive issues, chest tightness, blurred vision, memory impairment, possible neurological impairment, and loss of consciousness. Winder and Balouet (2002) found similar symptoms reported by exposed flight crew and passengers. Their findings for short-term exposures also included nausea, shaking, loss of balance, and increased heart rate. They found that long-term, low-level exposure or residual symptoms from the short-term exposures included many of the short-term symptoms in addition to joint pain, muscle weakness, diarrhea, hot flashes, skin itching and rashes, hair loss, and chemical sensitivity.

Spengler and Wilson (2003) also found skin contact could crack and dry exposed skin. Abou-Donia (2003) investigated the long-term exposure effects of the organophosphorous compounds, which are neurotoxic. An effect of a single exposure or repeated exposure could induce neurotoxic issues; one is currently known as organophosphorus ester-induced delayed neurotoxicity (OPIDN). OPIDN can lead to long-term neurological and neurobehavioral issues. The earliest recorded cases and the largest reported number of cases of OPIDN were caused by exposure to TOCP. Centers (1992) also examined the potential dangerous effects and formation of a neurotoxin called trimethylolpropoane-phosphate, which can be formed by the reaction of TCP and Trimethylolpropane esters, which are found in synthetic engine lubricants. This formation could only potentially occur when it is formed at extremely high temperatures from 350-700 degrees Celcius. Although this compound had not been found, the potential does exist, and the hazards of exposures should be examined.

Due to these health risks, Spirit Airlines Flight Attendants Association (2018) designed and published a 12-step fume event procedure for the flight attendants to follow in the event of a suspected fume event. They must follow a Fume Event Checklist and immediately notify the aircraft captain. This is due to the fact that, many times, the passenger cabin may be susceptible to a stronger fume smell through the recirculated air that provides air to the gasper fans for each passenger. Then, it is mandatory to get blood tests to test for carboxyhemoglobin, which tests for the compound that forms when carbon monoxide is inhaled into the blood. The other blood test they must receive is the cholinesterase test, which tests for an enzyme that is found in the heart, brain, and blood. The flight attendants have a 2-hour window to receive these blood tests. There is also reports that must be filed internally to document the fume event and also with the union. This initiative is unique due to the flight crews being proactive regarding the fumes incidents that have occurred at their airlines. Many airlines do not have this level of education and initiative on how to identify fume events and action to take. Winder and Balouet (2002) found that symptom severity depends on several factors. These include frequency and duration of exposure, intensity, contaminants present, levels of toxicity, and individual susceptibility.

Ozone Studies

Beko et al. (2015), Bell et al. (2006), Bull and Yeomans (2007), Spengler et al.

(2004), Spengler et al. (2012), Spengler and Wilson (2003), Waters et al. (2002), Rai and Chen (2012), and Weisel et al. (2013) investigated the impact of ozone concentrations on aircraft and the health effects. All were conducted inside an actual aircraft on revenue flights with passengers, except for one study by Rai and Chen (2012) who used a simulation of ozone distribution using computational fluid dynamics.

Spengler et al. (2004) found that the ozone levels in 20% of the flights that were monitored exceeded the FAA recommended limit of 100 ppb. Of 290 samples the study used, the aircraft with the lowest ozone levels was the B-747 400, and the B-757 had the highest levels of ozone with the only U.S. flights exceeding 80 ppb were on the B-757 aircraft. Ozone levels in commercial aircraft can exceed the FAA’s standards and the U.S. Environmental Protection Agency National Ambient Air quality standards. Weisel et al. (2013) also found that aircraft without catalytic convertors exceeded 100 ppb. In another study, Spengler et al. (2012) found that, on the 83 aircraft measured for ozone levels, no flights exceeded the FAA standard of 100 ppb. They found the difference of the average levels between the aircraft equipped with ozone convertors was not significantly different (i.e., 22.3 ppb vs. 28.2 ppb). However, the maximum levels were found to be significant (i.e., 47 ppb with the convertor vs. 209 without the convertor).

The studies demonstrated that catalytic convertors, which are installed in many newer models of aircraft such as the B-787, B-777, B767, could be 95% effective when installed and diminished to 60% effectiveness after 12,000 flight hours (Spengler & Wilson, 2003). Bull and Yeomans (2007) stated that the advantages to catalytic oxidation, which is used on many common ozone converters, is that there are no moving parts or electrical power needed. The disadvantages include that they must be periodically replaced or the catalyst has to be regenerated. Weisel et al. (2013) also found that ozone convertors could also be damaged by water, sulfur compounds, and contaminants from oil or hydraulic leaks, leading to a decrease in filtering and higher levels of ozone inside the aircraft. Factors that contribute to higher ozone levels on commercial aircraft include higher altitudes and northerly routes during the spring season. Waters et al. (2002) also confirmed the effectiveness of the catalytic convertors in their study that measured the air quality using all aircraft equipped with them and found no flight had exceeded the FAA limits.

Beko et al. (2015) examined the health effects from ozone exposure and found that, on the flights that had the highest ozone exposures, passengers expressed dry eyes, nasal stuffiness, dry mouth, and upper respiratory symptoms. Ozone-incurred reactions can occur at exposures much lower than the FAA recommended limits. Additional symptoms can develop from as by-products of ozone-related chemistry as the ozone in the aircraft cabin can react with unsaturated hydrogen compounds in the aircraft cabin air or on passengers (Spengler et al., 2004). The study also showed that chronic exposure to ozone could be associated with decreased pulmonary function. Flight attendants also demonstrated respiratory symptoms on long duration, high altitude flights. Bell et al. (2006) found that even low-level exposures to ozone have the ability to increase risk of premature mortality.

Rai and Chen (2012) conducted their study using a simulation of ozone distribution using computational fluid dynamics and found that the ozone depleted more rapidly in the passenger breathing zone than throughout the cabin. This could have been primarily related to reaction of the ozone at human surfaces.

Noise Studies

The effect of noise on health was the focus of four studies by Basner et al. (2013), Orsello (2013), Tomei et al. (2005), and van Kempen et al. (2002). Basner et al. investigated the auditory and nonauditory effects of noise on health. In addition to occupational noise-induced hearing loss, this study showed that noise exposure could have additional health effects, including sleep disturbances, annoyance, hypertension, and cardiovascular disease increase and could also have cognitive performance effects. Noise-induced hearing loss cannot be regained, and prevention is the only option to preserve hearing. This study also showed that occupational-induced hearing loss such as airline crew are exposed to is the most common occupational disease in the United States. van Kempen et al. (2002) found that noise exposure was associated with blood pressure increases and heart disease. In this study, a meta-analysis of 43 epidemiologic studies was conducted to investigate the relationship between noise exposure and blood pressure and heart disease.

In another study, Orsello et al. (2013) investigated the sensorineural hearing loss of military aviators from 1997 to 2011. They also found that noise-induced hearing loss was the most common cause of hearing loss in military aviation. This was due to occupational noise. They also found that sensorineural hearing loss rates increased with age. Tomei et al. (2005) studied the occupational exposure effects of noise and hypertension in pilots. They examined 77 male pilots who operated turboprop aircraft and jet aircraft. The findings from this study suggested that chronic exposure to occupational noise was a risk factor for hearing loss and hypertension in pilots. They found that the group of turboprop pilots was exposed to an average of 93 dBA versus the jet pilots exposure of 79 dBA and significant differences were found in their blood pressure and heart rate and electrocardiogram measurements after being exposed to occupational noise. This study demonstrated the exposure to higher levels of noise influenced blood pressure and the risk of developing hypertension in pilots.

CO_2 Studies

Spengler and Wilson (2003), Spengler et al. (2012), Lindgren and Norback (2002), Lee et al. (1999), and Waters et al. (2002) investigated the CO_2 levels on commercial aircraft. In five additional studies by Allen et al. (2013), Satish et al. (2012), Sechzer et al. (1960), Sliwka et al. (1996), and Thom et al. (2017) examined the effects of CO_2 exposures on performance, cognitive functioning, and overall health effects.

CO_2 levels vary with passenger occupancy, fresh air supply rates, and the phase of flight. Spengler et al. (2012) found that CO_2 levels were elevated during passenger boarding and when the aircraft was on the ground. Levels as high as 3,000 ppm had been documented with cruise levels dropping to 1,500 ppm or lower (Spengler & Wilson, 2003). These levels exceeded ASHRAE recommended levels of 1,000 ppm; however, they did not exceed the FAA or OSHA standards of 5,000 ppm.

In another study, Spengler et al. (2012) monitored 83 flights and found that the average CO_2 level during cruise flight was 1,404 ppm. The factors that affected the exposure level were aircraft phase of flight, occupancy, relative humidity, flight duration, and aircraft type. This study showed that the highest readings were on the Boeing 777 with a mean of 1,449 ppm. They also found that these limits all fell within the FAA limit of 5,000 ppm. Lee et al. (1999) monitored the air quality in 16 flights on one airline. They found that the average CO_2 readings exceeded the ASHRAE standard of 1,000 ppm. Average CO_2 readings in this study showed levels from 629 ppm to 1,097 ppm with maximum readings of 1,347 ppm to 4,725 ppm. Again, the elevated levels were found during passenger boarding and lower during cruise flight. This could be attributed to lower fresh air levels during boarding.

Waters et al. (2002) studied 36 commercial flights and found that the average CO_2 readings were 1,387 ppm with the highest level during cruise being recorded at 2,216 ppm. The highest correlating factor was passenger load factor. This study also showed that CO_2 levels were due to the lower ventilation rates in the aircraft cabin. Lindgren and Norback (2002) monitored the air quality on 26 commercial flights and found that the CO_2 concentrations were below the recommended limit of 1,000 ppm during 96% of the time measured. All of the measurements were conducted on a Boeing 767 aircraft. The average CO_2 reading was 709 ppm during cruise flight. However, during noncruise flight, the CO_2 levels exceeded the ASHRAE standard of 1,000 ppm. These studies confirmed that CO_2 levels were elevated during boarding and takeoff, the most critical phase of flight for the crew. The following five research teams investigated the health and performance effects of these elevated levels and exposures.

Sliwka et al. (1996) found that exposure to low levels of CO_2 indicated a readjustment of cerebral blood flow and headaches were also reported. In another study, Sechzer et al. (1960) found that respiratory volume, arterial pressure, heart rate, and plasma concentrations were also elevated in 12 male volunteers during a period of increased CO_2 exposure. Thom et al. (2017) also found that increases in CO_2 levels from 2,000 ppm to 4,000 ppm may have showed symptoms such as vascular leak in the brain, muscles, and colon and also elevations in circulating micropartiles and platelet activation. They conducted their study using mice and exposed them to these higher levels of CO_2.

Satish et al. (2012) investigated 22 participants who were exposed to three different levels of CO_2 (i.e., 600 ppm, 1,000 ppm, and 2,500 ppm) and found that decision making and performance were affected. At the 1,000 ppm level, subject performance and cognitive skills decreased moderately, but, at the 2,500 ppm level the subject performance decreased substantially. Allen et al. (2013) was the only study to investigate airplane pilot performance in a flight simulator under varying CO_2 levels. They used 700 ppm, 1,500 ppm, and 2,500 ppm during their study. The findings from this study suggested that CO_2 had a direct effect on pilot flight performance. The researchers used 30 male pilot participants, and they performed various flight maneuvers in the flight simulator. There was evidence of lower passing rates on the maneuvers being tested at 1,500 ppm when compared to performing the same maneuvers at 700 ppm. The findings from this study suggested that pilots performed better at lower CO_2 concentrations, and there was a direct correlation between CO_2 on performance, independent of aircraft ventilation.

Chapter 5: Discussion

Introduction

The purpose of this study was to evaluate, examine, and synthesize the research evidence on the environmental factors that can affect airline pilot health. The research questions also focused on the measures that can be taken to improve these conditions and how the stakeholders can benefit from additional research on these environmental effects that affect pilot health and the improvements that can be made. This chapter is organized as follows: (a) summary of findings, (b) interpretation of findings, (c) context of findings, (d) implications of findings, (e) limitations of the study, and (f) future directions of research.

Summary of Findings

Research findings indicated that the environmental effects of the cockpit that could affect pilot health were numerous and pilots were not made aware of many of these risks. Recently, pilot performance in the cockpit has received attention, focusing on the physical and mental aspects of the career (Wu et al., 2016). A finding from this systematic review and metasynthesis suggested that, in order to optimize airline pilot health and performance, pilots must possess the knowledge regarding these environmental factors that affect the cockpit environment in which they spend hundreds of hours a year and learn the preventative measures that can be taken to minimize their risks. Manufacturers and the airlines should also be aware of the findings from this study to aid in decision and policy making regarding the occupational health of the pilots.

Radiation Exposure

Research findings from current studies found that in-flight cosmic radiation exposure is effecting pilot's health and also support further education for pilots to be aware of the risks of exposure, especially on long-haul international routes. There were two studies in the metasynthesis by Oksanen (1998) and Grajewski et al. (2011) that supported these findings and four professional or government reports by *European Council Directive* (1996), FAA (1994), IARC (2000), and ICRP (2008). The main components of these studies included flight hours, routes, altitudes, and hours flown to estimate cosmic radiation exposure, which is measured in mSvs.

Radiation monitoring in the European Union prevents pilots from flying over the European Radiation Dosimetry Group recommended exposure limits. In May of 2000, the European Union adopted a safety standard to protect flight crews from ionizing radiation. The *European Council Directive* (1996) stated that, for aircrew who may receive more than a dose of 1 mSv per year, their employer must

> assess the exposure of the crew, take into the account the schedules of the exposed crew and their schedules to reduce the doses for future schedules, inform the workers of the health risks, and apply special protection to female crew members during declared pregnancy. This limits the exposure to the fetus to1 mSv for the duration of the pregnancy and allows the dose to stay as low as possible. (p. 25)

In the United States, to promote radiation safety of aircrews, the Radiobiology Research Team at the FAA Civil Aerospace Medical Institute provides educational materials on radiation exposure, recommends limits for occupational exposure to ionizing radiation, develops computer programs available via the Internet to calculate flight doses, operates a Solar Radiation Alert System, and publishes original research and review articles in peer-reviewed journals. However, there are no official limits or ways to prevent flight crews from exceeding the recommended exposure doses because there is no monitoring of U.S. flight crews' exposure estimates. The recommended dose by the FAA (2014) using ICRP limits is 20 mSv per year with no more than 50 mSv per year. The FAA formally recognizes that aircraft crews are occupationally exposed to ionizing radiation. The United Nations Scientific Committee on the Effects of Atomic Radiation (as cited in FAA, 2014) ranked flight crews the fourth most exposed group of employees. It recommended that crew members be informed about their radiation exposure and associated health risks and that they be assisted in making informed decisions with regard to their work environment. Airlines may be able to alter flight plans when there is predicted solar flare activity; however, this is also very costly and can add delays to flight schedules (Bagshaw, 2008).

Pilots flying at higher altitudes on long-haul flights are exposed to the highest levels of cosmic radiation (Oksanen, 1998). The increase of polar routing, larger aircraft, and longer flights expose pilots to a greater dose of radiation and circadian rhythm disruption (Grajewski et al., 2011). The levels of galactic cosmic radiation over the polar regions are double the levels over the equator at the same altitudes (FAA, 2014). Therefore, there is a need to educate pilots on the risks associated with these flights. Flying at lower altitudes or limiting long-haul flights with polar routing may help to reduce pilots' cosmic radiation exposure. Identifying pilots at risk of high exposure would benefit the airlines and occupational health programs. By providing an accurate assessment of pilot dose measurements, occupational health would benefit by utilizing the unique structure of an airline pilot's schedule due to aircraft and seniority. Actual measurements of radiation doses from inside the cockpit with monitoring equipment would also greatly enhance this knowledge (Hammer et al., 2000). Education for pregnant female crewmembers is needed regarding the recommended radiation doses and possible health effects to the fetus with exposure. Currently, 4% of the current airline pilot population is female with that number continuing to grow (Women in Aviation International, 2013). This is a health concern that should be addressed and researched more in-depth.

Bleed Air

Researchers have been able to identify several occupational health issues that have been associated with the quality of the bleed air entering into the cockpit and cabin. The presence of contaminants inside commercial jet air conditioning systems is an issue prudent to air safety and occupational health. Air quality in commercial aircraft has been a health concern for crew and passengers for over 30 years (Day, 2015). Winder and Balouet (2002) confirmed the toxicity of commercial jet oils and the potential for toxic exposure to airborne contaminants that may be present when an engine seal leaks in flight. Many times, the crew are not aware of the toxicity of the contaminants and how to identify the symptoms of contaminated air. There have been several documented cases of exposures inside aircraft leading to a multitude of health symptoms for crew and passengers (Cox & Michaelis, 2002). These short-term symptoms range from blurred vision, nausea, dizziness, confusion, headache, increased heart rate, skin irritations, confusion, shaking, breathing difficulties, and even loss of consciousness (Winder & Balouet, 2002). Long-term exposure may include hydrocarbon neurotoxicity, memory impairment, respiratory issues, fatigue, muscle weakness, skin irritation, and chemical sensitivity (Winder & Balouet, 2002).

Murawski and Supplee (2008) found that there were 470 air supply contamination reports in U.S. commercial aviation over an 18-month period. This was significant enough to warrant additional education for pilots and crew members on identification of an air contamination event, the correct action to take if an air contamination event is suspected, and how to document it correctly and report it. Many aircraft checklists contain a fumes event checklist; however, crews are not specifically informed of the symptoms to look for and may overlook this smell because oils and fuel smells are common in and around aircraft environments. Many events are underreported by the airlines and, thus, to the FAA.

There is currently no national or international database to report or monitor the frequency of contaminated air events (Murawski & Supplee, 2008). The only aircraft with published data involves an industry investigation into the BAe 146 aircraft, which was prone to frequent engine oil seal leaks by design (Cox & Michaelis, 2002). There have been aviation industry manufacturers and airlines that have attempted to minimize this issue and the frequency of events (Cox & Michaelis, 2002). After encountering this issue on multiple flights and the reported symptoms of flight crew members, Spirit Airlines implemented an educational protocol to educate all flight crew members on the identification, reporting, and symptoms of a fume event. They emphasized the importance of correct reporting of the event and also receiving immediate medical attention and obtaining blood samples. Their initiative includes training, which began in 2017, education, quick reference cards, and outside support from MedAire (an in-flight medical support; Spirit Airlines Flight Attendants Association, 2018). This should be an example for the airline industry.

The only current way to report these air quality and fume events accurately is from crew members' reports of the smell or health symptoms. If a reliable air quality measurement tool was installed on board, it would aid in reporting and accumulating data and frequency of air quality and fume events. Many times, even after it has been reported by the flight crew and the aircraft returns for maintenance, the smell and diagnosis cannot be duplicated (Murawski & Supplee, 2008). It would be beneficial to the airlines and stakeholders to monitor this issue and improve the reporting and identification of these events.

In the 470 air contamination reports that were found by Murawski and Supplee (2008), 57% of the flights reported in-flight diversions, and the ground-based reports resulted in flight delays and cancellations. These numbers may cost airlines a substantial monetary loss and also passenger loyalty. Also, aircraft manufacturers may follow the engineering of the Boeing 787, which is the only aircraft that does not use bleed air for the air conditioning system and has a dedicated air inlet (Day, 2005).

There are various filters that may be installed to prevent these air quality events from occurring. These include disposable carbon filters, photocatalytic oxidation, catalytic convertors, nonthermal plasma oxidation, and high particulate filtration (Bull & Yeomans, 2007). Currently, recirculated air is cleaned by using high energy particulate air filtration. These may capture particles but not gasses and vapors. Additional research is needed to assess the air quality inside aircraft, assess health risks to crews and passengers, and develop precise measuring equipment to monitor the air quality.

Ozone

During the process of examining studies for this review, Beko et al. (2015), Bell et al. (2006), Bull and Yeomans (2007), Spengler et al. (2004), Weisel et al. (2013), and Rai and Chen (2012) examined ozone exposure levels inside aircraft. Lee et al. (1999), Lindgren and Norback (2002), Spengler et al. (2012) Spengler and Wilson (2003), and Waters et al. (2002) examined air quality inside aircraft, including the levels of ozone. All of the studies provided evidence that ozone levels were elevated inside aircraft while flying at high altitudes and there were adverse health effects.

Beko et al. (2015) found that exposure to ozone during a flight can lead to dry mouth and eyes and nasal stuffiness and were the most common symptoms. Lee et al. (1999) described respiratory tract and lung issue irritation as a major health risk when exposed to ozone. These symptoms affect crew as well as passengers. In another study, Bell et al. (2006) found that elevated ozone levels could also lead to premature death. Spengler and Wilson (2003) also discussed that elevated ozone levels inside a commercial aircraft could aggravate asthma and impair the immune system, leading to an increased likelihood of bronchitis or pneumonia.

Weisel et al. (2013) found that there have been some improvements in ozone levels inside the aircraft in response to the 1985 FAA standard for ozone and some aircraft installed catalysts for removing ozone into the environmental control systems. However, there are still many commercial aircraft flying today that do not have the catalytic convertors installed and continue to have elevated ozone levels. They also found that even the aircraft that do have the convertors installed may not be as effective if they have been contaminated by water or sulfur, all commercial aircraft should be required to install catalytic convertors, and there should be required or improved maintenance to ensure the convertors are able to filter the highest percentage of ozone out of the breathable air for crews and passengers.

Ozone levels should also be continuously monitored on board the aircraft to get an accurate reading of the exposure levels. The FAA (2018) regulations on cabin ozone concentrations should also be revisited to ensure that all flights meet a lower ozone standard for crew and passenger health benefits. Additional studies on ozone levels and crew and passenger symptoms should be conducted.

Noise

Findings from four noise studies that were evaluated in this study by Basner et al. (2013), Orsello et al. (2013), Tomei et al. (2005), and Van Kempen et al. (2002) all showed evidence that the effects of noise in addition to hearing loss also included cardiovascular disease, loss of sleep, and degraded cognitive functioning. The combined research evidence seemed to suggest that noise has a greater effect on one's health than previously known. Occupational noise is often combined with social and environmental noise to compound these health effects. The understanding of occupational and environmental noise is critical for public health.

Basner et al. (2013) found that noise was the most preventable cause of hearing loss. Orsello et al. (2013) stated that hearing loss not only has a negative impact financially and mentally on the individual but it also has a significant monetary burden to the organizations. In the airline industry, occupational noise can be found constantly outside and inside the aircraft.

Tomei et al. (2005) found evidence that chronic exposure to noise is a risk factor for blood hypertension in pilots, along with hearing damage. Because most pilots begin their pilot training in small, propeller-driven aircraft, the assumption can be made that airline pilots have been exposed to high levels of occupational noise since the start of their pilot training and it will continue on throughout their careers, which may last over 30 years. Preventative measures for pilots include using noise-cancelling headsets throughout their aviation careers and the use of ear plugs. Educating the airline pilot group and industry on the negative effects of noise on health would be beneficial for the airline industry. Also, the need for further research into the area of noise and pilot health is recommended. Monitoring the actual noise levels inside the cockpit using a decibel meter is also recommended to obtain real-time dose levels, exposures, and intensity.

CO_2

After examining the two studies by Allen et al. (2017) and Satish et al. (2012) regarding the effects of CO_2 on cognitive performance, the evidence was found to support the findings that there was a direct effect of CO_2 on cognitive performance levels, especially above 1,000 ppm. The five studies that examined air quality inside aircraft by Lee et al. (1999), Lindgren and Norback (2002), Spengler (2012), Spengler and Wilson (2003), and Waters et al. (2002) showed that CO_2 levels were elevated and at their highest levels between 2,000 to 2,500 ppm during passenger boarding and shortly after. During cruise flight, the CO_2 levels fell to an average between 1,000 to 1,500 ppm, which is within the recommended FAA limits.

Allen et al. (2017) found that airline pilots performed better at lower CO_2 concentrations. Increased ventilation inside aircraft may help to lower the CO_2 levels and also increase pilot performance. However, by increasing ventilation on aircraft, the fuel efficiency may be affected, and operating costs may increase. CO_2 exposure has a direct impact on health. Satish et al. (2012) found that, in addition to the physical symptoms of exposure, including increased heart and respiratory rate, headaches, and increased blood pressure, human decision-making performance was also negatively affected. Additional studies are recommended in this area using various ventilation rates to measure the impact on pilot performance. CO_2 levels can also be measured in real time inside the cockpit of the aircraft to give a better understanding of the actual exposures and limits and also how long the elevated CO_2 levels that are found at boarding will last. This can have a critical effect on pilot performance during the takeoff segment when the crucial decision to reject a takeoff must be made a less than 3 seconds. By examining this area in more detail, safety may be increased, along with enhanced pilot performance.

Interpretation of Findings

There were several interpretations of the findings from this study. Research findings from the studies reviewed in this paper demonstrated that the environmental effects in the cockpit could affect pilot health and performance. The challenge still exists to prove the correlation of each individual effect and the combination of factors on pilot health and performance. Research evidence stressed the need for pilots and operators to possess a thorough understanding of the many factors that influence the health and outcomes of their performances in the cockpit.

With the aviation industry continuing to grow over the next decades, these challenges that affect pilot health and performance should be addressed to increase safety. Therefore, there is a need for airlines, unions, and industry leaders to provide ongoing, sustained, educational opportunities for pilots to understand the environmental factors that are affecting their occupational health. Research findings suggested that the more pilots understand about their work environment and performance, the more the proactive they will be in advocating for future research in this area of pilot health, an area that has been traditionally underserved. Findings also suggested that another responsibility of industry leaders is to seek the support of all airline pilot groups and organizations, including pilot unions to work together on these issues that could affect all of the airline industry worldwide.

Context of Findings

Researchers have supported the fact that additional research needs to be conducted in the areas of environmental factors that affect pilot health. The findings from this study also concurred with the findings of other researchers (i.e., that pilot health is an area that has not been studied as much in the past due to regulations and medical concerns of pilots). With the goal of implementing new procedures and policies that provide significant health benefits for pilots, policy makers and stakeholders should be well-informed and consider the context of the future research that needs to be conducted in their decision-making process.

Theoretical Findings

Research findings from this review suggested the need for pilots to understand better the implications of each environmental that is present in their working environment of the cockpit. These include, but are not limited to, radiation exposure, air quality, CO2 effects, noise, and the effect of ozone. For example, pilots need to know that altitude and latitude of the flight affect the radiation dose to which they are exposed. Additionally, research evidence in this study supported that increasing ventilation rates inside aircraft and using catalytic filters on all aircraft could significantly improve air quality and, in turn, could affect pilot performance and safety.

Additionally, the research findings in this study also supported the need for additional research into the area of the environmental factors that affect pilot health and performance. New technologies currently exist that could provide accurate readings of air quality, radiation, and noise doses and could also monitor the pilot's cognitive ability and performance. This technology should be used to give an accurate picture of the overall, combined effects that have been reviewed in this study.

Implications for Practice

By adding to the body of knowledge of the environmental effects in the cockpit that affect pilot health, the findings of this study could support the ability of pilots and industry leaders to provide preventative measures to limit these effects on pilot health and improve pilot performance. The synthesis could add to the body of knowledge that pilots should acquire to make educated and informative decisions to decrease the amounts of exposures and improve the overall conditions found in the cockpit environment.

The findings from this study could also serve as guidance for airlines, aircraft manufacturers, and regulatory bodies who have the responsibility of providing the materials and solutions to help minimize the effects of the environment and improve the overall working environment of pilots. This synthesis contains examples of preventative measures that could be effective as well as those practices and procedures that should be avoided, and this information could serve pilots who seek to be proactive in the health of their work environment. In addition, knowledge about the environmental factors that affect pilot health could provide pilots with a clearer understanding of the individual and combined effects of each factor present in the cockpit.

Moreover, the findings from this systematic review and metasynthesis could serve aviation industry leaders as they make regulatory, procedural, financial, and leadership decisions regarding aircraft systems, procedures, regulations, and practices. In addition, managerial support is needed that could provide clear and attainable goals to improve cockpit environmental conditions, a shared vision with the pilot for program success, guidance in implementation and training of new procedures or modifications of current procedures, the necessary resources available to implement the changes, and appropriate and sustained continued training for pilots and stakeholders.

Finally, these findings from this systematic review and metasynthesis could also serve as a reminder for policy makers and regulatory bodies of the factors that they must be cognizant of prior to making important regulation and policy changes and implementing them with the airlines and regulatory code so that the final results will be effective in supporting the changes to the environmental regulations that govern the cockpit. The FAA should implement a continuous monitoring system to ensure that all commercial aircraft meet the existing FAA air quality standards. Knowledgeable leaders in the aviation sector are critical in the implementation of these changes to regulation and procedures in each airline.

Limitations of Findings

This study was limited for several reasons. The limitations of this study included the quality of the original studies. Experts in the field of research synthesis cautioned that flaws in the original study may not be overcome in the synthesis. The focus of the extracted studies was on the environmental factors of the cockpit that affected pilot health. Thus, some of the factors in the studies were not relevant for the purpose of pilot health (e.g., flight attendant health studies) because the goal of this research study was the examination, synthesis, and evaluation of the environmental factors of the cockpit that affected pilot health.

Also, this systematic review used a limited time frame of the years between 1991 and 2017 to identify relevant studies. There was a possibility that, because of these inclusion criteria, other notable studies were missed. Additionally, the focus of this study was identifying research studies that focused on airline pilot health and the environmental factors that affected it; therefore, relevant studies that focused on military pilots and general aviation pilots were excluded. Another limitation was that non-occupational or additional exposure of the participants of the study may not have been reported.

Furthermore, in the course of the research for this review, the researcher identified other studies that provided excellent sources of the environmental factors that affected pilot health, but, because of the methodological approach (mixed methods) used in these studies, they did not meet the specific inclusion criteria for this metasynthesis and, thus, could not be included in this review. Furthermore, there were other studies where researchers examined the effects of radiation on pilots, but those studies did not meet the inclusion criteria of this systematic review because they were conducted prior to the time frame included in this study and did not provide accurate record keeping and data. Another limitation to this study was that the analysis leading to the current findings was based on many original studies that had only male populations in their samples such as in these cases correlating to the majority of the current pilot population; therefore, the findings may not have been applicable to the current female airline pilot population or may have had slightly different affects (e.g., prostate cancer or pregnancy).

Directions for Future Research

Directions for future research could include conducting a similar study for the female pilot population. During the process of research for this study, many studies on this topic conducted for female flight attendants were identified, but all were not included in this metasynthesis because they did not meet the inclusion criteria for this study.

Future studies could also focus on recording actual measurements from inside the cockpit and gaining approval from regulators and airlines to monitor radiation doses, air quality (CO2, ozone, and VOCs), and noise levels on each flight. There exists minimal, non-evasive monitors that could be in every cockpit to get an accurate look at the doses and exposures that pilots are receiving on each flight segment. Future research could focus on the additional factors that could affect pilot performance such as fatigue and circadian rhythm disruption that had not been addressed in depth in this systematic review. Additionally, future research could focus on finding ways to promote pilot health and educate pilots about the challenges that affect them from working in the unique cockpit environment. Government, industry, unions, and academics, along with the regulatory organizations, should be working together to identify further research and technological advances in the area of these environmental factors that could affect pilot health and, ultimately, their safety.

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Appendix A

Preferred Reporting Items for Systematic Reviews and Metasyntheses Checklist

Preferred Reporting Items for Systematic Reviews and Metasyntheses Checklist

Section/Topic	#	Checklist for PRISMA Item	Reported on pg
Title	1	Identify the report as a systematic review, meta-analysis, or both	
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rational.	

Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	
Summary measures	13	State the principal summary measures (e.g., risk ration, difference in means).	
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I(2)) for each meta-analysis.	

		PRISMA Checklist	Reported on pg
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	

RESULTS

Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each state, ideally with a flow diagram.	
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with forest plot.	
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measure of consistency.	
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	

DISCUSSION

Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	

FUNDING

Funding		Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	

Adapted from "Preferred Reporting Items for Systematic Reviews and Meta-Analyses. The PRISMA Statement," by D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, 2009, PLos *Med*, *6*(6), e1000097. doi:10.1371/journal.pmed1000097

Appendix B

Data Extraction Form

Data Extraction Form

Citation Study No.

Study Author & Date	
Theoretical Perspective	
Publication Source/Database	Book, Journal, Article, Thesis, Dissertation, Conference Proceeding Report, Database
Design	
Purpose of Study	
Sample Size/Characteristics	
Sampling Socioeconomic status	
How were participants selected?	
Study Setting	
Duration of Study	
Methodology and Data-Collection Methods	
Data Analysis Methods	
Major Findings	
Conclusions	
Risk of Bias	Publication Source Funding Source Concealment Number of results reported Neutrality
Retrieval Information	
Overall Study Quality Use +/-	Rating 1, 2, 3
Discernible purpose	
Consistency/Logical conclusion	
Literature Review Adequate	
Adequate Sample size	
Methodological quality	
Efficient data presentation method	
Validity Addressed	
Findings are clear and reported	
Discussion based on findings presented	
Rigor/Applicability	

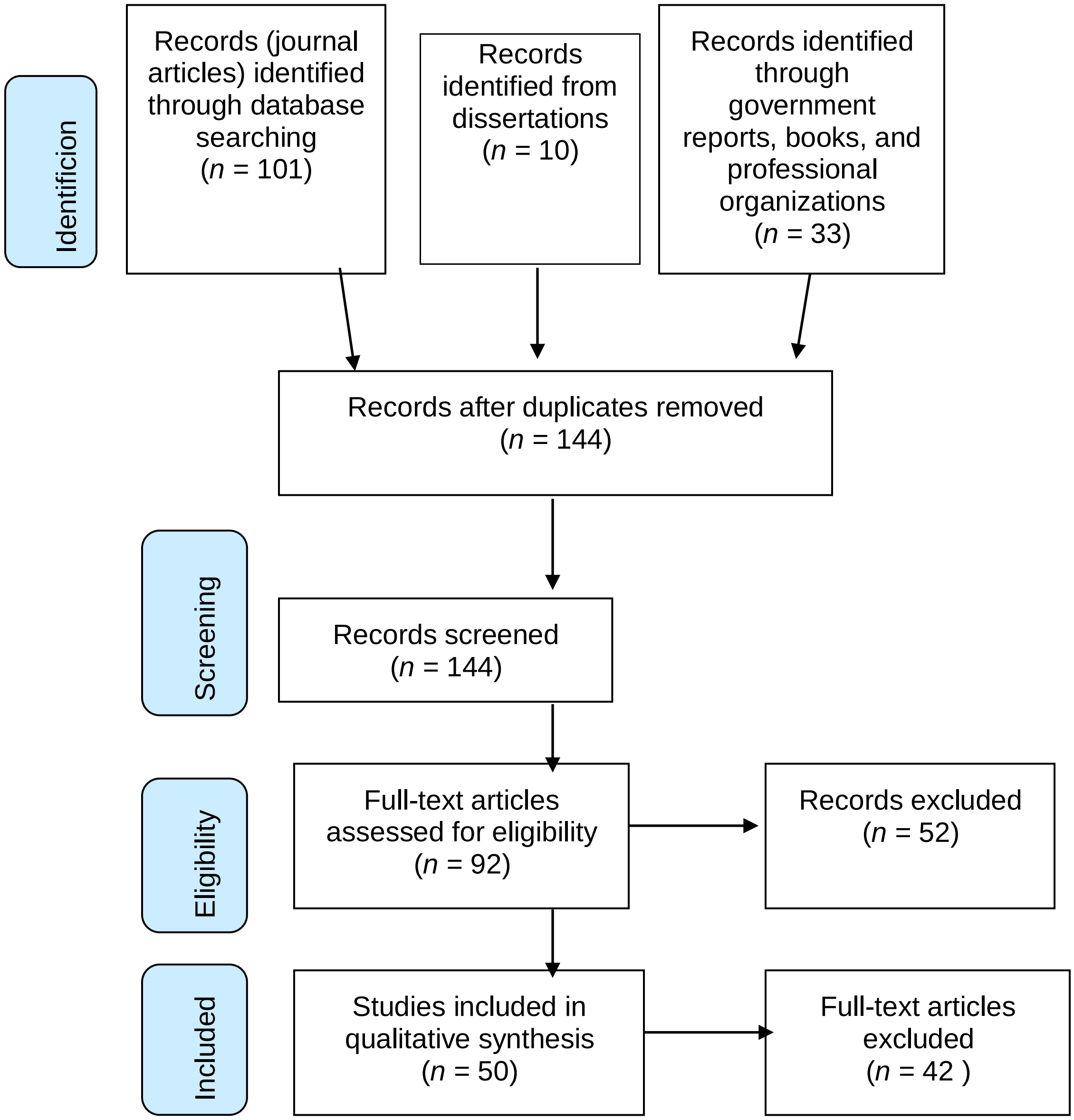
Adapted from *Reading and Understanding Research,* by L. F. Locke, S. J. Silverman, and W. W. Spirduso, 2010. Thousand Oaks, CA: Sage; *Handbook for Synthesizing Qualitative Research,* by M. Sandelowski and J. Barroso, 2007, New York, NY: Springer, and Systematic Coding for Research Synthesis, by W.A. Stock, 1994, in *The*

Handbook of Research Synthesis (pp. 125-138), New York, NY: Russell Sage Foundation.

Appendix C

Preferred Reporting Items for Systematic Reviews and Metasyntheses Flowchart Diagram

Preferred Reporting Items for Systematic Reviews and Metasyntheses
Flowchart Diagram



Note. Adapted from Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement, by D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, 2009, PLoS *Med 6(6),* e1000097. doi:10.1371/journal.pmed1000097

Appendix D

Critical Appraisal Skills Program Tool

Critical Appraisal Skills Program Tool

Making sense of evidence about effectiveness
Ten questions to help you make sense of qualitative research

These questions consider the following:

1. Are the results of the review valid?

2. What are the results?

3. Will the results help?

A number of prompts are given after each question. These prompts are designed to remind the reviewer why each question is important.

Screening Questions

1. Was there a clear statement of the aims of the research?

Consider:

- What the goal of the research was
- Why is it important?
- Consider its relevance

2. Is a qualitative methodology appropriate?

Consider:

- If the research seeks to interpret or illuminate the actions and/or subjective experiences of research participants

Detailed questions

3. Was the research design appropriate to address the aims of the research?

Consider:

- If the researcher has justified the research design (e.g. have they discussed how they decided which method to use)?

4. Was the recruitment strategy appropriate to the aims of the research?

Consider

- If the researcher has explained how the participants were selected
- If they explained why the participants they selected were the most appropriate to provide access to the type of knowledge sought by the study

- If there are any discussions around recruitment (e.g. why some people chose not to take part)

5. Were the data collected in a way that addressed the research issue?

Consider:

- If the setting for the data collection was justified. If it is clear how data were collected
- (e.g. focus group, semi-structured interview etc.)
- If the researcher has justified the methods chosen

- If the researcher has mad e the methods explicit (e.g. for interview method, is there an indication of how interviews were conducted, or did they use a topic guide)?

- If methods were modified during the study. If so, has the researcher explained how and why?
- If the form of data is clear (e.g. tape recordings, video material, notes etc.)
- If the researcher has discussed saturation of data

6. Has the relationship between researcher and participants been adequately considered?

Consider:

- If the researcher critically examined their own role, potential bias and influence during:
- Formulation of the research questions
- Data collection, including sample recruitment and choice of location

- How the researcher responded to events during the study and whether they considered the implications of any changes in the research design

- Has the relationship between researcher and participants been adequately considered?

Consider:

- If the researcher critically examined their own role, potential bias and influence during:

- Formulation of the research questions

- Data collection, including sample recruitment and choice of location

- How the researcher responded to events during the study? Have they considered the implications of any changes in the research design?

7. Have ethical issues been taken into consideration:

Consider:

- If there are sufficient details of how the research was explained to participants for the reader to assess whether ethical standards were maintained

- If the researcher has discussed issues raised by the study (e.g. issues around informed consent or confidentiality or how they have handled the effects of the study on the participants during and after the study)

- If approval has been sought from the ethics committee

8. Was the data analysis sufficiently rigorous?

Consider:

- If there is an in-depth description of the analysis process

- If thematic analysis is used. If so, is it clear how the categories/themes were derived from the data?

- Whether the researcher explains how the data presented were selected from the original sample to demonstrate the analysis process

- If sufficient data represented to support the findings

- To what extent contradictory data are taken into account

- Whether the researcher critically examined their own role, potential bias and influence during analysis and selection of data for presentation

9. Is there a clear statement of findings?

Consider:

- If the findings are explicit
- If there is adequate discussion of the evidence both for and against the researcher's arguments

- If the researcher has discussed the credibility of their findings (e.g. triangulation, respondent validation, more than one analyst)

- If the findings are discussed in relation to the original research question

10. How valuable is the research?

Consider:

- If the researcher discusses the contribution the study makes to existing knowledge or understanding e.g. do they consider the findings in relation to current practice or policy, or relevant research-based literature?

- If they identify new areas where research is necessary
- If the researchers have discussed whether or how the findings can be transferred to other populations or considered other ways the research may be used

Appendix E

Journals, Other Sources, A to L, Number, and Author of Studies

Journals, Other Sources, A to L, Number, and Author of Studies

Journal name	*N*	Study authors
Aircraft cabin bleed air: A review	1	Day, (2015)
Annual Occupational Hygiene	1	Grajewski, Waters, Yong, Tseng, Zivkovich, & Cassinelli, (2011)
American Journal of Public Health	1	Detels, Tashkin, Sayre, Rokaw, Massey, Coulson, & Wegman (1991)
Archives of Environmental Health	1	Abou-Donia, (2003)
Archives of Toxicology	1	Centers, (1992)
Atmospheric Environment	1	Rai & Chen, (2012)
Aviation safety network news: List of aircraft accidents and Incidents intentionally caused by pilots	1	Flight Safety Foundation, (2015)
Aviation Space and Environmental Medicine	5	Sliwka, Kransey, Simon, Schmidt & Noth, 1996; Oksanen, 1998; Irvine & Davies, 1999; Parker, Stepp, & Snyder 2011; Orsello, Moore & Reese, 2013
The airliner cabin environment and the health of passengers and crew	1	National Research Council, 2002
Cabin air quality and aerotoxic Syndrome	1	Spirit Airlines Flight Attendants Association, (2018)

Crew member training on in-flight radiation exposure	2	Federal Aviation Administration, (1994), Federal Aviation Administration, (2014)
Environmental Health	2	McNeely, Gale, Tager, Kinel, Bradley, Coull & Hecker, 2014; Wu, Donnelly-McLay Weisskopf, McNeely, Betancourt, & Allen, 2016
Environmental Health Perspectives	3	Van Kempen, Kruize, Boshuizen, Ameling, Staatsen & De Hollander, 2002; 2006; Bell, Peng, & Dominici, Satish, Mendell, Shekhar, Hotchi, Sullivan, Steufert & Fisk, 2012
Environmental Research	1	Winder & Balouet, (2002)
Environmental Science and Technology	1	Weisel, Weschler, Mohan, Vallarino, & Spengler, 2013
Indoor Air	4	Lee, Poon, Li, & Luk, 1999; Lindgren & Norback, 2002; Waters, Bloom, Grajewski & Deddens, 2002; Spengler, Ludwig, & Weker, 2004
Inflight monitor/onboard Monitoring: ACER's component For ASHRAE 1262	1	Spengler, Vallarino, McNeely, Estephan & Sumner, (2012)
International Journal of Environmental Health	1	Tomei, De Sio, Tomao, Anzelmo, Boccolo, Ciarrocca, & Rosati (2005)

Appendix F

Systematic Review of Studies

Systematic Review of Studies

Author and date	Topic	Source design
Abou-Donia, 2003	Examined & reviewed the neurotoxicity of compounds organophosphorus found in jet oils & the long-term neurological effects	Journal article
Allen, Sumner, Nishioka, Vallarino, Turner, Saltman, & Spengler, 2013	Investigated the exposure of flight crew to air concentrations of PBDEs	Journal article, observational study
Bagshaw, 2008	Examined & reviewed the effects of cosmic radiation on commercial flight crew & passengers	Journal article, multicase study
Basner, Babisch, Davis, Brink, Clark, Janssen & Stansfeld, 2013	Examined the auditory & nonauditory effects of noise in occupational settings on health	Journal article, cross case study
Beko, Allen, Weschler, Vallarino & Spengler, 2015	Examined the adverse effect of ozone on aircraft passengers in commercial aircraft	Journal article, case study
Bell, Peng, & Dominici, 2006	Investigated ozone exposure and the risk of premature mortality	Journal article, modeling study
Buja, Mastrangelo, Perissinotto, Grigoletto, Frigo, Rausa, & Dominici, 2006	Examined the incidence of various types of cancer among female flight attendants	Journal article, meta-analysis
Bull & Yeomans, 2007	Review of current technologies & future solutions of aircraft cabin air filtration	Technical report
Centers, 1992	Examined the potential formation of a powerful neurotoxic substance trimethylol-propane phosphate in thermally degraded ester turbine lubricants	Journal article
Cox & Michaelis, 2002	Investigated the health symptoms of crew that fly the BAe aircraft in Australia	Journal article, case study

Day, 2015	Reviewed aircraft bleed air contaminants	Technical report
Detels, Tashkin, Sayre, Rokaw, Massey, Coulson, & Wegman, 1991	Examined the lung function changes associated with chronic exposure to photochemical oxidants	Journal article, cohort study
El Ghissassi, Baan, Straif, Grosse, Secretan, Bouvard, Benbrahim-Tallaa, Guha, Freeman, Galichet & Cogliano, 2009	Reviewed & assessed the carcinogenicity of the types of radiation previously classified as carcinogenic to humans & identified additional mechanisms of carcinogenesis	Journal article, IARC official report
Federal Aviation Administration, 1994	Recommended flight crew members be informed about the health risks associated with radiation exposure & provided assistance to make informed decisions regarding their work on commercial air carriers	Government report, FAA Advisory Circular
Federal Aviation Administration, 2004	Updated info for flight crew members be informed about the health risks associated with radiation exposure & provided assistance to make informed decisions regarding their work on commercial air carriers	Government report, FAA Advisory Circular
Flight Safety Foundation, 2015	Investigated the number of aircraft accidents & incidents intentionally caused by pilots not including general aviation	Safety report
Friedberg, Snyder, Faulkner, Darden, & O'Brien, 1992	Examined typical the dose of galactic cosmic radiation received annually by a flight crew member based on flying 1,000 block hours per year and the health effects	Government document, case study
Grajewski, Waters, Yong, Tseng, Zivkovich, & Cassinelli, 2011	Investigated cosmic radiation & circadian rhythm disruption in airline pilots using logbooks	Journal article, case study
Hammer, Blettner, & Zeeb, 2009	Examined the epidemiological studies of aircrew health with a focus on cancer	Journal article, meta-analysis
Hammer, Zeeb, Tveten & Blettner, 2000	Examined the comparability of radiation exposure estimation for methods flight crew	Journal article, multiple case study
Irvine & Davies, 1999	Examined the mortality & life expectancy of male flight deck crew & established if excesses were shown for earlier brain cancer, colon cancer & melanoma	Journal article, comparison case study

Jackson & Earl, 2006	Examined the amount of fatigue that short-haul pilots experienced, comparing low cost and scheduled air line pilots	Journal article
Lee, Poon, Li & Luk, 1999	Investigated the air quality in the cabin of aircraft to measure humidity, carbon dioxide, temperature, ozone, carbon monoxide, & particulate levels	Journal article, case study
Lindgren & Norback, 2002	Examined cabin quality air and in-flight exposure for cabin attendants of specific pollutants during intercontinental flights	Journal article, case study
McNeely, Gale, Tager, Kincl, Bradley, Coull & Hecker, 2014	Examined the health status of flight attendants & compared it to the general population	Journal article, qualitative case study
Murawski & Supplee, 2008	Investigated the health impact, frequency & operational costs of contaminated aircraft air supply on U.S. commercial aircraft	Journal article, cross case study
National Research Council, 2002	Examined the health & safety issues related to cabin air quality in passenger cabins on commercial aircraft, including the aircraft environmental control systems, the sources of contaminants & the toxicity & health effects & how to improve cabin air quality	Government report, multiple case study, book
Oksanen, 1998	Examined the calculated doses of cosmic radiation for full-time flight crew members	Journal article, case study
Orsello, Moore, & Reese, 2013	Examined the effects of noise-induced hearing loss in military aviation & if a difference in incidence rates exists between fixed wing aircraft pilots & rotary wing helicopter pilots	Journal article, case study
Parker, Stepp & Snyder, 2011	Examined the morbidity of pilots airline using the Aviation Medicine Advisory Service & disease conditions reported	Journal article, case study
Rai & Chen, 2012	Investigated & developed a Computational Fluid Dynamics model to predict the ozone distribution in the aircraft cabin	Journal article, case study
Satish, Mendell, Shekhar, Hotchi, Sullivan, Steufert & Fisk, 2012	Examined direct effects of CO2within the range of indoor concentrations on decision making	Journal article, case study

Sechzer, Egbert, Linde, Cooper, Dripps & Price, 1960	Examined the effect of CO2 on arterial pressure, heart rate & plasma concentrations	Journal article, case study
Sliwka, Kransey, Simon, Schmidt & Noth, 1996	Examined the effects of low level elevations of carbon dioxide on cerebral blood flow & autoregulation of the intracerebral arteries in humans	Journal article, case study
Spengler, Ludwig & Weker, 2004	Investigated ozone exposures during transcontinental & transpacific flights	Journal article, case study
Spengler, Vallarino, McNeely, Estephan & Sumner, 2012	Examined the environmental conditions in the passenger cabin of aircraft to measure levels of carbon monoxide, carbon dioxide, particles, ozone, volatile organic compounds, semivolatile organic compounds, carbonoyls, & tricresyl phosphate	Industry technical report
Spengler & Wilson, 2003	Reviewed the NRC reports regarding air quality in aircraft	Conference proceeding Multiple case study
Spirit Airlines Flight Attendants Association, 2018	Policy for fume event procedure	Technical report
Thom, Bhopale, Hu & Yang, 2017	Investigated the impact of CO2 elevated levels in mice & the inflammatory responses	Journal article, controlled study
Tomei, De Sio, Tomao, Anzelmo, Boccolo, Ciarrocca & Rosati, 2005	Evaluated if chronic exposure to noise could be a risk for hypertension	Journal article, case study
Van Kempen, Kruize, Boshuizen, Ameling, Staatsen & de Hollander, 2002	Investigated the relationship between noise & blood pressure & heart disease	Journal article, meta-analysis
van Netten, 1998	Investigated the relationship between air quality & health effects on the BAe146-200 aircraft	Journal article, case study
Waters, Bloom, Grajewski & Deddens, 2002	Measured &examined the levels of contaminants on commercial aircraft & their relationships between flight factors such as aircraft size, flight length, occupancy, ventilation & environmental parameters	Conference proceedings, case study

Weisel, Weschler, Mohan, Vallarino & Spengler, 2013	Examined the ozone levels on aircraft during cruise flight with a catalytic convertor & without	Journal article, case study
Winder & Balouet, 2002	Examined the hazards of the toxicity of ingredients found in commercial jet oils	Journal article, case study
Wu, Donnelly-McLay, Weisskopf, McNeely, Betancourt & Allen, 2016	Examined airline pilot mental health& suicidal thoughts	Journal article, cross-sectional descriptive study

Author and date	*N* Sample Characteristics	Data collection method	Data anaylsis method	Findings	Quality
Abou-Donia, 2003	Lab rats, mice, & guinea pigs	Documents, observations	Cross case analysis, triangulation of data	Exposure to organophosphorus compounds may cause OPICN, which produces several neurological disorders	9
Allen, Sumner, Nishioka, Vallarino, Turner, Saltman, & Spengler, 2013	*N* = 59 Air samples collected from different aircraft	Field samples	Bayesian Decision Analysis quantitative analysis	The inhalation exposures aboard in-flight aircraft are not likely to cause the average daily dose of polybrominated diphenyl ethers to exceed EPA standards	10
Bagshaw, 2008	Country specific commercial pilots-- Iceland, Britain, Germany	Documents, archival information	Examination, synthesis, qualitative triangulation of data	Evidence indicates airline crew & passengers are exposed to elevated levels of cosmic radiation with a low probability of disease from exposure	10
Basner, Babisch, Davis, Brink, Clark, Janssen & Stansfeld, 2013	*N* = 81 Studies & reports regarding	Database studies & reports from PubMed &	Cross case analysis, triangulation	Environmental noise exposure should be	10

	noise & nonauditory effects on health	Social Sciences Citation Index	from various sources of data	regulated &enforced to reduce the auditory & nonauditory health effects, including cardiovascular disease, sleep disturbances, & negative cognitive performance	
Beko, Allen, Weschler, Vallarino & Spengler, 2015	*N* = 83 U.S. domestic & international flights	Qualitative questionnaire, ozone level measurements	Linear regression, multivariate logistic, qualitative data analysis	Exposure to ozone can produce discomfort & various eye & upper respiratory symptoms. It is recommended that the FAA revisit the 1985 regulation on cabin ozone concentration & the mandatory use of catalytic converters on all aircraft should be in place	10
Bell, Peng, & Dominici, 2006	*N* = 98 Large U.S. urban communities	Database documents (U.S. EPA, NMMAPS, U.S. National Climatic Data Center, National Center for Health, iHAPSS)	Bayesian hierarchial model, quantitative analysis	Evidence strongly displays that daily changes & increases in ozone exposure are linked to premature mortality, even at very low pollution levels	
Buja, Mastrangelo, Perissinotto, Grigoletto, Frigo, Rausa, & Dominici, 2006	*N* = 7 Published studies reporting a standard incidence ratio for several cancer types	Meta-analysis, database search of studies: MEDLINE, Toxline, NIOSHTIC, NLM	Two stage Bayesian hierarchial model, qualitative analysis	Studies demonstrated a significant excess of melanoma & breast carcinoma in female flight attendants. Further studies are recommended to study occupational hazard & pregnant flight attendants should be given special protection.	10
Bull & Yeomans, 2007	*N* = 8 Current	Technical assessments	Triangulation of data	Reviewed advantages & disadvantages of	9

	& future technologies for commercial aircraft	& documents		HEPA filters & filter elements for odor & VOC removal. Investigated future technologies for outside air treatment, including carbon adsorbent, catalytic converters, photo catalytic oxidation, plasma oxidation & particulate filtration	
Centers, 1992	Synthetic ester turbine lubricants heated to 350-700 degrees Celcius containing Tmpe & Tcp	Experiments	Data analysis, triangulation of data	Extreme caution must be used in the applications of synthetic lubricants containing both Tricresyl-Phosphate (Tcp) & Trimethylol-propane Esters (Tmpes), both both found in synthetic turbine lubricants, when heated to extreme temperatures between 350-700 degrees C. This combination may produce a highly dangerous neuro-toxic substance called Trimethylol-propane Phosphate	9
Cox & Michaelis, 2002	*N* = 21 19 pilots & 2 flight attendants	Surveys, questionnaires	Qualitative data analysis, triangulation of data	Demonstrated high rates of symptoms, including headaches, eye, skin, & respiratory problems The need for crew to identify & report fume events, along with the airlines & regulatory authority to acknowledge	10

				the issues is recommended to protect crew	
Day, 2015	Representative number of commercial flights in the United States	Air samples, review of previous studies, government policy documents	Qualitative & quantitative data analysis, triangulation of data	Need for additional study & evaluation of air quality on commercial aircraft to assess health risks	10
Detels, Tashkin, Sayre, Rokaw, Massey, Coulson, & Wegman, 1991	*N* = 1099, *N* = 1117, First cohort of nonsmoking residents living in a community with moderate levels of photochemical pollution & second cohort of nonsmoking residents living in a community with high levels of photochemical pollution	Questionnaires, Lung function tests	Triangulation of data, Qualitative analysis	Chronic exposures to a mix of photochemical oxidants, sulfates, & particulates are associated with increase loss of lung function	10
El Ghissassi, Baan, Straif, Grosse, Secretan, Benbrahim-Bouvard, Tallaa, Guha, Freeman, Galichet & Cogliano, 2009	*N* = 11 Radiation types	Documents, case studies	Triangulation of data, qualitative data analysis	Evidence is consistent with previous findings of the cancer causing particles radiation from exposure & the tumor types associated with each type	10
Federal Aviation Administration, 1994	Flight crew members in the U.S.	Policy documents	Policy framework analysis	Air carrier crew members are occupationally exposed to ionizing radiation & it is recommended that they are informed of the health effects & radiation protection practices outlined in this publication	10

Federal Aviation Administration, 2004	Flight crew members in the U.S.	Policy documents	Policy framework analysis	Air carrier crew members are occupationally exposed to ionizing radiation & it is recommended that they are informed of the health effects & radiation protection practices outlined in this publication, along with how to calculate & estimate doses & manage exposures	10
Flight Safety Foundation, 2015	*N* = 13 Aircraft accidents & incidents intentionally caused by pilots.	Aviation Safety official Network reports	Qualitative data	There have been 13 accidents or incidents since 1976 in large aircraft which were intentionally caused by pilots The most common reason was depression	10
Friedberg, Snyder, Faulkner, Darden, & O'Brien, 1992	*N* = 32 U.S. nonstop flights	Computer generated radiation	Quantitative data analysis doses	On the flights compared, the highest dose of galactic radiation received by a crew member based on flying 1,000 annual block hours would be approximately 7.2 msv, which is under the recommended dose of 20 msv per year. However, it does exceed the 2 msv recommended limit for pregnant crew members & precautions should be taken	10
Grajewski, Waters, Yong, Tseng, Zivkovich, & Cassinelli, 2011 circadian	*N* = 83 Male pilots from U.S. major airline	Pilot logbooks, company records, questionnaire data	Constant comparative method, triangulation of data	Pilot's flight exposures to radiation & disruption have increased as found with record-based assessments	10
Hammer, Blettner, & Zeeb, 2009	*N* = 65 Peer reviewed publications from 1990-2008	Documents, case studies	Cross case analysis, triangulation of data, document analysis	Aircrew are at risk for certain cancer types & show an elevated risk of breast cancer & melanoma. Additional data are needed to analyze the risk factors & cancer occurrences of flight	10

				crews	
Hammer, Zeeb, Tveten & Blettner, 2000	*N* = 4 radiation exposure assessment methods	Documents, assessment results	Software, cross case comparison analysis	Recommends using a data set that can use a comparison of all methods, including the job-exposure matrix, logbook data, flight-specific measurements, & employment period for more accurate doses. On board measurement programs may increase data	10
Irvine & Davies, 1999	*N* = 7362 British Airways male pilots & flight engineers employed between 1950 & 1992	Company records	Standardized mortality ration (SMR), cross case comparison analysis	The SMR for melanoma was raised significantly for pilots although the other cancers were not statistically significant	9
Jackson & Earl, 2006	*N* = 162 short-haul pilots in the UK	Qualitative questionnaire	Qualitative data analysis	Found that .75 of the pilots were operating while feeling severely fatigued. The role of fatigue should be examined for short-haul pilots & possible changes or limitations to schedules may be needed	10
Lee, Poon, Li & Luk, 1999	*N* = 16 Cathay Pacific flights from June 1996 to August 1997	Air quality measurements, questionnaires	Qualitative & quantitative data analysis, triangulation of data	The air quality was within standards, however, odor, humidity, noise & temperature provided the highest complaints	10
Lindgren & Norback, 2002	*N* = 26 Intercontinental flights on Boeing 767 aircraft	Air measurements of humidity, temperature carbon dioxide, ozone, respirable particles, nitrogen	Triangulation of data, quantitative data analysis	Relative humidity is low during cruise flight. During noncruise flight, CO2 levels mostly exceeded the recommended value of 1,000 ppm. Better temperature control is also	10

		dioxide, & formaldehyde		recommended	
McNeely, Gale, Tager, Kincl, Bradley, Coull & Hecker, 2014	*N* = 4,011 Flight attendants from 2 domestic airlines	Surveys	Qualitative data analysis, cross case analysis	Higher rates of specific diseases found in-flight attendants than the general population, including cardiac disease chronic bronchitis, sleep disorders, depression, fatigue & reproductive cancers	10
Murawski & Supplee, 2008	*N* = 470 air supply contamination reports in the U.S. commercial aviation from Jan. 2006-June 2007	Official airline documents & reports, including Service Difficult Reports & Accident & Incident Data Systems reports to the FAA, qualitative data	Qualitative data analysis, triangulation of multiple forms of data	The analysis identified an average of .86 air quality events per day over an 18-month period. This frequency finding recommends airlines & regulators to develop & enforce preventive actions	10
National Research Council, 2002	*N* = 6 Air quality measurements in commercial aircraft	Case studies, air quality measurements, documents & reports	Qualitative data analysis, triangulation of multiple forms of data	In flight aircraft occupants are exposed to a combination of environment factors that have negative health effects. This report outlines these effects & recommends approaches to improve cabin air quality	10
Oksanen, 1998	*N* = 2,000 Flight crew members, pilots & cabin crew	Block time, aircraft flight profiles, actual flight time from company records	Triangulation of multiple forms of data	The calculated doses are lower than previously assumed doses. Long distance pilots received the highest doses among all flights	9
Orsello, Moore, & Reese, 2013	*N* = 467,064 all active duty military pilots between 1997-2011, measured in person-years	Defense Medical Epidemio-logical Database	Statistical analysis-two way & multivariate analysis of variance	The mean annual sensorineura hearing loss was higher among fixed wing pilots, & also increased with age	9

Parker, Stepp & Snyder, 2011	*N* = 20,522 All AMAS cases of airline pilots & flight engineers from Jan. 1996-Nov. 1999 from 51 U.S. & Canadian	Aviation Medicine Advisory Service Database	Case analysis, Qualitative data analysis	Cardiovascular conditions accounted for 25% of cases & further study of aviator nondisclosure of medical issues is needed	10
Rai & Chen, 2012	Mockup B767 aircraft cabin, constant ozone concentration of 100 ppb at inlets	Ozone measurements	CFD & Reynolds-averaged Navier-Stokes equations	The human related surfaces removed much more ozone than cabin surfaces. The retention ratios were lower than the FAA recommended values	9
Satish, Mendell, Shekhar, Hotchi, Sullivan, Steufert & Fisk, 2012 Simulation)	*N* = 24 University students	Questionnaires, computerized test of decision making skills (Strategic Management Simulation)	Multivariate analysis of variance, Quantitative data analysis	The direct impacts of elevated CO2 on performance was found	10
Sechzer, Egbert, Linde, Cooper, Dripps Price, 1960	*N* = 12 male volunteers	Observations, blood sampling, ECG readings	Quantitative data analysis, triangulation of data	Respiratory volume, arterial pressure & plasma concentrations were increased for every subject	9
Sliwka, Kransey, Simon, Schmidt & Noth, 1996	*N* = 4 male subjects, healthy, nonsmokers, 22-27 years of age	Blood sampling, cerebral blood flow velocity, fundoscopy	Triangulation of data	The data proves a readjustment of cerebral blood flow over time during exposure to low levels of hypercapnia.	9
Spengler, Ludwig & Weker, 2004	*N* = 106 Commercial flight segments monitored for 145 time-integrated measurements	Ozone monitoring samplers, flight data information Standards.	Quantitative data analysis, predictive data analysis	Ozone concentrations on long haul flights are high enough to exceed U.S. EPA & FAA Recommended that the FAA revise its ozone regulations	10
Spengler, Vallarino, McNeely, Estephan & Sumner, 2012	*N* = 83 passenger flights	Air quality measurements	Quantitative data analysis, triangulation	The findings suggest the FAA should reevaluate current Federal Aviation	10

			of data	Regulations on environmental requirements on aircraft. There are additional data now available on irritation & discomfort of exposures on aircraft	
Spengler & Wilson, 2003	Multiple flight segments	Document analysis, federal reports of data	Qualitative data analysis, triangulation	Environmental conditions on aircraft exposed crew & passengers to greater risk of toxic exposures	10
Spirit Airlines Flight Attendants Association, 2018	*N* = 12 Procedures for fume event reporting	Policy documents, aircraft checklists	Qualitative data analysis, triangulation of data	Aerotoxic syndrome & cabin air quality events must be identified & reported	10
Thom, Bhopale, Hu & Yang, 2017	*N* = 16 Mice exposed to CO2, purchased from Jackson Laboratories	Measurements of elevations in circulating microparticles (MPs) & whether the MPs cause vascular insult	Quantitative data analysis	Environmentally relevant elevations of CO2 generate MPs causing vascular injury	9
Tomei, De Sio, Tomao, Anzelmo, Boccolo, Ciarrocca & Rosati, 2005	*N* = 301 male pilots, jet & turboprop aircraft	Electro-cardiogram, stress tests, & audiometric tests	Observations, triangulation of data	Ergometric tests conclude that exposure to higher levels of noise influence & increase the risk for blood hypertension & hearing loss in pilots	10
Van Kempen, Kruize, Boshuizen, Ameling, Staatsen & de Hollander, 2002	*N* = 43 epidemiologic studies from 1970-1999	Medline, Embase, Biosis, & Scisearch databases	Triangulation of data, cross case analysis	A significant association was found between noise exposure, both air traffic & occupational noise and hypertension	10
van Netten, 1998	*N* = 3 noncompliant aircraft tested (two BAe 146 & one de Haviland Dash 8-100)	Air quality measurements	Quantitative data analysis, triangulation of data	The air quality measurements showed 800-2,700 ppm for carbon dioxide, & no detectable levels of carbon monoxide	10
Waters, Bloom,	*N* = 36	Air sampling,	Triangulation	Carbon dioxide exposures	10

Grajewski & Deddens, 2002	commercial aircraft	environmental monitoring	of data, quantitative data analysis	were highest on shorter, high occupancy flights in narrow body aircraft & the levels indicated lower ventilation rates than most other indoor environments.	
Weisel, Weschler, Mohan, Vallarino & Spengler, 2013	*N* = 52 U.S. transcontinental & international flights	Air samples	Linear regression models, quantitative data analysis	Peak ozone levels on aircraft without catalytic convertors exceeded 100 ppb & ozone was greatly reduced on aircraft with catalytic convertors. Ozone is also added to the air by reacting with common indoor contaminants	10
Winder & Balouet, 2002	Commercial jet oil containing synthetic compounds	Document analysis	Qualitative analysis; document analysis	Jet oils are known to contain toxic ingredients, & exposure through oil leaks may cause health implications	10
Wu, Donnelly-McLay, Weisskopf, McNeely, Betancourt & Allen, 2016	*N* = 1,837 Pilots in unions, airlines, & airports via convenience sampling	Anonymous web-based survey	Calculating absolute number and prevalence of health characteristics and depression scores	12.6% of pilots meet depression thresholds & 4.1% have suicidal thoughts. There is a significant number of pilots flying with depressive symptoms	10