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Distinguishing Between Dynamic Altitude Breathing Threats to Improve Training

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ABSTRACT

Breathing related adverse physiological conditions are a prominent Warfighter pilot problem (Inspector General 2020). As a result of an investigation citing multiple types of adverse physiological conditions with various causes and symptoms (DoN 2017), there have been changes to training requirements to broaden the focus to include Dynamic Altitude Breathing Threat Training (DoN 2020). However, there remain questions about symptom definitions, distinctiveness, and response procedures that influence the content of this new training. In order to investigate the effects of different breathing conditions, the authors propose a between subjects design with adjustments to breathing conditions (i.e., restricted oxygen, restricted inhalation, restricted exhalation) using a mask on breathing device. Dependent measures include physiological data and pilot symptomology. The objective of this investigation is to inform awareness training for dynamic altitude breathing threats by validating instructional strategies and standard operating procedures for training implementation.

Keywords: Aviation survival training, Instructional capabilities, Navy aviation, Feedback

INTRODUCTION

Dynamic altitude breathing threats that result in adverse symptoms of a physiological, psychological, pathological, or physical nature and occur during or after a flight have a long history in aviation (Department of the Navy [DoN], 2020; Eckstien 2020). Adverse physiological conditions have been identified by multiple U.S. Government agencies as one of the prominent Warfighter pilot problems requiring attention and rapid solutions (DoN 2017; Inspector General 2020; National Aeronautics and Space Administration [NASA], 2020). Over the last decade, investigations resulted in a distinction between adverse symptoms that are not caused by normal or abnormal operation of the aircraft and adverse symptoms that are suspected to be caused by aircraft or system malfunctions (DoN 2020). Historically, hypoxia (i.e., a deficiency in the amount of oxygen reaching the tissues) has been the primary adverse physiological condition of interest, given that the relationship with increasing altitude and decreasing oxygen availability is well-established

(NASA 2020). However, the increasing occurrence of adverse physiological symptoms not resolved by hypoxia incident emergency procedures (EPs) led to a more thorough investigation into adverse physiological conditions and their potential causes (DoN 2017). Extensive investigation and reporting found that there was not one simple solution (Eckstien 2020); instead, multiple types of adverse physiological conditions were identified with various causes (NASA 2020). This finding has resulted in changes to Dynamic Altitude Breathing Threat Training requirements outlined in Naval Aviation Training and Operating Procedures Standards (NATOPS) General Flight and Operating Instructions Manual (DoN 2020). For instance, hypoxia, decompression illness, and hypocapnia (i.e., a state of reduced carbon dioxide in the blood)were identified as adverse physiological conditions with causes including insufficient oxygen, evolved gases, and depressurization requiring awareness training (DoN 2017; DoN 2020). Further, a range of adverse physiological conditions and common symptoms were published to increase aviator awareness (DoN 2020).

As gaps are found throughout the Department of Defense (DoD) aviation system, actions are taken to address them. One of the gaps identified is the knowledge gap of understanding the multiple adverse physiological conditions and root causes not always engrained in aircraft and system malfunctions. Addressing this knowledge gap will require better matching of conditions and causes to inform training requirements, as well as clearly defining symptoms and mapping them to their potential root causes. Finally, appropriate response procedures must be outlined according to the cause of the adverse condition. It is especially important to distinguish between adverse physiological conditions that may have a similar subset of symptoms but opposite response procedures. Another gap that has been identified is insufficient equipment-based alerting systems and/or sensors incorporated into aircraft prior to the 2018 NASA investigation (United States Air Force Scientific Advisory Board [USAF SAB], 2012). As a result, pilots participated in testing of sensors integrated into DoD aircraft oxygen systems for real-time capture of a variety of variables (Cobham Mission Systems 2018). The new capabilities facilitate the collection of data (i.e., physiological variables, breathing gas composition, cockpit environmental factors) in addition to the standard pilot self-report data. A main takeaway from this data pairing is that every incident pilots reported was supported by equipment and/or sensor data (NASA 2020). In part due to the success of this initial technology integration effort, DoD services continue to explore means to increase sensors and alerting technology to inform future exploration and integration to increase aviator safety.

USING SYMPTOMS AS POSSIBLE TRAINING VARIABLES

Given the current gaps in research and training, there is a need to develop procedures or instructional methods that increase the likelihood of operator detection of adverse physiological conditions and support sound decision making to distinguishing between physiological conditions and, as a result, their potential root causes (e.g., equipment malfunctions). The most studied and understood adverse physiological condition is hypoxic hypoxia. Hypoxic hypoxia is defined “as a reduction in available oxygen” (DoN 2017; Federal Aviation Administration [FAA], 2016). Within aviation environments specifically, the most common causes are altitude or a problem with the oxygen supply system leading to reduced partial pressure (DoN 2017). Symptoms include but are not limited to: euphoria, visual disturbances, nausea, lightheadedness, tingling or cold extremities, headache, fatigue, dizziness, cognitive impairment or disorientation, and in severe cases loss of consciousness (DoN 2020; NASA 2020). The listed symptoms are not unique to hypoxic hypoxia. There are challenges related to the fact that different conditions can cause similar symptoms.

An example of the ambiguity of symptoms creating challenges is that both hypoxic hypoxia and hypocapnia (low blood CO2 caused by hyperventilation) can cause almost identical symptoms. According to current DON training (DoN 2020), symptoms associated with hypocapnia include cognitive impairment or disorientation, dizziness, fatigue, headache, tingling or cold extremities, lightheadedness, and visual disturbances. This list of symptoms are identical to that of hypoxia with the exceptions of nausea and euphoria, which are only associated with hypoxia (DoN 2020). In addition, while hyperventilation is suggested as a cause for hypocapnia, there is not uniform agreement on the cause(s) of hyperventilation. It is possible hyperventilation is caused by a psychological response such as anxiety (FAA 2016) or a reflex triggered by CO2 concentration (USAF SAB 2012). Further, mask malfunctions may contribute to breathing changes that result in hyperventilation. Current aviation guidance recommends treating both hypoxia and hyperventilation if hyperventilation is suspected by having pilots slow their breathing rate and access supplemental oxygen (FAA 2016). In sum, the symptoms listed overlap significantly, and although they may have different root causes, the prescribed self-treatment for both conditions is identical. Further investigation to validate the current prescribed treatment as the best approach is warranted.

Another breathing related adverse physiological condition is hypercapnia, which may be related to restricted exhalation. Similar to hypocapnia, hypercapnia is a high level of CO2 in the blood, and is “often due to hypoventilation (decreased breathing rate)” (DoN 2017). When breathing rate decreases, the amount of incoming oxygen decreases, which leads to more CO2 retention. Another potential cause of hypercapnia is a decrease in nominal flow rate, which accidentally occurred during NASA training and led to acute CO2 exposure training since the 1990s (Law, et al. 2017). The most commonly reported symptoms of hypercapnia during this training were respiratory related symptoms (e.g., air hunger, breathing difficulty, increased breathing rate, shortness of breath) followed by symptom groupings flushing sensation/sweating, dizziness/feeling faint/lightheadedness, headache, and visual disturbance (Law, et al. 2017). However, as previously noted, the grouping of symptoms makes direct comparisons between adverse physiological condition symptom frequencies difficult. Further, the increase of CO2 content may physiologically present similarly to hypoxia (DoN 2017). In fact, the symptoms associated with hypercapnia include visual disturbances, nausea, tingling or cold extremities, headache, fatigue, dizziness, and cognitive impairment or disorientation (DoN 2020). As with hypocapnia, the only symptoms not associated with hypercapnia and only associated with hypoxia are euphoria and lightheadedness. When comparing hypercapnia and hypocapnia, the only symptom differences are nausea (experienced in hypercapnia) and lightheadedness (experienced in hypocapnia; DoN 2020).

The overlap in symptomology presents a challenge for aviators to determine which adverse physiological condition they may be experiencing without additional training or sensor-based information. Current training lacks the capability to provide an experience that emulates a variety of adverse physiological conditions, and therefore has not focused on distinguishing among these experiences and required EPs. Further research is needed to design training capabilities and evaluate instructional methods that enable aviator understanding of a broader range of adverse physiological conditions. Through this research, there is an opportunity to define and validate effective training for more comprehensive identification, troubleshooting, and decision making related to physiological symptoms experienced in flight. Part of the solution is to leverage what is known about symptomology to extend testing of adverse symptom causes and development of possible training solutions.

ADVERSE PHYSIOLOGICAL SYMPTOMS AND EQUIPMENT VARIABLES

After training aircraft were grounded for unexplained adverse physiological symptoms in 2017 (DoN 2017), pilot interviews were implemented to better understand the symptoms they had experienced (NASA 2020). While pilots may not have described the specific adverse physiological conditions mentioned above, there are excerpts that discuss occasional difficulties associated with using the equipment to breathe that align with physiological symptoms or conditions. Specifically, these experiences seem to indicate restricted breathing, the causes of which may be equipment related. For instance, one pilot reported that "during maximum inhalation, [they] noticed one of the valves in my mask seemed to collapse, restricting O2 flow by about 50%. This happened multiple times during Max inhalation both on the ground and in flight" (NASA 2020). Another comment found the "O2 mask exhalation valve sticky after max exhale events" (NASA 2020). These comments about difficulty inhaling or exhaling represent a larger sample where sensor system readings (i.e., cabin pressure, line pressure, mask pressure, flow, oxygen levels) corroborated pilot reports (NASA 2020).

Since it is clear that adverse symptoms are at times related to equipment malfunctions, failures, or human factors issues (e.g., oxygen system malfunctions, mask valve failure, improper mask fit) in addition to warfighter physiology, it would be logical to extend training to reflect these situations. Extending training may require testing capabilities and studying the effects (symptoms) of introducing potential breathing complications that could result from equipment in order to induce adverse physiological conditions. Given that equipment is not infallible, but is often repairable, when feasible, there may be opportunities for aviators to diagnose and repair equipment issues that might affect their breathing. However, as outlined in the previous section, similar obstacles exist for training these breathing experiences compared to other adverse physiological conditions. Symptoms can largely be similar, and current training does not expose aviators to these situations nor provide a means for them to differentiate between their individual physiological responses. With advances in training to include these types of scenarios, at a minimum, aviators will be better positioned to think critically regarding their situation and, at best, optimize troubleshooting and decision making associated with varying emergency procedures or mitigation techniques. A key element in meeting these objectives is to determine symptoms and factors that distinguish adverse physiological conditions and system-based issues to inform training.

POSSIBLE PHYSIOLOGICAL TRAINING VARIABLES

The common symptoms of adverse physiological conditions suggest a wide range of organ systems are involved when breathing-related challenges occur, and indeed, medical research suggests conditions such as hypoxia and hypercapnia impact various systems in different ways. For instance, altitude induced hypoxia (measured by blood/arterial oxygen saturation) is related to changes in heart rate, respiratory responses, hormone levels, and neurological responses (Cymerman, et al. 2005; Cymerman, et al. 2003). The detailed interactions of these systems in response to hypoxia are better understood in some systems than others. For example, reduced oxygen would presumably trigger a respiratory and/or pulmonary response as measured by oxygen saturation (SpO2) or heart rate, as the system is directly responsible for supplying oxygen to the body. In hypoxia research, changes in both heart rate and breath rate differ between normal and hypoxic states, indicating potential physiology-based indicators (Haran & Florian 2014). Neurological responses to adverse physiological conditions are logical, as the brain and nervous system are responsible for a large portion of metabolic demand, including oxygen. Hypoxia and hypercapnia have been found to cause delayed reaction time and cognitive performance decreases (Morgan, et al. 2015). In addition, the brain controls physiological functioning and therefore may cause physiological responses to hypoxia. In fact, investigations in aviation have found that ocular metrics such as blink rates and dwell time, or the amount of time spent focused on a single stimulus, increase during hypoxic conditions compared to normal conditions (Stepanek, et al. 2014; Thropp, et al. 2018).

Better understanding of physiological changes that come with adverse physiological conditions can provide a missing puzzle piece when considering how to identify and train mitigation approaches. There is an opportunity to integrate physiological data into training (e.g., heart rate, SpO2, breath rate, ocular metrics) such that aviators can better understand individual reactions to various adverse physiological conditions and react accordingly. This will help aircrew make the link between physiological response, symptoms, and emergency procedures.

APPLYING KNOWLEDGE FROM RELEVANT DOMAINS

Research in other domains (e.g., diving, medical, driving) can provide some additional insight into the challenge of understanding the complexity of adverse physiological conditions and how best to conduct safety training related to them. In diving, similar to aviation, breathing practices have serious implications. Hyperventilation can increase this ability while leaving oxygen levels relatively unchanged since it expels carbon dioxide in the blood, delaying the urge to breathe (Lindholm & Lundgren 2006; Kumar & Ng 2010; Wilmshurst 1998). However, that same reduction in hypercapnia and the urge to breathe can lead to hypoxic loss of consciousness (Lindholm & Lundgren 2006; Kumar & Ng 2010). The complexity of hyperventilation, hypercapnia, and hypoxia in a similar air-deprived environment underlines the importance of training good breathing practices. In the medical domain, research has found that pupil responses are effective at predicting prognosis in cardiac-arrest induced hypoxia patients (Oddo, et al. 2018; Riker, et al. 2020) and predicting increased intracranial pressure hours before patients experience that symptom (Chen, et al. 2011; McNett, et al. 2017; Solari, et al. 2018). The driving domain has taken ocular metric findings one-step further than aviation by creating both proof-of-concepts and real-life products for alerting operators of fatigue (Hartley, et al. 2000; Shekari Soleimanloo, et al. 2019). In addition, driving research has found heart rate data is a physiological measure indicating operator status (e.g., fatigue; O'Hanlon 1972; Tran, et al. 2009) which may carry over into aviation. Therefore, reliable and fully validated physiological indicators or predictors of adverse physiological conditions have the potential to better inform effective training that encompasses dynamic breathing related threats.

PROPOSED INVESTIGATION

To address this emerging training need and explore the variation in experiences associated with different adverse physiological conditions and symptom profiles, the authors designed a study to provide guidance and solutions for broader dynamic altitude breathing threats training requirements.

In order to investigate the effects of different breathing conditions, the study will use a mask-on breathing device – the Flight Breathing Awareness Trainer (Atkinson, et al. 2002) – to modify breathing-related variables (e.g., flow rate, pressure, oxygen concentration) during training. A between subjects design with breathing condition (reduced oxygen, restricted inhalation, restricted exhalation) is planned. Dependent measures include physiological data (SpO2, heart rate, respiration rate), pilot symptomology (type and severity), eye tracking, and speech analysis. Participants will experience the breathing condition while completing flight related tasks in a medium-fidelity simulator.

The study findings are necessary to inform awareness and mitigation procedure training. The differences between these conditions in terms of physiological data, equipment output, and pilot experience are required baselines to craft training procedures that support instruction of the dynamic nature of altitude breathing threats and, if possible, increase aviators' ability to critically think about each event type experienced to enhance troubleshooting and decision making. Identifying differences in adverse physiological conditions is required to accomplish the ultimate goal of creating valid training technologies and strategies for dynamic altitude breathing threats training.

FUTURE DIRECTIONS

The first step to creating useful dynamic altitude breathing threats training for pilots is finding useful indicators of each type of adverse physiological condition. Traditionally, this has meant informing pilots of potential adverse physiological conditions and common symptoms associated with each specific condition such as hypoxia, then relying on pilots to self-identify when these symptoms are occurring. Based on the NASA report, additional metrics from sensor-based equipment might be better suited to indicate or predict when a particular adverse physiological condition is occurring. Any equipment or physiological indicators such as the proposed eye tracking or speech metrics will need to be validated in future studies. Future efforts will also need to establish the best practices for debriefing in training, to include reliable metrics, effectiveness of feedback leveraging data, and visualizations that increase understanding and retaining information. The authors propose one study toward this aim, and will use its results to provide guidance and solutions for broader dynamic breathing threats training requirements in Naval aviation applications.

AUTHOR'S NOTE

The views of the author expressed herein do not necessarily represent those of the U.S. Navy or Department of Defense (DoD). Presentation of this material does not constitute or imply its endorsement, recommendation, or favoring by the DoD. NAWCTSD Public Release 22-ORL021 Distribution Statement A. Approved for public release; distribution is unlimited.

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