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THESIS

**TRUSTING YOUR INSTRUMENTS: LEVERAGING
WEARABLE DEVICES TO IMPROVE PRE-OPERATIONAL
FATIGUE ASSESSMENT BY U.S. COAST GUARD AIRCREWS**

by

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**TRUSTING YOUR INSTRUMENTS: LEVERAGING WEARABLE DEVICES TO
IMPROVE PRE-OPERATIONAL FATIGUE ASSESSMENT BY U.S. COAST
GUARD AIRCREWS**

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ABSTRACT

Existing U.S. Coast Guard (USCG) aviation policies rely on crew members to self-diagnose their personal level of fatigue based on their perceived hours of sleep, with the only quantifiable factor at their disposal being their alleged hours of sleep. With the continued improvement in wearable technology, measurable data may be readily available for aircrew to make a more informed and accurate assessment of their preflight readiness. This study sought to identify the legal and social considerations affecting the implementation of wearable technology to assess crew fatigue in the USCG, and provide recommendations regarding how to incorporate these new technologies into preflight operation risk-assessment processes. The results of this study do not support an immediate investment in a full-scale USCG aviation wearables program. However, they do highlight the potential role that wearables might play in helping policymakers by quantifying the fatigue currently experienced by aircrew under existing policies and practices. Finally, the study identifies data privacy as a key potential barrier to wearable acceptance and recommends the unprecedented preemptive application of legal privilege to wearable data used by aircrew as part of risk-management process in order to encourage user acceptance.

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LIST OF ACRONYMS AND ABBREVIATIONS

AARP	American Association of Retired Persons
AC	Aircraft Commander
BIPA	Biometric Information Privacy Act
CAGR	compound annual growth rate
CCPA	California Consumer Privacy Act
COTS	commercial off-the-shelf
ECG/EKG	electrocardiogram
EEG	electroencephalogram
EEOC	Equal Employment Opportunity Commission
EOG	electrooculogram
EULA	end user license agreement
FAST	Fatigue Avoidance Scheduling Tool
GDPR	General Data Protection Regulation
HIPAA	Health Information Portability and Accountability Act
HRV	heart rate variability
IBI	inter-beat interval
MUTAUT	Modified Unified Theory of Acceptance and Use of Technology
NHRC	Naval Health Research Center
NMCCA	Navy and Marine Corps Court of Military Appeals
ORM	operational risk management
RATE	Rapid Analysis of Threat Exposure
SAFTE	Sleep and Fatigue Task Effectiveness
SAO ₂	blood oxygen saturation
TAM	technology acceptance model
USCG	United States Coast Guard
UTAUT	Unified Theory of Acceptance and Use of Technology

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EXECUTIVE SUMMARY

This study sought to identify the legal and social considerations affecting the implementation of wearable technology to assess crew fatigue in the U.S. Coast Guard (USCG), and specifically provide recommendations regarding how to incorporate these new technologies into preflight operation risk assessment processes. The study includes a business case analysis, in which the theoretical cost of a USCG aviation wearables program is compared to the historical financial cost of Class A and B aviation mishaps attributed to fatigue-related causal factors. Qualitative analysis then addresses three key aspects policymakers should consider as part of implementing such a program: accuracy, authority, and acceptance.

Qualitative analysis of existing studies indicate that some wearables are capable of providing accurate physiological data that may provide insights into aircrew fatigue. Specifically, devices which measure heart rate variability and ocular measurements, like blink rate, may prove useful in providing an improved quantitative depiction of aircrew fatigue. However, existing research indicates that the field of wearable technology is rapidly changing, and capabilities are specific to each device and software configuration. As such, policymakers should leverage recent, scientifically sound assessments of specific devices considered for any specific program.

The rapidly evolving field of wearable devices creates another dimension of ambiguity related to the USCG's authority to monitor its members' physiological markers both on and off duty. While military service members have historically been deemed to have a reduced expectation of privacy by military courts, the Supreme Court has yet to rule on cases in which limitations on Fourth Amendment protections are defined. Further, the evolving application of privacy laws to increasingly capable and ubiquitous personal devices provides as many questions as answers. The USCG may have the authority to mandate that its members participate in wearable monitoring programs, both on and off duty. However, such a mandate would be an unprecedented test of military authority. In the context of *Carpenter vs. the United States*, policymakers would do best to assume that

the Court may place an increased emphasis on citizens' technological privacy expectations, even if they are military members.¹

To provide insight into the potential acceptance of wearables by USCG aviation personnel, this study issued a wearable wrist strap to 20 active-duty aircrew for a 30-day period, and allowed members to utilize the data that the straps provided as part of their normal preflight operational risk-management practices. Using a modified version of the Unified Theory of Acceptance and Use of Technology (UTAUT) as a model,² pre- and post-surveys gathered input from subjects on the relative importance of five key influencing variables related to acceptance, as well as changes in subjects' preferences based on a 30-day exposure to the device. The results of the observation were statistically inconclusive, primarily due to the small sample size and short duration of the experiment. However, the descriptive statistics suggested that subjects may experience an increase in performance expectancy after using the device. Subjects rated their relative trust for information to determine their level of fatigue (1–6 scale) between their own intuition (1) and a wearable device (6). Over the course of observation, mean responses shifted from slight distrust of wearables on pre-survey scores ($M = 2.90$) to slightly greater trust for wearables ($M = 3.45$) on post-surveys. Additionally, survey responses regarding privacy concerns about commercial ($M = 3.81$) and USCG ($M = 3.87$) data access identified privacy as a potential factor for inhibiting wearable acceptance, and remained ostensibly unchanged between pre- and post-surveys. Qualitative input received from subjects in the form of survey comments provided additional support for this likelihood. Sleep data gathered by the wearable devices reported a mean nightly hours of sleep for all subjects as $M = 6.82$ and identified three subjects who averaged less than six hours of sleep over the course of the 30-day period. These data align with previous studies that raise questions as to whether existing USCG aviation crew rest policies are effective at ensuring that aviators receive adequate sleep prior to flight.

¹ *Carpenter v. United States*, 585 U.S. No. 16–402 (2018), 119. Justia Law, <https://supreme.justia.com/cases/federal/us/585/16-402/>.

² Viswanath Venkatesh et al., “User Acceptance of Information Technology: Toward a Unified View,” *MIS Quarterly* 27, no. 3 (2003): 425–78, <https://doi.org/10.2307/30036540>.

The results of this study do not support an immediate investment in a full-scale USCG aviation wearables program. However, they do highlight the potential role that wearables might play in helping policymakers quantify the fatigue experienced by aircrew under current policies and practices. Additional research should seek to leverage such devices on a larger scale and for a more prolonged period. The data provided by such research might be useful for other USCG subgroups as well. Training environments in particular (Bootcamp, Aviation Survival Technician A-School) could gather objective measurements of the strain and recovery placed on students, and modify programs based on quantifiable data.

The importance of trust in facilitating the effective implementation of a wearables program became clear throughout the study. In particular, survey results regarding privacy concerns identified this factor as a potential roadblock to successful implementation. Based on these observations, this study recommends that only voluntary programs be pursued in the near term in order to continue to normalize wearable use. Finally, the study recommends the potential preemptive application of legal privilege to wearable data used by aircrew as part of risk-management processes. Though unprecedented, this strategy may enable the application of a proven safety concept that would enable military members to incorporate wearable data into their risk-management decisions without fear of having that data used against them in a legal or administrative processes.

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Thanks to the commands and crew at Coast Guard Aviation Training Center Mobile, Alabama, and Air Station Port Angeles for shouldering the burden of this effort. Thank you to the Naval Postgraduate School's Crew Endurance Program and the U.S. Coast Guard's Aviation Safety program for their support, inspiration, and insight.

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Most importantly, thank you to my wife, Heidi, and our two little heroes. You put the team on your back in order to create the time for this program in the midst of a global crisis. Thanks for the love, support, and kicks in the butt.

Lastly, thanks to the aircrews who sacrifice so much and are willing to sacrifice everything to defeat our adversaries or save those in need. Fly safe. Have fun.

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I. INTRODUCTION

The alarm sounds, propelling each crew member of the 420-foot long U.S. Coast Guard (USCG) cutter into action. Another asset has identified what may be a drug smuggling “go-fast” vessel within the vicinity of the cutter, transiting north at a high rate of speed. The cutter’s crew moves quickly into assigned positions to interdict the suspicious vessel. A few members of the crew are already awake, standing watch through the night. The rest are drawn immediately from their slumber and channeled into a thoroughly practiced and well-choreographed operation. Among those, the cutter’s embarked aircraft commander musters in the vessel’s Combat Information Center while his crew prepares the helicopter for launch and readies its weapons. In a matter of minutes, his aircrew will be airborne and tasked with locating and identifying the go-fast, and, if necessary, firing .50 caliber rounds from the precision marksman’s rifle into the vessel’s engines in order to facilitate its interdiction.

Following the brief, the aircraft commander walks deliberately to the aircraft, loads his personal weapon, and musters his aircrew. Under the blue lights that illuminate the flight deck beneath the darkened sky, the crew briefly discusses the specific details related to this specific mission. This discussion includes the application of operational risk management (ORM), in which they identify the effects of potential hazards that may impact the execution of the mission, and ways to eliminate or mitigate them. Earlier that evening, the aircraft commander conducted a preflight inspection of their aircraft and conducted a systematic review of its maintenance records. He is intimately familiar with the status of the aircraft, and he knows that a change in any of the aircraft’s systems will be easily identified during the aircraft’s starting sequence, when redundant sensors will provide an immediate and quantifiable indication of whether each system is operating properly. As they near the completion of their preflight ORM discussion, the topic of crew fatigue is addressed. Despite being awakened at 0320, each member of the aircrew reports perceiving no significant risk from their individual fatigue level. They are keenly aware of the need for adequate rest and recovery, but are left to assess their current status based solely on the number of hours of sleep they believe they got and their perceived level of alertness.

“I’m good,” they each say, as they break from their preflight discussion and ready themselves for flight.

As the aircrew straps in, the aircraft commander wonders, for just an instant, if his crew actually *is* rested enough to conduct this mission. Now in his early forties, he has conducted more middle-of-the-night launches for rescue or interdiction than he can remember, but he has recently noticed that the sleepless nights take a slightly greater toll than they did in his early days. His co-pilot, on her first deployment and in her late twenties, seems better suited to the zero dark thirty alarms, but has yet to experience their effect on the mental and physical acuity necessary to execute one of these missions and safely recover to the back of the pitching cutter’s flight deck. His precision marksman seems to function almost entirely without sleep. Fueled by two-a-day workouts and the occasional energy drink, he always seems awake, alert and ready to launch. But would the marksman be ready to make a precision shot within just a few feet of the go-fast’s occupants in the dead of night? As the aircraft’s electronics come to life and the gauges display pressures and readings on the screens before him, the aircraft commander wishes there were a way to have sensors installed on the aircrew to let him know when he or part of his team were nearing a state of unsafe operation. He dismisses the idea outright. Thoughts like that are the subject of space missions or science fiction...or are they?

A. PROBLEM STATEMENT

Existing pre-watch and preflight risk-management procedures for USCG aircrews rely on crew members to report whether they are well rested, based on perceived hours of sleep. While these practices are grounded in scientific analyses that identify generalized models for cognitive impairment based on sleep patterns, they fail to provide specific, individualized depictions of a person’s cognitive state.¹ Aviation crew rest practices have historically leveraged advances in scientific understanding of rest–impairment relationships and currently serve as industry best practices within civilian and commercial industries.²

¹ Salaheddine Bendak and Hamad S. J. Rashid, “Fatigue in Aviation: A Systematic Review of the Literature,” *International Journal of Industrial Ergonomics* 76 (March 2020), <https://doi.org/10.1016/j.ergon.2020.102928>.

² Bendak and Rashid.

The idea of measuring fatigue is not new. For the purposes of this analysis, *fatigue* refers to “a physiological state in which there is a decreased capacity to perform cognitive tasks and an increased variability in performance as a function of time on task,” as defined by the Federal Aviation Administration.³ The terms *fatigue* and *cognitive fatigue* are used interchangeably throughout this document. Scientific research identifies certain physiological responses that occur with increased states of physical and mental fatigue. One’s heart rate, heart rate variability, eye movements, and brain activity all provide quantifiable indicators of mental fatigue.⁴ Based on the obvious interest in ensuring that aircrews avoid operating in unsafe cognitive states, the study of these factors has long been the focus of aviation safety researchers.⁵ With the scientifically supported utility of these physiological markers well established, the challenge for policymakers has been finding a practical, non-invasive way to allow operators to monitor as many measures as possible.⁶ Wearable devices, or “wearables,” represent a non-invasive technological advance that may enable aviation crews to better assess their preflight fatigue.

Not all wearables provide the same level of accuracy. For instance, tests of some devices have determined that they cannot provide sufficiently accurate measurements of basic activity levels in order effectively track simple fitness markers like steps or estimated calories. However, studies of other products have validated the ability to accurately measure electrocardiogram (ECG) information (including heart rate and heart rate variability), respiratory rate, and sleep phases—and even predict the onset of atrial fibrillation, an irregular

³ Federal Aviation Administration, *Basics of Aviation Fatigue*, AC No. 120–100 (Washington, DC: Federal Aviation Administration, 2010), 2, https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentid/244560.

⁴ Zara Asif, “Measurements to Detect Mental Fatigue” (neural engineering student project, George Mason University, May 2020), <http://mars.gmu.edu/handle/1920/11768>.

⁵ Bendak and Rashid, “Fatigue in Aviation.”

⁶ Xinyun Hu and Gabriel Lodewijks, “Detecting Fatigue in Car Drivers and Aircraft Pilots by Using Non-Invasive Measures: The Value of Differentiation of Sleepiness and Mental Fatigue,” *Journal of Safety Research* 72 (February 2020): 173–87, <https://doi.org/10.1016/j.jsr.2019.12.015>.

beating of the heart that greatly increases a person's risk of stroke.⁷ With this broad range of wearables' capabilities, from highly effective to effectively useless, researchers must first determine whether sufficient wearable technologies exist to accurately measure the specific indicators needed to provide a useful measure of a subject's fatigue level.

If the accuracy of the data is sufficient to provide an increased level of insight to users seeking to quantify their personal fatigue level, the remaining questions include whether legal and political considerations make such a pursuit expedient or even feasible, and if so, how to ensure the optimal acceptance of the new technology by the workforce. For example, as technological advancements enable military organizations like the USCG to increase the monitoring of its members both on and off duty, questions arise over the applicability of Fourth Amendment protections. While military members have long accepted a diminished expectation of privacy, could a military organization extend the bounds of its monitoring to require 24-hour physiological monitoring of members while off duty?⁸ If the USCG can impose full-time monitoring of its members in the name of operational safety, the bounds of technological privacy protections may require a modernized definition. To date, these bounds remain relatively untested.⁹ Even if legally authorized within the confines of military application, policymakers from various communities are certain to benefit from an analysis of the legal implications of such a program and future challenges that it may encounter.

Finally, should a business case analysis support the implementation of a wearable program within the USCG, leaders must identify a preferred method through which to implement policies that will result in the most effective use of the devices for their intended purpose. The Unified Theory of Acceptance and Use of Technology (UTAUT) is a conceptual tool which addresses some of the variables that may contribute to the successful or failed

⁷ Lynne M. Feehan et al., "Accuracy of Fitbit Devices: Systematic Review and Narrative Syntheses of Quantitative Data," *JMIR MHealth and UHealth* 6, no. 8 (2018), <https://doi.org/10.2196/10527>; Mary Caffrey, "Giant Study Suggests Apple Watch Accurately Catches Atrial Fibrillation," *American Journal of Managed Care*, March 16, 2019, <https://www.ajmc.com/conferences/acc-2019/giant-study-suggests-apple-watch-accurately-catches-afib>; "Atrial Fibrillation," Centers for Disease Control and Prevention, September 8, 2020, https://www.cdc.gov/heartdisease/atrial_fibrillation.htm.

⁸ Major Walter M. Hudson, "A Few New Developments in the Fourth Amendment," *The Army Lawyer*, Department of the Army Pamphlet 27-50-317, April 1999, https://www.loc.gov/rr/frd/Military_Law/pdf/04-1999.pdf.

⁹ Bendak and Rashid, "Fatigue in Aviation."

adoption of this new technology.¹⁰ Of note, the wearable device's perceived usefulness, the voluntariness of use, and social influences are likely to play a significant role in determining if such a program is practically actionable.

Lessons garnered from this research are likely to be useful within military branches as well as state, local, and civilian homeland security organizations.

B. RESEARCH QUESTIONS

1. What are the legal and social considerations affecting the implementation of wearable technology to assess crew fatigue in the USCG?
2. How should the USCG preflight risk assessment processes incorporate the use of emerging wearable technologies to assess crew member fatigue?

C. METHODOLOGY

This thesis employed a qualitative research design to identify existing current states and trends within wearable technology performance, wearable technology litigation, and USCG aviation safety program performance. Using a structured review of literature published in peer reviewed journals and historical USCG aviation data, a qualitative thematic analysis identified possible influential variables for determining the potential utility and method for incorporating wearable technologies into USCG aviation risk-management processes. Additionally, based on a financial estimate of potential program cost as compared to potential annual savings, the study applied a business case analysis to validate the potential fiscal feasibility of a theoretical wearable program. Finally, the study used empirical observation to gather information on USCG aviators' perceptions of wearable technology's utility within risk management, facilitating factors in determining their acceptance of such a technology, and the impact of exposure to such a technology on those individuals' perceptions. Information gathered in the empirical observation included stated preferences, in the form of survey answers, as well as demonstrated preference in the form of measurements of physiological data and wearable usage.

¹⁰ Viswanath Venkatesh et al., "User Acceptance of Information Technology: Toward a Unified View," *MIS Quarterly* 27, no. 3 (2003): 425–78, <https://doi.org/10.2307/30036540>.

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II. LITERATURE REVIEW

This literature review discusses research on fatigue mitigation in aviation operations, what measures flight crew need for effective risk mitigation, which types of wearables may provide the needed data, and potential policy considerations that might accompany the implementation of a wearable program. The review first addresses the potential need for improved aircrew fatigue analysis and then examines studies concerning the ability of various types of wearable devices to accurately measure physiological markers related to crew member fatigue. Finally, it addresses legal limitations on monitoring off-duty military personnel, sociopolitical considerations, and potential models for determining the successful implementation of such a program.

A. FATIGUE IN AVIATION

The role of pilot fatigue has been evident in aviation since the earliest days of flight. In 1928, the U.S. Commerce Department's newly formed Aeronautics Branch published its first analysis of civil aviation accidents for the first half of that year. Of the 390 reported accidents, 43.29% were blamed on pilot error.¹¹ Understanding the dangers inherent to the previously unregulated aspect of flight, in 1931 the Commerce Department implemented a requirement for flights with schedules spanning more than five hours to include both a pilot and co-pilot within their crews.¹² These regulations were further expanded in 1943 to limit airline pilots' monthly flight time to 85 hours, the first regulatory effort toward preserving crew rest.¹³

As noted above, the idea that tired aviators equate an increase in accident risk did not take long to codify itself in policy. Just a few years after the USCG's first aviator, Elmer F. Stone (USCG Aviator #1 and Naval Aviator #38) earned his wings in 1917, federal regulations and naval flight policies sought to mitigate the dangers of fatigued flyers by

¹¹ "FAA Historical Chronology, 1926–1996," Federal Aviation Administration, accessed February 3, 2021, https://www.faa.gov/about/history/chronolog_history/media/b-chron.pdf.

¹² "FAA Historical Chronology, 1926–1996."

¹³ "FAA Historical Chronology, 1926–1996."

implementing what would later come to be known as the concept of “crew rest.”¹⁴ Fatigue plays such a critical role in cognitive performance that it is included in the Federal Aviation Administration’s “Dirty Dozen,” a list of twelve human performance factors that account for more than 80% of aircraft preflight maintenance mistakes.¹⁵ The Naval Safety Center cited fatigue as a cause of more than 24% of Naval aviation mishaps between 1997 and 2002.¹⁶ Existing USCG policies explicitly define the “spirit” of existing regulations as being “to ensure that flight crews are well rested, alert, and capable of performing their duties safely.”¹⁷ Additionally, these policies go further, citing the impact of off-duty activities on a crew member’s on-duty fatigue and flight performance and stating, “It is the moral and military responsibility of each flight crew member to engage only in those off-duty activities that will allow the crew member to report to duty fully rested.”¹⁸

Within the USCG, fatigue and aircrew error were top causal factors in 41 major mishaps since 1982.¹⁹ Current practices limit the flight times and crew days of USCG air crews, restricting the crew members’ flight hours (operating the aircraft) and crew mission hours (conducting operations related to flight) and establishing mandatory periods of rest to prevent aircrews from operating in a state of cognitive fatigue.²⁰ Additional restrictions on the number of days of duty that members can stand as well as specific limitations for members

¹⁴ William H. Thiesen, “Elmer F. Stone ‘13 and the Pioneering Role of Coast Guard Academy Graduates in Early Naval and Coast Guard Aviation,” Foundation for Coast Guard History, *The Bulletin*, (April, 2010), <https://www.history.uscg.mil/Portals/1/Documents/StoneElmerApr2010.pdf?ver=2019-03-21-144548-913>

¹⁵ Greg Michael Mellema, “Application of Dupont’s Dirty Dozen Framework to Commercial Aviation Maintenance Incidents” (PhD diss., Embry Riddle Aeronautical University, 2018), <https://commons.erau.edu/cgi/viewcontent.cgi?article=1477&context=edt.>; Federal Aviation Administration, “Avoid the Dirty Dozen” (Washington, DC: Federal Aviation Administration Safety, 2020), <https://www.faa.gov/files/gslac/library/documents/2012/Nov/71574/DirtyDozenWeb3.pdf>.

¹⁶ Ryan P. Beshany, “Analysis of Navy Flight Scheduling Methods Using Flyawake,” (Master’s thesis, Naval Postgraduate School, 2009), <https://apps.dtic.mil/sti/pdfs/ADA508920.pdf>

¹⁷ U.S. Coast Guard, *Air Operations Manual*.

¹⁸ U.S. Coast Guard.

¹⁹ U.S. Coast Guard e-AVIATRIS Database, “Coast Guard Aviation Mishap Data 1982–2021,” October 9, 2020.

²⁰ U.S. Coast Guard, *Air Operations Manual*, Commandant Instruction 3710.H (Washington, DC: U.S. Coast Guard, 2018), https://media.defense.gov/2018/Nov/01/2002058346/-1/-1/0/CIM_3710_1H.PDF.

on reverse cycle (night shift) operations further guard against tasking members to aviate while critically fatigued.²¹ These policies are the result of decades of fatigue-related studies commissioned by all branches of the military and academia.²² However, beyond highlighting their moral responsibility to do so, existing policy only provides loose guidance on how a member can verify their own physiological readiness upon assuming watch. The USCG may benefit from research into the potential ability for wearable devices to fill this gap.

Research indicates that a number of physiological indicators can provide quantifiable insight into a person's level of fatigue:

Brain Wave Patterns: The electroencephalogram (EEG) measurement is held as the gold standard for detecting impaired alertness.²³ Measured by affixing sensors to a subject's head, EEG data provide insight into changes in brain wave patterns that display clear indications of stress, excitement, and most notably, cognitive fatigue.²⁴ Comparing changes in the alpha and theta bands of five EEG rhythms provides a real-time indication of a subject's cognitive fatigue.²⁵

Blood Oxygen Saturation (SAO₂): Monitored through the use of a digit-mounted device, blood oxygen can indicate potential cognitive impairment, particularly at the extreme ends of cognitive capacity.²⁶ While SAO₂ levels may not accurately reflect subtle changes in cognitive fatigue, they are a failsafe indicator of users reaching levels of severe cognitive impairment or loss of consciousness.²⁷

²¹ U.S. Coast Guard, Air Operations Manual.

²² Bendak and Rashid, "Fatigue in Aviation."

²³ Joseph Geeseman et al., "Functional Near-Infrared Spectroscopy (fNIRS) in an Aerospace Environment: Challenges and Considerations," *Aerospace Medicine and Human Performance* 91, no. 10 (October 2020): 833–35, <https://doi.org/10.3357/AMHP.5723.2020>.

²⁴ Gang Li et al., "The Impact of Mental Fatigue on Brain Activity: A Comparative Study Both in Resting State and Task State Using EEG," *BMC Neuroscience* 21 (2020), <https://doi.org/10.1186/s12868-020-00569-1>.

²⁵ Li et al.

²⁶ Daniel W. Repperger and Lloyd D. Tripp, Fatigue indicator based on arterial oxygen, U.S. Patent US5337743A, filed June 17, 1993, and issued August 16, 1994, <https://patents.google.com/patent/US5337743A/en>.

²⁷ Repperger and Tripp.

Eye Tracking: Measured via software-based videographic analysis or electrooculogram (EOG), rapid changes in eye movement and blink patterns have been found to indicate increased levels of fatigue.²⁸

Respiration Rate: Increased levels of fatigue cause a corresponding change in respiration, making steady breathing patterns erratic.²⁹ These changes can be measured using airflow-based devices or derived via video photoplethysmography, calculating the respiratory rate based on comparisons of heart rate characteristics.³⁰

Heart Rate Variability (HRV): HRV is the measured time interval between heartbeats, or inter-beat interval (IBI). A decrease in the beat-to-beat variation of heart rhythm correlates with a decrease in cognitive performance.³¹ Heart rate variability can be measured by electrocardiogram (EKG/ECG).³²

With these physiological markers providing insight into a subject's level of fatigue, the challenge becomes identifying wearable devices that can accurately monitor the user in a real-world environment, and implementing policies to enable the successful acceptance of such devices by the workforce.

B. WEARABLES

1. The Quantified Self

As Deborah Lipton points out in her 2016 book, *The Quantified Self*, the habit of tracking personal thoughts, actions, and measurements is not a new concept.³³ For many generations, individuals have logged personal information in various forms using technology as simple as pen and paper. This activity provides insights into how they function, for purposes

²⁸ Asif, "Measurements to Detect Mental Fatigue."

²⁹ Asif.

³⁰ Asif.

³¹ Christopher L. Schaich et al., "Association of Heart Rate Variability with Cognitive Performance: The Multi-Ethnic Study of Atherosclerosis," *Journal of the American Heart Association* 9, no. 7 (2020), <https://doi.org/10.1161/JAHA.119.013827>.

³² Schaich et al.

³³ Deborah Lupton, *The Quantified Self* (Cambridge: Polity Press, 2016).

as varied as curiosity or improved performance. However, significant technological advances within the last two decades have placed computerized devices at the center of individuals' lives. Introduced into the mass market with the Fitbit Tracker in 2009, wearable technologies originally focused on fitness and activity tracking using an electronic device worn on the user's wrist to measure and record steps taken, heart rate, and sleep information.³⁴ In just over a decade since Fitbit was launched, the market for wearable technologies, or "wearables," grew to surpass \$32 billion in 2019.³⁵ During that period, wearables expanded in number and type, and improved their ability to detect and log body signal parameters, including heart rate, heart rate variability, respiratory rate, temperature, sleep phases, movement, GPS position, and mechano-acoustic signatures (swallowing and breathing sounds normally observed with a stethoscope) with varying degrees of accuracy and reliability. In the early 2000s, a small group of technology entrepreneurs met in San Francisco to discuss how to best use these new tracking technologies to optimize their personal productivity and performance. As Jessica Wilson explained in her article for Northwestern's *Helix Magazine*, "They were the first bona-fide 'biohackers'—those who sought to use science, technology and medicine to maximize their own abilities. But in order for people to improve on their abilities, they first had to conceive ways of measuring them. Thus, the Quantified Self movement was born."³⁶

The term "quantified self" was originally coined by two *Wired* editors, Gary Wolf and Kevin Kelly, who went on to create a website bearing the name and an associated lab group, each dedicated to encouraging and enabling individuals to conduct their own personal, personalized research. The concept takes advantage of the growing ability for individuals to leverage computerized devices to quantifiably measure, track, and analyze (either personally or with the assistance of third parties) physiological information on an "N-of-1."³⁷ Today,

³⁴ David M. Ewalt, "Getting Fitbit," *Forbes.com*, June 11, 2010. <https://www.forbes.com/2010/06/11/fitbit-tracker-pedometer-lifestyle-health-lifetracking.html#2bb07f1f555>.

³⁵ Grand View Research, *Wearable Technology Market Size, Share and Trends Analysis Report by Product (Wrist-wear, Eye-wear and Head-wear, Foot-wear, Neck-wear, Body-wear), by Application, by Region, and Segment Forecasts, 2020 – 2027*, Report ID: 978–1-68038-165-8 (San Francisco: Grand View Research, June 2020), <https://www.grandviewresearch.com/industry-analysis/wearable-technology-market>.

³⁶ "The Quantified Self," *Helix Magazine*, accessed April 18, 2021. <https://helix.northwestern.edu/article/quantified-self>.

³⁷ "Homepage," Quantified Self, accessed April 17, 2021, <https://quantifiedself.com/>.

digital self-tracking has expanded well beyond a niche group of quantified self-devotees, as smartphones, smartwatches, and other wearables become an increasingly omnipresent part of modern society.³⁸ As noted earlier the wearable market is growing at an exponential rate, and is projected to expand at a compound annual growth rate (CAGR) of 15.9% over the next six years.³⁹

Vast improvements in technology have made the collection and analysis of personal information virtually effortless for a growing number of consumers. Individuals indulge the same tendency that made them mark their children's height on a doorframe by donning a wrist-worn strap to count their steps or track their sleep. They hope to acquire an improved insight into how they live and function. When the increasingly ubiquitous nature of technological self-monitoring is considered within the context of aviation safety, the potential to better quantify aircrew fatigue appears increasingly possible.

2. Wearable Accuracy and Utility

One of the fundamental steps in evaluating the potential use of wearables for assessing crew fatigue is determining whether the wearable devices are capable of accurately measuring the physiological markers that might provide insight into an individual's cognitive state. Due to the breadth of types of wearable devices available—including glasses, headbands that monitor brain activity, wrist- and chest-worn straps, and clip-on activity trackers—it is necessary to evaluate such devices by style to provide an actionable assessment. For that reason, this evaluation focuses on wrist- and finger-worn devices targeted at measuring cardiovascular signals. Even within this narrowed scope, the number and type of wearable devices varies widely. In a 2017 study of 423 devices from 123 different brands, André Henriksen explains, “The wearable landscape is in constant change,” noting the continuous influx and withdrawal of devices as technology evolves.⁴⁰ With this in mind, most useful

³⁸ Nils B. Heyen, “From Self-Tracking to Self-Expertise: The Production of Self-Related Knowledge by Doing Personal Science,” *Public Understanding of Science* 29, no. 2 (February 1, 2020): 124–38, <https://doi.org/10.1177/0963662519888757>.

³⁹ Grand View Research, Wearable Technology Market Size, Share and Trends Analysis Report.

⁴⁰ André Henriksen et al., “Using Fitness Trackers and Smartwatches to Measure Physical Activity in Research: Analysis of Consumer Wrist-Worn Wearables,” *Journal of Medical Internet Research* 20, no. 3 (2018), <https://doi.org/10.2196/jmir.9157>.

research identifies the most accurate devices rather than establishing an industry standard of performance.

Toward that end, a number of studies have attempted to validate the accuracy of wrist-worn devices, particularly with regard to heart rate monitoring. Notably, Daniel Fuller conducted a 2020 review of studies evaluating nine brands—Apple, Fitbit, Garmin, Mio, Misfit, Polar, Samsung, Withings, and Xiaomi—to assess their performance in monitoring step count, energy expenditure, and heart rate.⁴¹ His aggregation of data from 158 publications found that performance on each of the metrics varied from device to device.⁴² For instance, Apple Watch’s heart rate measurement was within 3% of clinical measurement 71% of the time while Garmin wearables performed to that standard only 49% of the time.⁴³ Additionally, Fuller notes a relatively small number of studies analyzing the accuracy of heart rate measurement in “free-living” conditions to provide data on the potential real-world utility of the devices in question.⁴⁴ This conclusion corresponds with the majority of studies that validate wearable heart rate detection performance, but only within periods of sedentary or light activity. For instance, a 2020 study by Peter Düking found that the Apple Watch Series 4 and Polar Vantage V are effective at measuring heart rate at up to light activity levels (within 3.9 bpm and 7 bpm respectively compared to the Polar HR Strap), but the Garmin fenix 5 and Fitbit Versa show an higher level of inaccuracy (9.9 and 11.4 bpm, respectively), which renders their readings less useful.⁴⁵ Likewise, a 2017 study by Robert Wang found that “in general, accuracy of wrist-worn monitors was best at rest and diminished with exercise.”⁴⁶

⁴¹ Daniel Fuller et al., “Reliability and Validity of Commercially Available Wearable Devices for Measuring Steps, Energy Expenditure, and Heart Rate: Systematic Review,” *JMIR MHealth and UHealth* 8, no. 9 (2020), <https://doi.org/10.2196/18694>.

⁴² Fuller et al.

⁴³ Fuller et al.

⁴⁴ Fuller et al.

⁴⁵ Peter Düking et al., “Wrist-Worn Wearables for Monitoring Heart Rate and Energy Expenditure While Sitting or Performing Light-to-Vigorous Physical Activity: Validation Study,” *JMIR MHealth and UHealth* 8, no. 5 (2020), <https://doi.org/10.2196/16716>.

⁴⁶ Robert Wang et al., “Accuracy of Wrist-Worn Heart Rate Monitors,” *JAMA Cardiology* 2, no. 1 (2017): 104–6, <https://doi.org/10.1001/jamacardio.2016.3340>.

These findings reflect a trend in research, validating some wearables as accurate, but only under low activity levels.

In general, Fitbit, Apple Watch, and Garmin devices appear to be the most assessed. Henriksen's aforementioned review also notes that these brands represent the majority of scholarly evaluations.⁴⁷ While the limited sample size of assessments encourages continued evaluation, the frenetic pace of innovation within the wearables field supports consideration of newer and less-tested devices, if their performance shows promise.⁴⁸ Within this category, devices like the Whoop wrist strap and Oura ring have been the subjects of limited evaluation but show promise, according to some scholars.⁴⁹ In 2019, Sarah Berryhill et al. used the Whoop strap for a sleep study, noting a performance of $\pm 1.5\%$ precision in measuring heart rate.⁵⁰ Another 2020 study by Dean Miller validated the effectiveness of the Whoop in measuring sleep/wake cycles, a metric for which heart rate is a key component, but the limited sample size (12 persons) and Whoop's sponsorship of the study should also be noted.⁵¹ Similarly, a 2020 study by Hannu Kinnunen validated the Oura ring with remarkable accuracy, noting a mean bias of just 0.63 bpm, but the study's sponsorship by Oura should entail some level of skepticism from scholars.⁵² However, a dearth of validated, scholarly assessments does not necessarily mean that the devices in question are inadequate for the subject at hand.

It should be noted that the limited nature of validation studies and the corporate involvement therein have not prohibited government agencies and corporate entities from

⁴⁷ Henriksen et al., "Trackers and Smartwatches to Measure Physical Activity."

⁴⁸ Nino Isakadze and Seth S. Martin, "How Useful Is the Smartwatch ECG?," *Trends in Cardiovascular Medicine* 30, no. 7 (2020): 442–48, <https://doi.org/10.1016/j.tcm.2019.10.010>.

⁴⁹ Dean J. Miller et al., "A Validation Study of the WHOOP Strap against Polysomnography to Assess Sleep," *Journal of Sports Sciences* 38, no. 22 (2020): 2631–36, <https://doi.org/10.1080/02640414.2020.1797448>; Hannu Kinnunen et al., "Feasible Assessment of Recovery and Cardiovascular Health: Accuracy of Nocturnal HR and HRV Assessed via Ring PPG in Comparison to Medical Grade ECG," *Physiological Measurement* 41, no. 4 (May 2020), <https://doi.org/10.1088/1361-6579/ab840a>.

⁵⁰ Sarah Berryhill et al., "Effect of Wearables on Sleep in Healthy Individuals: A Randomized Crossover Trial and Validation Study," *Journal of Clinical Sleep Medicine* 16, no. 5 (2020): 775–83, <https://doi.org/10.5664/jcsm.8356>.

⁵¹ Miller et al., "Validation Study of the WHOOP Strap."

⁵² Kinnunen et al., "Feasible Assessment of Recovery and Cardiovascular Health."

leveraging such devices for research or operational use. For instance, Oura rings were the National Basketball Association's device of choice for monitoring the physiological data of its players during the 2020 tournament.⁵³ Skeptics of the device's utility, specifically for the purpose of COVID-19 detection, purport a lack of sufficient evidence to link the device to early detection capability but also fail to provide any data negating the Oura ring's accuracy.⁵⁴ Additionally, the Defense Threat Reduction Agency used Oura rings and Garmin fēnix devices to implement its Rapid Analysis of Threat Exposure (RATE) program in 2020, which seeks to use wearables as an early warning detection system to identify infirm personnel well before members appear noticeably symptomatic.⁵⁵ As noted above, the rapid introduction of new and upgraded wearables creates the circumstance in which the least-tested devices may present superior performance, an interesting dichotomy for identifying the most accurate device.

C. LEGAL CONSIDERATIONS

While the United States Court of Military Appeals holds that Fourth Amendment protections apply to members of the armed forces, except where explicitly or implicitly inapplicable, the Supreme Court has never ruled on the subject.⁵⁶ With this in mind, imposed monitoring of USCG members while off duty *may* extend beyond the scope of military authority, though due to the untested nature of this area of the law, no specific precedent could be found to specifically limit the service's ability to impose such an order. Department of Defense initiatives aimed at leveraging wearable technology predominantly focus on equipping users during the execution of military operations.⁵⁷ Those programs that aim to

⁵³ Ryan Basen, "Sports Leagues' COVID-19 Research: Who Will It Help?," *Medpage Today*, July 16, 2020, <https://www.medpagetoday.com/infectiousdisease/covid19/87604>.

⁵⁴ Anthony Pearson, "A Wearable for Early COVID-19 Diagnosis?," *Medpage Today*, July 20, 2020, <https://www.medpagetoday.com/blogs/skeptical-cardiologist/87651>.

⁵⁵ David Vergun, "AI Aids DOD in Early Detection of COVID-19," Department of Defense, September 22, 2020, <https://www.defense.gov/Explore/News/Article/Article/2356086/ai-aids-dod-in-early-detection-of-covid-19/>.

⁵⁶ Frederic L. Borch, "Does the Fourth Amendment Apply to the Armed Forces?," *William & Mary Bill of Rights Journal* 3, no. 1 (1994), <https://scholarship.law.wm.edu/wmborj/vol3/>.

⁵⁷ Sofwerx, "Physiological Analysis Tool Tech Sprint" (Tampa: Sofwerx, 2019), https://www.sofwerx.org/wp-content/uploads/pat_tech_sprint_participating_company_responses.pdf.

push monitoring technologies into off-duty application, like the aforementioned RATE program, rely heavily on wearers' consent.⁵⁸

Other legal considerations regarding the use of data garnered from wearable devices in punitive actions or legal proceedings have been addressed in legal precedent. Data from the internet of things and wearable devices have been submitted as evidence in court. Fitbit data were used to refute allegations of sexual assault and leveraged in murder trials, and in the famous *Ohio v. Ross* case, pacemaker data were used to charge the defendant with arson and insurance fraud, disproving his testimony based on the physiological data from the pacemaker.⁵⁹ While research has established the legal admissibility of data in these and similar circumstances, little could be found investigating the privacy expectations that might be applied to data retrieved from mandated wearable use. Due to the diverse nature of data privacy and security agreements unique to each wearable provider, wearable data privacy analysis appears primarily focused on the lowest common denominator: poorly protected and widely shared information.⁶⁰ As technology enables new forms of intrusion, these unprecedented questions bear investigation.

D. SOCIOPOLITICAL CONSIDERATIONS

The evolving nature of social privacy expectation is central to this topic. Significant research exists regarding changes in user privacy expectation based on perceived gain. In recent years, the privacy-convenience tradeoff has become a central consideration in the design of “user experience” (UX).⁶¹ Studies show general agreement on the growing acceptance of limited privacy expectations, exchanged by users for the increasing levels of

⁵⁸ Vergun, “AI Aids DOD in Early Detection of COVID-19.”

⁵⁹ Marie-Helen Maras and Adam Scott Wandt, “State of Ohio v. Ross Compton: Internet-Enabled Medical Device Data Introduced as Evidence of Arson and Insurance Fraud,” *International Journal of Evidence & Proof* 24, no. 3 (2020): 321–28, <https://doi.org/10.1177/1365712720930600>.

⁶⁰ Thora Knight, “Data Ownership: Legalities Concerning Wearable Technologies,” in *Privacy Concerns Surrounding Personal Information Sharing on Health and Fitness Mobile Apps*, ed. Devjani Sen and Rukhsana Ahmed (Hershey, Pennsylvania: IGI Global, 2021), 60–82, <https://doi.org/10.4018/978-1-7998-3487-8.ch003>.

⁶¹ George Chalhoub and Ivan Flechais, “‘Alexa, Are You Spying on Me?’: Exploring the Effect of User Experience on the Security and Privacy of Smart Speaker Users,” in *HCI for Cybersecurity, Privacy and Trust*, ed. Abbas Moallem, Lecture Notes in Computer Science (New York: Springer International Publishing, 2020), 305–25, https://doi.org/10.1007/978-3-030-50309-3_21.

service that technological devices provide. This acceptance is further encouraged by technology companies' specific strategies to make technology interact with consumers in a more human-like manner.⁶²

A surplus of research exists regarding the consumer acceptance of technologies, including wearables. The technology acceptance model (TAM), developed in 1986, is a widely used tool for predicting user adoption of new devices or methods.⁶³ The TAM draws much of its foundation from the concept of “diffusion of innovation,” a theory proposed by Everett Rogers in 1962 in a book by the same name.⁶⁴ Rogers' theory included five innovation characteristics that determined the potential adoptability of a new technology (observability, relative advantage, compatibility, trialability, and complexity).⁶⁵ The earliest version of the TAM shared a similar focus with Rogers' characteristics, identifying two key determinants for user acceptance: perceived usefulness and perceived ease of use.⁶⁶

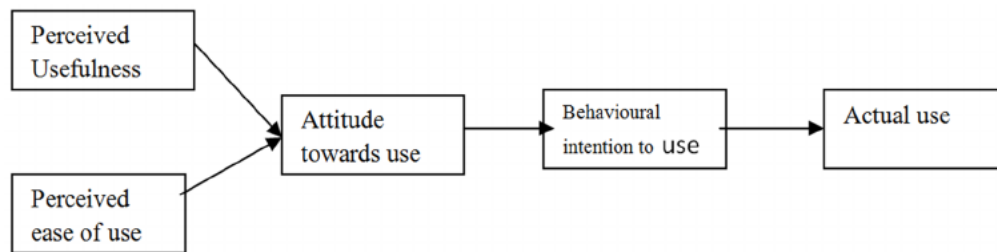


Figure 1. The Original Technology Acceptance Model⁶⁷

⁶² Charulata Ghosh and Matthew S. Eastin, “Understanding Users’ Relationship with Voice Assistants and How It Affects Privacy Concerns and Information Disclosure Behavior,” in *HCI for Cybersecurity, Privacy and Trust*, ed. Abbas Moallem, Lecture Notes in Computer Science (New York: Springer International Publishing, 2020), 381–92, https://doi.org/10.1007/978-3-030-50309-3_25.

⁶³ Fred D. Davis, “A Technology Acceptance Model for Empirically Testing New End-User Information Systems: Theory and Results” (Ph.D. Thesis, Massachusetts Institute of Technology, 1985), <https://dspace.mit.edu/handle/1721.1/15192>.

⁶⁴ Everett M Rogers, *Diffusion of Innovations* (New York: Free Press, 2003).

⁶⁵ Rogers.

⁶⁶ Fred D. Davis, “Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology,” *MIS Quarterly* 13, no. 3 (1989): 319–40, <https://doi.org/10.2307/249008>.

⁶⁷ Davis, “A Technology Acceptance Model for Empirically Testing New End-User Information Systems.”

Since its inception, many variations of the model have been proposed, adding to its two fundamental variables to forecast technology acceptance.⁶⁸ Studies have applied these models to identify key motivators for technology adoption, including the adoption of wearables by civilian airline transport pilots in one instance.⁶⁹ While such studies present useful generalized data and trends as well as potential frameworks for future research, a void still exists in examining wearable adoption by military aviation personnel.

E. WEARABLE ACCEPTANCE IN AVIATION

A limited field of research addresses the acceptance of wearable devices as a means to measure physiological readiness for flight in both civilian and military applications. A 2020 survey-based study by Rachelle Strong of Embry Riddle found that the two most influential factors in determining whether civilian airline transport pilots adopted fatigue-measuring technology were perceived usefulness and perceived ease of use.⁷⁰ Additionally, a 2015 study by Lauren E. Menke equipped Australian military pilots with chest-worn physiological monitoring devices monitoring prior to combat training flights, and then surveyed the pilots to gather information regarding their acceptance of the monitoring technology. Menke's study concluded that,

Overall, the operators surveyed in this experiment expressed high positive regard for future monitoring and augmentation approaches. Though substantial work is required to mature those technologies, it appears that operators are generally ready to accept them. In developing these devices, care must be taken to ensure that the capabilities and limitations of any such systems are communicated to operators, thereby appropriately calibrating their trust in and expectations of those devices.⁷¹

⁶⁸ Younghwa Lee, Kenneth A. Kozar, and Kai R.T. Larsen, "The Technology Acceptance Model: Past, Present, and Future," *Communications of the Association for Information Systems* 12 (2003), <https://doi.org/10.17705/1CAIS.01250>.

⁶⁹ Rachelle Strong, "Pilot Acceptance of Personal, Wearable Fatigue Monitoring Technology: An Application of the Extended Technology Acceptance Model" (PhD diss., Embry-Riddle Aeronautical University, 2020), <https://commons.erau.edu/edt/540>.

⁷⁰ Strong.

⁷¹ Lauren Menke et al., "A Coalition Study of Warfighter Acceptance of Wearable Physiological Sensors," *18th International Symposium on Aviation Psychology*, January 1, 2015, 440–45.

These studies each note the common observations that wearable technology is becoming a more ubiquitous part of society writ large, with Menke's work noting the potential for eventual off-duty physiological monitoring and the privacy concerns that may inhibit acceptance.⁷²

F. CONCLUSION

While research collectively validates the importance of preventing aircrew fatigue as a form of accident mitigation, the emerging technology of wearables is largely untested in the legal realm. Additionally, while models exist for predicting and influencing the adoption of new technologies, little research exists regarding efforts to successfully integrate physiological monitoring into aviation preflight risk analysis. This thesis addresses both subjects in its findings. With these questions in mind, additional evaluation of the potential uses of wearables, as well as effective methods to ensure their operational adoption by end users, might assist policymakers to consider leveraging such emerging technologies to reduce risk to aircrews.

⁷² Menke et al.

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III. THE POTENTIAL VALUE OF QUANTIFICATION

An ideal analysis of a proposed wearable program would compare the cost of program implementation with potential cost savings such a program could provide; if the anticipated business case resulted in a net gain, the analysis would offer recommendations for execution. However, such an analysis requires data in which the analyst can place significant confidence and the creation of assumptions that, if inaccurate, render the analysis moot. Within the realm of wearables, examination of the USCG's historical aviation safety data records demonstrates that current efforts to conduct such a business case analysis for a wearable program lack the necessary reliable data. However, in an ironic twist, wearables may provide opportunities to gather the very data required to validate their potential utility.

According to the USCG's E-AVIATORS safety mishap database, aircrew fatigue played a major contributing role in just 2% of Class A and B aviation accidents (3 of 143 accidents) between 1982 and 2021 (see Figure 2).⁷³ By comparison, material/equipment failure and physical environment account for 53% of Class A and B accidents, a proportional contribution orders of magnitude beyond that of fatigue. A superficial analysis of this data might lead researchers to believe that fatigue is a well-mitigated threat and that policy and resource efforts would be best focused on other potential causative factors. After all, as mentioned earlier, aviators have been creating policies and procedures to account for the dangers of sleep-deprived crews for decades. Having a solution in place by this point in time seems plausible. But upon further investigation, it may be a bit early to declare victory on fatigue. In order to understand why, it is useful to look at what methods existing policies use to prevent and detect fatigue in aircrews before and after an aviation mishap.

⁷³ "Coast Guard Aviation Mishap Data 1982–2021," U.S. Coast Guard, e-AVIATRIS Database, accessed June 21, 2021.

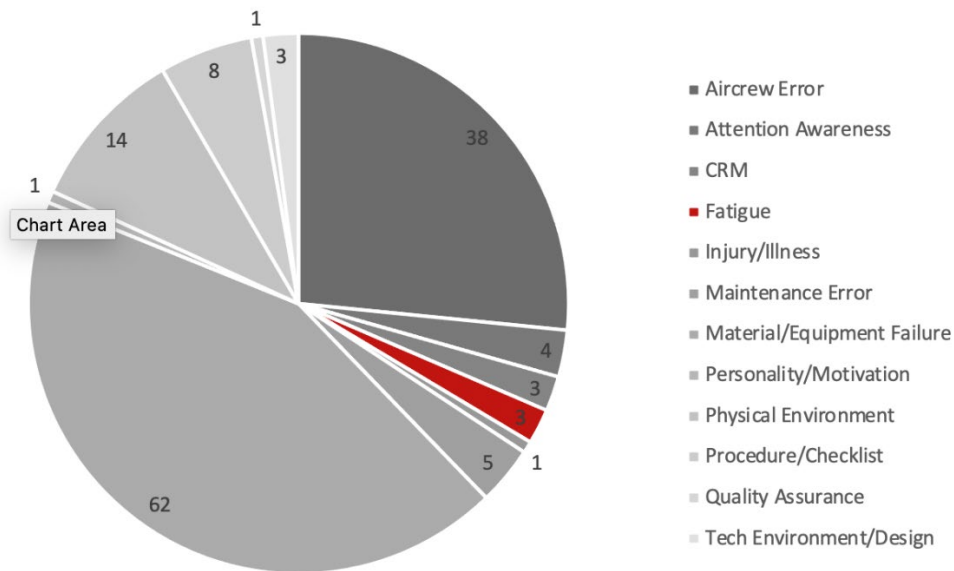


Figure 2. Causal Factors in USCG Class A and B Mishaps (1982-2021), Highlighting Fatigue

Under current practices, USCG air crews are limited in the duration of their flight and crew days based on by-hour limitations. These policies limit the crew members' flight hours (hours operating the aircraft) and crew mission hours (hours conducting operations related to flight), and establish mandatory periods of rest once these limits are reached in order to preclude aircrews from operating in a state of cognitive fatigue. Additional restrictions on the number of days of duty that members can be assigned as well as specific limitations for members on reverse cycle (night shift) operations further guard against tasking members to aviate while critically fatigued. However, even with the aforementioned policies in place, the USCG's Air Operations Manual includes the following disclaimer at the beginning of its discussion on crew readiness:

Crew utilization standards impose limits upon operational commanders in order to improve mental and physical readiness of flight personnel. Individual benefits derived depend upon the proper use of off duty time to ensure good mental and physical condition. It is the moral and military responsibility of each flight crewmember to engage only in those off duty activities that will allow the crewmember to report to duty fully rested. It is impossible for the Commanding Officer or cognizant department head to be aware of how crewmembers use off duty time.

This emphasis on the impacts of off-duty activity and preparedness highlight the importance of empowering members to monitor and recognize their own specific state of fatigue. However, beyond highlighting their moral responsibility to do so, existing policy provides only vague guidance on how a member can verify their physiological readiness upon assuming watch. This lack of guidance is not the fault of previous policymakers. Until recently, existing technologies did not offer practical avenues for members or their supervisors to objectively evaluate their level of fatigue, beyond perceived hours of sleep and personal intuition. To their credit, the existing policies described above leverage these existing markers to an arguably significant extent. They set objective hours-based limits on aircrew flights and operations that are supported by physiological research, and not only empower, but implore personnel to ensure that they arrived for flights rested and ready. Put plainly, policymakers did the best they could with what they had at the time.

In the dynamic field of aviation, the inherent dangers of flight create a scenario in which accidents, though preventable, are to some degree inevitable. With that in mind, USCG aviation safety experts are trained to conduct post-accident analyses aimed at identifying the causative factors of mishaps and create training, equipment, and policy solutions to prevent such incidents from recurring. In the event of a significant “Class A” mishap, in which at least \$2 million of equipment is lost or personnel are killed, the investigation process includes steps through which investigators account for a 72-hour history of each person involved in the accident, to assist in determining if “human factors” played a causative role in the accident. These procedures include the collection of urine samples to test for potential impairment based on drugs or alcohol, as well as interviews in which interviewees account for the quantity and quality of sleep they obtained during the two days prior to the incident under investigation. Using this interview information, safety investigators determine if fatigue played a significantly causal role in the event. Again, these methods make use of sound, twentieth-century science to attempt to detect potential fatigue-causing behaviors, but when compared to the potential capability to gather continuous, objective measurements of a person’s physiological markers they appear lacking. By comparison to the preventative and post-event analytical capabilities that wearables may provide, existing methods seem as effective as police officers only inquiring

of erratic drivers, “How many drinks have you had?” or perhaps, “Are you impaired?” The idea of ceasing investigation at that point seems ineffective, given the quantifiable data that a breathalyzer test could provide. Similarly, wearables may offer a far more objective insight into a subject’s physiological state.

To continue that analogy, it is possible that a certain number of drivers are capable of and effective at monitoring the number of drinks they consume, as well as the specific effects of those drinks on their physiology, and that more invasive investigations are completely unnecessary. In such a theoretical case, a police officer’s efforts are best spent pursuing some other threat. Similarly, it is possible that existing methods of fatigue intervention within USCG aviation are as effective as needed at determining when individual members are cognitively fatigued. If such a circumstance exists, then the cost of wearable programs would likely provide a negligible improvement. However, when viewed in the context of society writ large, as well as compared to recent in-service research, it seems unlikely that existing methods are sufficient.

In general, Americans are sleeping less than they did previously. A comparison of 1942 and 2013 Gallop polls shows the number of Americans getting less than six hours of sleep per night increased from 10% to 40%, with a significant portion of society getting less than the Center for Disease Control’s recommended seven hours or more per night.⁷⁴ A 2017 National Health Interview Survey found similar results, as nearly 33% of respondents reported sleeping less than six hours per night.⁷⁵ More recent surveys that seek to account for the COVID-19 pandemic’s effect on an individual’s sleep habits are not encouraging. A 2020 poll conducted by Sleep Standards found that 53% of Americans take less time for sleep since the beginning of the 2020 lockdown, and 52% go to bed later than they did before the lockdown.⁷⁶ These trends are dangerous, as the Center for Disease

⁷⁴ “Data and Statistics,” in “Sleep and Sleep Disorders,” Centers for Disease Control and Prevention, last reviewed May 2, 2017, https://www.cdc.gov/sleep/data_statistics.html.

⁷⁵ Connor M. Sheehan et al., “Are U.S. Adults Reporting Less Sleep?: Findings from Sleep Duration Trends in the National Health Interview Survey, 2004–2017,” *Sleep* 42, no. 2 (February 1, 2019), <https://doi.org/10.1093/sleep/zsy221>.

⁷⁶ “Sleep Habits Post Lockdown in the U.S. - New Study (2020),” SleepStandards.com, accessed April 16, 2021, <https://sleepstandards.com/sleep-habits-post-quarantine/>.

Control and Prevention (CDC) notes, “Sleeping less than seven hours per day is associated with an increased risk of developing chronic conditions such as obesity, diabetes, high blood pressure, heart disease, stroke, and frequent mental distress.”⁷⁷ With studies linking sleep deprivation to more than 20% of all serious car crashes and a 70% greater likelihood for workplace accidents, it would appear that a significant and increasing portion of modern society is sleeping too little.⁷⁸

The behaviors of USCG members do not necessarily reflect societal trends at a proportional level. That is, just because the majority of Americans are sleeping too little does not mean that the USCG personnel are following suit. With Federal Aviation Administration and service programs touting the importance of sleep, and earlier referenced policies touting the “moral and military responsibility” of being well rested before flight, one might assume that military aviators would make sleep a significant priority.⁷⁹ But a 2019 study done at Tufts University portrays a more negative reality. In the study, of 43 aviators surveyed:

71% of pilots responded that they have unknowingly flown fatigued more than 10 times.

63% of aircrew have unknowingly flown fatigued more than 10 times.

72% of aircrew responded that they have conducted maintenance while feeling overly fatigued.

99% of pilots and aircrew responded that they have unknowingly flown fatigued at least once in the last six months.⁸⁰

While the Tufts study represented a small sample size and the results were not peer reviewed, the results of the survey align with other findings. Another 2019 study from the Naval Postgraduate School investigating the role of sleep inertia on USCG aircrews throughout the fleet found that “the participants of this study stated they received less than

⁷⁷ Centers for Disease Control and Prevention, “Data and Statistics,” in “Sleep and Sleep Disorders.”

⁷⁸ Centers for Disease Control and Prevention, “Data and Statistics,” in “Sleep and Sleep Disorders.”

⁷⁹ U.S. Coast Guard, *Air Operations Manual*.

⁸⁰ Robert P. O’Donnell, “Using Heart Rate Variability to Manage Crew Fatigue in U.S. Coast Guard Aircrews,” (M.A. capstone project, Tufts University, 2019).

seven hours of sleep while standing over five duties on average per month. Of these five duties per month, participants stated they flew an average of 2.67 non-scheduled missions, while quite possibly in a sleep deprived state.”⁸¹ While these studies may not provide sufficient evidence to label fatigue as a pervasive threat that remains unmitigated within USCG aviation, they do suggest some reason to doubt the validity of fatigue accounting for only 2% of Class A and B mishap causes in the last 39 years.⁸²

As former Secretary of Defense Donald Rumsfeld explained in a 2002 press conference, “There are known knowns. There are things we know we know. We also know there are known unknowns. That is to say, we know there are some things we do not know. But there are also unknown unknowns, the ones we don’t know we don’t know.”⁸³ While Secretary Rumsfeld’s sought to explain the limitations of intelligence reporting, his sentiments also apply to the realm of risk management. As demonstrated earlier in this report, USCG policymakers may have been unaware that aircrews could be currently operating in cognitively fatigued state despite their adherence to existing crew rest protocols. Data reflecting actual operational crew physiological markers simply have not been available for analysis. Under these circumstances, fatigue’s true impact on USCG aviation safety has remained an unknown unknown. The potential use of wearables to validate assumptions about the role of fatigue changes this status to known unknown.

A 2009 study by Yaron Rabinowitz identified this same challenge as it pertained to Army helicopter pilots more than a decade ago. The study tested the efficacy of a Fatigue Avoidance Scheduling Tool (FAST) in preventing cognitive fatigue in Army aircrews.⁸⁴ FAST is a software tool in which work and flight schedule times can be input along with sleep data from the aircrew members. The software used the DOD-approved Sleep and

⁸¹ Brendan A. Blain, “An Exploration of Sleep Inertia and Crew Rest Facilities in U.S. Coast Guard Alert-duty Watchstander Performance” (Master’s thesis, Naval Postgraduate School, 2009), <https://apps.dtic.mil/sti/pdfs/AD1086953.pdf>

⁸² U.S. Coast Guard, “Coast Guard Aviation Mishap Data 1982–2021.”

⁸³ Donald Rumsfeld, 6 June 2002 Press Conference at NATO Headquarters, Brussels, Belgium, accessed September 2, 2021. <https://www.nato.int/docu/speech/2002/s020606g.htm>.

⁸⁴ Yaron G. Rabinowitz, Jill E. Breitbach, and Christopher H. Warner, “Managing Aviator Fatigue in a Deployed Environment: The Relationship Between Fatigue and Neurocognitive Functioning,” *Military Medicine* 174, no. 4 (April 2009): 358–62, <https://doi.org/10.7205/MILMED-D-01-5008>.

Fatigue Task Effectiveness (SAFTE) model to predict the impact that certain sleep-wake schedules would have on individuals. FAST can also incorporate data from actigraph devices worn by the members to track their sleep. As explained in the study,

The actigraph is a wrist-worn device, similar to a wrist watch, which objectively estimates sleep quantity and quality by measuring wrist movements. An actigraph consists of an accelerometer as well as a filter, which filters out everything except the 2- to 3-Hz band, thereby ensuring external vibrations are ignored. From wrist movements, the actigraph makes a determination of whether the participant is asleep or awake. Sleep and wake information can then be used to predict overall level of effectiveness.⁸⁵

By harnessing the potential of a wearable device and an effective algorithm, the study found that the system was an impressive predictor of cognitive fatigue as measured by individuals' performance on a computerized Synthetic Work for Windows (SynWin) test. Additionally, the study found that, "The findings also suggest that in aviation units, fatigue, and its negative sequelae, may be a pervasive problem not necessarily identifiable by examining quantity of sleep alone."⁸⁶ In the study's conclusion the researchers suggest, "the observed relationship between FAST scores and SynWin scores indicate that actigraphy and data analysis with FAST software may be a viable tool for aviation units to employ so that true effectiveness determinations can be made before flight operations."⁸⁷ Twelve years ago, the same year that Fitbit released its first device, a U.S. Army study suggested that wrist-worn sleep trackers might provide an improved form of preflight fatigue assessment.

Given that fatigue may play a larger role than previously assumed in causing aviation mishaps and that wearable devices may provide a means through which to acquire data related to fatigue, a business case analysis might provide additional support for leveraging wearable technology to fill this information gap. Analysis of the primary causative factors listed in the E-AVIATORS safety mishap database for USCG Class A

⁸⁵ Rabinowitz, Breitbach, and Warner, 359.

⁸⁶ Rabinowitz, Breitbach, and Warner.

⁸⁷ Rabinowitz, Breitbach, and Warner.

and Class B mishaps from 1982 to 2021 demonstrates that while fatigue was specifically cited for only 3 of 50 Class A and zero Class B mishaps, human error was the second leading cause of Class A and B mishaps (27% or 38 out of 143), behind material/equipment failure. Attention/awareness and procedural errors also accounted for an additional 8% of mishaps recorded in those categories (see Figure 3). Given the unknown variable of whether such causative factors (procedural error, attention/awareness, or human error) were in fact fatigue related, such causal factors will be considered as potentially fatigue related for the purpose of this analysis.⁸⁸

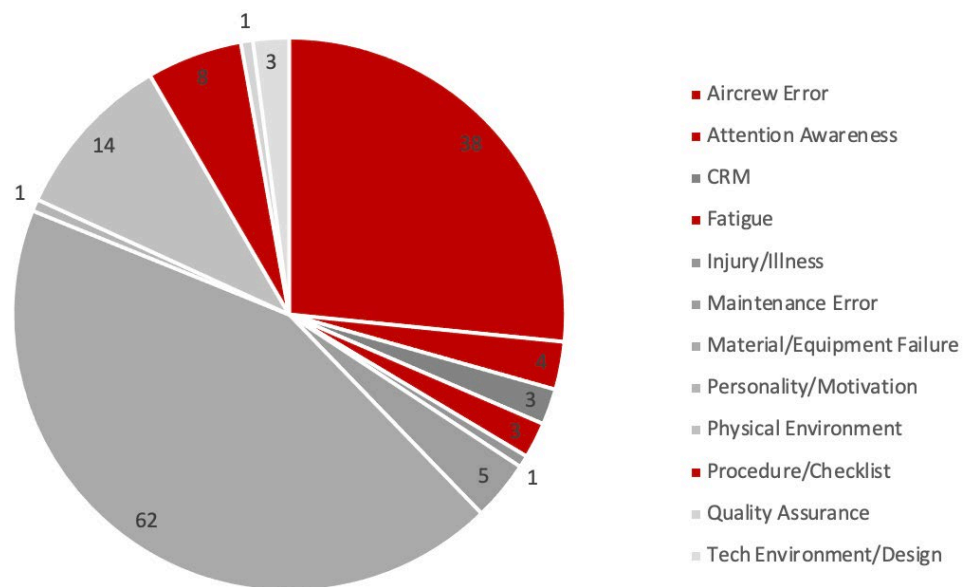


Figure 3. Causal Factors in USCG Class A and B Mishaps (1982-2021), Highlighting Aircrew Error, Attention Awareness, and Procedure/Checklist along with Fatigue

⁸⁸ While additional human factors might be attributed to fatigue (Crew Resource Management, Maintenance Error, Personality/Motivation), this study sought the most conservative approach in order to avoid unintentionally inflating the impact of fatigue on mishap prevalence, and those factors were not included.

Performance gaps in early mishap data collection prevent the exact calculation of costs for those mishaps cited above; the total cost of many mishaps (particularly in the 1980s and 1990s) was not accurately tracked, or is not available in existing databases. However, given the minimum cost requirements for respective aviation mishap categories as defined by USCG policy, one can estimate that Class A and B aviation accidents caused by fatigue, attention/awareness, procedural error, and human error have cost a minimum of \$67 million and 59 lives, totaling more than \$657 million over the last four decades.⁸⁹ Class C and D mishaps would account for an even greater service burden, as they represent incidents in which damage to USCG property reached a baseline cost of \$50,000 and \$5,000, respectively.⁹⁰ However, these categories may also be applied to events which result in one or more days away from work (Class C) or simply in treatment by a medical professional (Class D).⁹¹ Because of the need to base calculations on minimum classification cost requirements for each class of mishap, and because of the potential of Class C and D mishaps to include mishaps that were based solely on medical care or a single lost workday, this study focused on Class A and B mishaps exclusively.

Table 1. USCG Aviation Mishap Determination Variables By Class⁹²

	Baseline Cost	Other Notable Variables
Class A	\$2,000,000 or greater	Fatality or permanent disability
Class B	\$500,000 - \$1,999,999	Permanent partial disability
Class C	\$50,000 - \$4,999,999	One or more days away from work
Class D	\$5,000 - \$49,999	Medical treatment, no work loss beyond shift

⁸⁹This cost analysis is based on the \$10 million Value of a Statistical Life (VSL) presented in Jonathan Colmer, “What Is the Meaning of (Statistical) Life? Benefit–Cost Analysis in the Time of COVID-19,” *Oxford Review of Economic Policy* 36, Supplement 1 (September 28, 2020): S56–63, <https://doi.org/10.1093/oxrep/graa022>.

⁹⁰ U.S. Coast Guard, *Safety and Environmental Health Manual* COMDTINST M5100.47C, 385.

⁹¹ U.S. Coast Guard, *Safety and Environmental Health Manual* COMDTINST M5100.47C.

⁹² U.S. Coast Guard, *Safety and Environmental Health Manual* COMDTINST M5100.47C.

There is significant variation in the performance and style of existing commercial wearable devices that might serve the purpose proposed in this study. Additionally, there are varied cost estimates that might be considered when estimating the potential cost of issuing such devices to military aircrew. These include single purchase prices and recurring contracts.⁹³ For the purpose of comparison, this thesis will use the advertised price of the commercial off-the-shelf wrist-worn wearable device used as part of the study. This device is included as part of a monthly contract price, and this study will not apply any cost discount for bulk purchases or federal government contract pricing. With these variables in mind, the estimated annual cost to issue wearable devices to each of the 3,300 pilots and aircrew personnel in the USCG would be \$950,400.⁹⁴

By extrapolating the aggregated cost of the Class A and B mishaps associated with fatigue and human error across the 39 years in which data was available, the estimated annual cost of these factors equates to \$16.8 million. Based on that estimated cost, a wearable device program would need to account for a 5.6% reduction in annualized mishap cost before such a program would be fiscally beneficial or the equivalent of preventing 1.9 Class B mishaps per year.

Considering the relatively unknown impact of fatigue on aviation safety, wholesale support for a USCG wearables program is far from a practical next step, but so is peremptory dismissal of this potentially useful technology. Based on the existing research, prudent strategies might focus on leveraging wearable devices to ascertain whether fatigue is in fact a ubiquitous part of USCG aviation, or if existing crew rest protocols are effective. Such efforts need not be fleetwide, but large enough in scope so as to provide an accurate depiction of fleet norms, and allow comparison of objective physiological data to existing organizational policy assumptions. Regardless of the outcome, these efforts would likely move fatigue from being a known unknown to a known known. Additionally, assuming

⁹³ “Overview of Membership Pricing,” WHOOP, accessed July 17, 2021, <https://www.whoop.com/membership/pricing/>; “Oura Ring: The Most Accurate Sleep and Activity Tracker,” Oura Ring, accessed July 14, 2020, <https://ouraring.com>.

⁹⁴ “Direct Commission Aviator (DCA)” GoCoastGuard.Com, United States Coast Guard, accessed July 17, 2021, <https://www.gocoastguard.com/active-duty-careers/officer-opportunities/programs/direct-commission-aviator-dca>

wearable devices are technically capable of detecting and providing accurate information, these strategies should include steps to ensure that barriers to use are eliminated, and that any trial program provides the greatest opportunity for device acceptance by the users in order to provide the most accurate information.

The following portions of this study will focus on addressing the challenges noted above, in order to determine how to best incorporate wearable technologies into aviation preflight risk assessment programs, if at all. Specifically, the study will determine if sufficient evidence exists to support the assumption that commercial off-the-shelf wearable devices are capable of accurately measuring physiological information that will give users improved insight into their personal level of cognitive fatigue. That is, can wearables accurately measure fatigue? This study will then address legal considerations that may impact the implementation of a wearable program within a military service branch. Given legal protections of personal privacy, is the USCG allowed to monitor members on and off duty, and what challenges might the accumulation and ownership of that data present? Finally, this study will investigate influences that may prevent or encourage personnel from using wearable devices, using a modified version of the Unified Theory of Acceptance and Use of Technology to answer the question: Will aircrew use wearables if given the opportunity?

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IV. ASSESSING THE POTENTIAL UTILITY OF WEARABLES: ACCURACY, AUTHORITY, AND ACCEPTANCE

In determining whether or how to incorporate new technologies into their organization, decision makers benefit from applying standardized, repeatable technology assessment processes. These processes may incorporate steps to assess needs, test products, and deploy chosen technologies.⁹⁵ This thesis will make use of a three-step assessment sub-model for evaluating the potential use of wearable devices, evaluating accuracy, authority, and acceptance. This thesis first evaluates the accuracy of wearable device technology as a baseline for consideration. Logically, if such technology is not capable of accurate measurement, its utility would not warrant further investigation. Second, the process turns to consider the legal authorities and constraints that exist or may be anticipated to apply to the technology in question. Though accurate, if legal restrictions would prohibit the effective employment of the technology, its use would not be advisable. Third, the study evaluates the potential acceptance of the technology by the target demographic, and seeks to identify potential barriers to use. This final step will assist decision makers in identifying policies or strategies for most effectively implementing the new technology, should they choose to do so.

The Accuracy-Authority-Acceptance sub-model does not seek to replace existing technology assessment processes, but provides a supplement to existing programs, enabling decision-makers to evaluate novel technologies in light of anticipated technological, legal, and social considerations.

A. ACCURACY: WEARABLE PERFORMANCE

As a reminder, for the purposes of this analysis, “fatigue” will be used to refer to “a physiological state in which there is a decreased capacity to perform cognitive tasks and an increased variability in performance as a function of time on task,” as defined by the

⁹⁵ “Technology Assessment 101—Process Overview,” National Telehealth Technology Assessment Resource Center (TTAC), accessed July 17, 2021, <https://telehealthtechnology.org/toolkit/technology-assessment-101-process-overview/>.

Federal Aviation Administration,⁹⁶ and terms “fatigue” and “cognitive fatigue” will be used interchangeably. Previous research indicates that a number of physiological indicators provide quantifiable insight into a person’s level of fatigue:

Brain Wave Patterns: Electroencephalogram (EEG) measurement is held as the gold standard for detecting impaired alertness.⁹⁷ Measured by affixing sensors to a subject’s head, EEG data provides insight into changes in specific brain wave patterns that display clear indications of stress, excitement, and most notably - cognitive fatigue.⁹⁸ Comparison of changes in the alpha and theta bands of five EEG rhythms can potentially provide a real-time indication of subject cognitive fatigue.⁹⁹

Heart Rate Variability: HRV is the measured time interval between heartbeats. An increase in cognitive fatigue correlates with a decrease in the beat-to-beat variation in heart rhythm.¹⁰⁰ A number of aviation focused studies specifically suggest that HRV presents a useful method of measuring pilots’ increased level of fatigue due to workload and sleep deprivation.¹⁰¹ Additionally, Heart rate variability can be measured by electrocardiogram (EKG/ECG).¹⁰²

Eye Movement: Measured via software-based videographic analysis, or electrooculogram, rapid changes in eye movement and blink patterns indicate increased levels of fatigue.¹⁰³

With these physiological markers providing potential insight into a subject’s level of fatigue, the challenge becomes identifying wearable devices that can accurately monitor the subject in a real-world environment. To provide a beneficial level of perceived usefulness, wearables will first have to provide an accurate measurement of one or more of the aforementioned physiological markers. Put simply, not all wearables are equal in

⁹⁶ Federal Aviation Administration, *Basics of Aviation Fatigue*.

⁹⁷ Geeseman et al., “Functional Near-Infrared Spectroscopy (FNIRS) in an Aerospace Environment: Challenges and Considerations.”

⁹⁸ Li et al., “The Impact of Mental Fatigue on Brain Activity.”

⁹⁹ Li et al.

¹⁰⁰ Schaich et al., “Association of Heart Rate Variability With Cognitive Performance.”

¹⁰¹ Hao Qin et al., “Detection of Mental Fatigue State Using Heart Rate Variability and Eye Metrics during Simulated Flight,” *Human Factors and Ergonomics in Manufacturing & Service Industries*, accessed September 2, 2021, <https://doi.org/10.1002/hfm.20927>.

¹⁰² Schaich et al., “Association of Heart Rate Variability With Cognitive Performance.”

¹⁰³ Asif, “Measurements to Detect Mental Fatigue.”

capacity, accuracy, or capability. This research attempts to identify demonstrations of commercial off-the-shelf technological capability that meet levels likely to increase usefulness perceived by a user, and not to gauge industry-wide levels of performance or identify specific devices for use.

As noted above, EEG data provides the most widely accepted, accurate indication of cognitive fatigue available.¹⁰⁴ Many devices exist on the consumer market claiming to provide accurate EEG without requiring the user to remain stationary within the clinical environment.¹⁰⁵ However, no validated study of such devices could be found. A 2019 study noted the significant strides that EEG technology has made over the last decade, citing in particular the improved performance electrodes that have enabled successful use of wearable EEG devices in academic, lab-based movement experiments (walking and cycling), and brief manufacturer performed demonstrations prior to extreme sports or in conjunction with outdoor activities.¹⁰⁶ The same study noted that two key limitations on EEG wearable efficacy are the correct placement and retention of electrodes, and the significant power requirement for detecting and transmitting EEG data.¹⁰⁷ The study also noted the incredible potential of emerging forms of electrode technology, particularly temporary-tattoo-style electrodes which promise the ability to provide a stable, effective connection for days at a time.¹⁰⁸ Additionally, these impending advances in electrode technology may provide a more discrete form of wearable EEG. While this trait does not necessarily play into a user's perceived usefulness, it will likely improve the perceived ease of use as wearable EEGs become slightly more...wearable.

¹⁰⁴ Li et al., "The Impact of Mental Fatigue on Brain Activity."

¹⁰⁵ Tara Thiagarajan, "The Fantastical Claims of Consumer Brain Wearables," *Sapien Labs* (blog), June 3, 2019, <https://sapienlabs.org/the-fantastical-claims-of-consumer-brain-wearables/>.

¹⁰⁶ Alexander J. Casson, "Wearable EEG and Beyond," *Biomedical Engineering Letters* 9, no. 1 (February 1, 2019): 53–71, <https://doi.org/10.1007/s13534-018-00093-6>.

¹⁰⁷ Casson.

¹⁰⁸ Casson.

Portable, handheld devices for measuring blood oxygen saturation can be obtained relatively inexpensively in many, if not most, American pharmacies.¹⁰⁹ Battery powered and placed over the user's finger, the device is able to provide an accurate reading comparable to in-clinic devices. Additionally, an article in the *Journal of Medical Systems* found that smartphone based pulse oximetry applications (particularly based on the Samsung Galaxy S8) measured SAO₂ levels within a 96–98% correlation of medical-grade devices.¹¹⁰ Lastly, a 2019 study using the Garmin fēnix found that the wrist-worn device presented measurements biases ranging from only 0.7% to 0.8%, and noting that the device “may be a viable method to monitor SAO₂ and HR under most ambient environmental conditions.”¹¹¹ However, despite the ease of accurate measurement, the utility in tracking SAO₂ levels may not be as significant as other metrics during normal operations. As noted in a 1993 U.S. Air Force patent application for a fatigue indicator based on arterial oxygen, low blood oxygen saturation levels correlated with decreased cognitive function. The low SAO₂ levels are most commonly experienced at extreme levels of physiological performance, such as performing high-G maneuvers.¹¹² Consequently, while accurately measurable by wearables, SAO₂ may not serve as an ideal indicator of crew fatigue for consideration in *preflight* risk assessment, at least on its own.

In 2013, Google Glass brought wearable performance into the mainstream of wearable glasses, incorporating, among other things, electrooculogram (EOG) capabilities.¹¹³ Nearly a decade later, Google Glass is on its third iteration and studies have validated wearable technology in the form of glasses to measure horizontal and vertical gaze angles within less than 2 degrees of error—less than .02 degrees less accurately than

¹⁰⁹ Jason Teo, “Early Detection of Silent Hypoxia in Covid-19 Pneumonia Using Smartphone Pulse Oximetry,” *Journal of Medical Systems* 44, no. 8 (June 19, 2020): 134, <https://doi.org/10.1007/s10916-020-01587-6>.

¹¹⁰ Teo.

¹¹¹ Claire J. Lauterbach et al., “Accuracy and Reliability of Commercial Wrist-Worn Pulse Oximeter During Normobaric Hypoxia Exposure Under Resting Conditions,” *Research Quarterly for Exercise and Sport*, July 7, 2020, 1–10, <https://doi.org/10.1080/02701367.2020.1759768>.

¹¹² Repperger and Tripp, Fatigue indicator based on arterial oxygen.

¹¹³ Wendy Glauser, “Doctors Among Early Adopters of Google Glass,” *Canadian Medical Association. Journal* 185, no. 16 (November 5, 2013): 1385.

prior gold standard non-wearable devices.¹¹⁴ With this in mind, a number of industries have incorporated wearable glasses into their workforce model. Given the societal predisposition towards accepting such devices, and the proven accuracy of its EOG data, wearable glasses present a potentially heightened perception of usefulness. Additionally, new devices, like the Tobii Pro Glasses 3 offer high levels of EOG accuracy in a device that also possess a less tech-centric appearance, which may increase perceived ease of use.¹¹⁵ A 2016 study identified the potential utility of measuring saccades, the rapid eye movements that shift eyes from one target to another, to determine real-time pilot fatigue levels.¹¹⁶ A 2017 study by Alexander Leube compared the effectiveness of 60HZ versus 120HZ devices at measuring saccades for such analysis.¹¹⁷ His study found that 120HZ devices were much better at accurately detecting rapid eye movements.¹¹⁸ While screen-based eye trackers like the Tobii Pro Fusion operate at 120HZ, this study could not identify any wearable devices with that characteristic.¹¹⁹ More useful, and easier to measure, blink rate was proven as an accurate predictor of fatigue after simulated flight in studies as far back as 1996.¹²⁰ A 2021 study recently validated the ability of glasses outfitted with a flexible iontronic sensor to measure blink patterns with 96.3% accuracy.¹²¹

¹¹⁴ Nathaniel Barbara, Tracey A. Camilleri, and Kenneth P. Camilleri, “Comparative Performance Analysis of a Commercial Wearable EOG Glasses for an Asynchronous Virtual Keyboard,” in Proceedings of the 32nd International BCS Human Computer Interaction Conference (HCI) (Belfast, UK: BCS Learning and Development Ltd., July 2018), <https://doi.org/10.14236/ewic/HCI2018.6>.

¹¹⁵ Tobii Pro, “The Latest in Wearable Eye Tracking | Choose Tobii Pro Glasses 3,” accessed June 2, 2020, <https://www.tobiiipro.com/product-listing/tobii-pro-glasses-3/>.

¹¹⁶ L. L. Di Stasi et al., “Saccadic Peak Velocity as an Alternative Index of Operator Attention: A Short Review,” *European Review of Applied Psychology* 63, no. 6 (November 1, 2013): 335–43, <https://doi.org/10.1016/j.erap.2013.09.001>.

¹¹⁷ Alexander Leube, Katharina Rifai, and Siegfried Wahl, “Sampling Rate Influences Saccade Detection in Mobile Eye Tracking of a Reading Task,” *Journal of Eye Movement Research* 10, no. 3 (2017), <https://doi.org/10.16910/jemr.10.3.3>.

¹¹⁸ Leube, Rifai, and Wahl.

¹¹⁹ Tobii Pro, “Screen Based Eye Tracker for Research | Tobii Pro Fusion,” accessed October 18, 2019, <https://www.tobiiipro.com/product-listing/fusion/>.

¹²⁰ T. L. Morris and J. C. Miller, “Electrooculographic and Performance Indices of Fatigue during Simulated Flight,” *Biological Psychology, Psychophysiology of Workload*, 42, no. 3 (February 5, 1996): 343–60, [https://doi.org/10.1016/0301-0511\(95\)05166-X](https://doi.org/10.1016/0301-0511(95)05166-X).

¹²¹ Rui Chen et al., “Blink-Sensing Glasses: A Flexible Iontronic Sensing Wearable for Continuous Blink Monitoring,” *IScience* 24, no. 5 (May 21, 2021): 102399, <https://doi.org/10.1016/j.isci.2021.102399>.

Perhaps the most promising area of wearable insight comes in the form of HRV. Appealing primarily to fitness markets, wrist-worn wearable devices like the Whoop fitness tracker and Apple watch demonstrate the capability to accurately track this marker using hardware that can be continuously worn by the user, both on and off duty. A 2019 study by the American College of Cardiology analyzed data from more than 400,000 subjects to determine that the Apple watch measured ECG data with sufficient accuracy to even predict atrial fibrillation.¹²² Additionally, a 2020 study published in the Journal of Clinical Sleep Medicine validated the Whoop wrist-worn wearable's ability to measure HR/HRV and respiratory rate within 1.5% and 6.7% precision error respectively.¹²³ It is worth noting that the Whoop study was conducted using stationary subjects, and that other studies have suggested that other wrist-worn wearables suffer degradations in accuracy when users are in motion.¹²⁴ However, because the HRV readings needed for pre-watch/preflight assessment would be based on readings taken by the device while the user was asleep, the HRV data provided by wearables like the Whoop would still be accurate and useful for analysis.¹²⁵

Findings by recent studies continue to support the conclusion that some wearable devices are capable of providing useful data for determining a user's fatigue level.¹²⁶ A 2021 study published in *Human Factors and Ergonomics in Manufacturing & Service Industries* found that HRV and ocular indices worked best when analyzed together to identify indications of pilots' mental fatigue.¹²⁷ Another recent experiment by the Naval Health Research Center (NHRC) compared the performance of seven COTS wearable devices to polysomnography. To do so, the research team compared the performance of the

¹²² Caffrey, "Giant Study Suggests Apple Watch Accurately Catches Atrial Fibrillation."

¹²³ Berryhill et al., "Effect of Wearables on Sleep in Healthy Individuals."

¹²⁴ Stephen Gillinov et al., "Variable Accuracy of Wearable Heart Rate Monitors during Aerobic Exercise," *Medicine & Science in Sports & Exercise* 49 (March 1, 2017): 1, <https://doi.org/10.1249/MSS.0000000000001284>.

¹²⁵ "Everything You Need to Know About Heart Rate Variability (HRV)," WHOOP, accessed October 12, 2020, <https://www.whoop.com/thelocker/heart-rate-variability-hrv/>.

¹²⁶ Qin et al., "Detection of Mental Fatigue State Using Heart Rate Variability and Eye Metrics during Simulated Flight."

¹²⁷ Qin et al.

COTS wearables to the information provided by actigraphy devices.¹²⁸ Actigraphy, the industry standard in wrist-worn sleep measurement, uses research-grade wrist-worn devices to collect physical activity measurements that can be processed via algorithms to estimate user sleep and wake periods. The results of the test validated most of the devices as performing “as well as or better than actigraphy.”¹²⁹ However, given the rapidly evolving nature of these technological devices, the researchers recommended that “Devices should be tested in different populations and settings to further examine their wider validity and utility.”¹³⁰

Definitive analysis of wearable performance suffers from two major challenges: sheer number and types of devices, and the rapid pace at which wearable technology is improving. Put simply, if you’ve tested one wearable, you’ve tested one wearable. The variable performance by different brands and models demonstrated in the studies noted above show that any program seeking to employ a device in an organizational context should ensure the validity of that *specific* device, either via organization-sponsored pilot programs/studies or via prior published research. Additionally, the rapid pace of technological improvement within this field will make pursuit of the “best” wearable device difficult. As such, policymakers might do well to ensure that wearable devices under consideration have been validated against industry standards. However, despite these challenges, sufficient research exists to validate the claim that some wearable devices are capable of providing useful measurement of a user’s physiological markers to assist in quantifying that user’s level of fatigue.

B. AUTHORITY: LEGAL CONSIDERATIONS

1. Civilian Programs

The idea of leveraging wearable devices to improve workforce health, safety, and performance is not new. In 2019, the CEO of Fitbit told CNBC interviewers that more than

¹²⁸ Evan D. Chinoy et al., “Performance of Seven Consumer Sleep-Tracking Devices Compared with Polysomnography,” *Sleep* 44, no. 5 (December 30, 2020), <https://doi.org/10.1093/sleep/zsaa291>.

¹²⁹ Chinoy et al.

¹³⁰ Chinoy et al.

6.8 million individuals currently wore Fitbit fitness tracking devices as part of corporate wellness programs.¹³¹ The use of such devices by businesses is understandable, as the new technology floods commercial markets and becomes a ubiquitous part of many employees' lives. In general, such programs tend to be focused on one of two objectives: employee wellness and employee performance. Those programs focused on employee wellness use wearables to provide insight to the user on physiological markers that promote improved health and fitness, like activity tracking, step counts, and sleep analysis. The company may also track or promulgate this information in order to provide corporate or peer accountability for members seeking to improve their personal fitness.

Performance-focused programs use devices to ensure optimal output by employees, using the data provided by wearable devices to confirm that workers are performing as efficiently as possible. These programs include position tracking devices that ensure employees take the most efficient routes to fill warehouse shelves as well as augmented reality initiatives like those of Amazon programs, which provide wearers with real-time directions to locate and move merchandise without the need to reference a smartphone or ledger.¹³² In some instances, like the use of heartrate and temperature-tracking devices to ensure construction workers do not reach a point of exhaustion on demanding worksites, programs provide mutual benefits to performance and wellness. In every example, the employer stands to benefit by using the data garnered from the wearable devices to improve the overall productivity of its workforce, either by directly monitoring that data or through the tangential benefit of employees using that data to inform healthier personal lifestyles.

In each of these programs, the employer assumes the role of data management, potentially storing significant amounts of intimate information about each individual's physical health, location, activities, and more. A 2021 study published in the *International*

¹³¹ Stefania Marassi and Philippa Collins, "Is That Lawful? Data Privacy and Fitness Trackers in the Workplace," *International Journal of Comparative Labour Law and Industrial Relations* 37, no. 1 (February 1, 2021), <https://kluwerlawonline.com/journalarticle/International+Journal+of+Comparative+Labour+Law+and+Industrial+Relations/37.1/IJCL2021003>.

¹³² Alessandro Delfanti and Bronwyn Frey, "Humanly Extended Automation or the Future of Work Seen through Amazon Patents," *Science, Technology, & Human Values*, July 29, 2020, 0162243920943665, <https://doi.org/10.1177/0162243920943665>.

Journal of Comparative Labour Law and Industrial Relations analyzed the legal limitations on European corporate wellness programs that make use of wearable devices and found that many of such programs are in conflict with the General Data Protection Regulation (GDPR), which sets out legal restrictions on data privacy and the use of collection, storage, and use of data by European employers.¹³³ Chief in the legal challenges to these programs, the study found that the information derived from wearable devices amounts to “personal health data” as defined by the GDPR, and that analyzing such data could allow employers to arrive at a number of “diagnoses” about employees, despite the stated purpose for the data collection. For example, data gathered from a step-counting fitness challenge could be used to identify more sedentary employees who could be marginalized or terminated in order to avoid long term financial stress of employee medical benefit budgets.

Of course, employers in the United States are not subject to the limitations of the GDPR. Additionally, regulation of such information is not found under traditional U.S. health information protections. In fact, though the information gathered by wearables may include physiological markers often associated with health information, including heartrate, respiratory rate, and temperature, protections for this information are not included in the Health Information Portability and Accountability Act (HIPAA). This restriction exists because HIPAA regulations apply only to “covered entities,” which include health care providers, health plans, or health care clearinghouses.¹³⁴ Additionally, many wearable companies make use of “deidentification,” eliminating direct links between the user’s data and the ability to easily associate the individual.¹³⁵ However, this second method often proves less effective in practice, as the need to ensure that data and analysis provided to the user meet desired expectations of usability, reidentification can often be a

¹³³ Marassi and Collins, “Is That Lawful?”; European Union, *General Data Protection Regulation*, Intersoft Consulting, accessed March 27, 2021, <https://gdpr-info.eu>.

¹³⁴ Health and Human Services Office for Civil Rights, “Covered Entities and Business Associates,” last reviewed on June 16, 2017, <https://www.hhs.gov/hipaa/for-professionals/covered-entities/index.html>.

¹³⁵ Health and Human Services Office for Civil Rights, “Guidance Regarding Methods for De-identification of Protected Health Information in Accordance with the Health Insurance Portability and Accountability Act (HIPAA) Privacy Rule.” Last reviewed November 26, 2012. <https://www.hhs.gov/hipaa/for-professionals/privacy/special-topics/de-identification/index.html>.

risk. A 2014 analysis by Greg Paul and James Irvine found that “data can be either useful or perfectly anonymous, but never both.”¹³⁶

The limiting legal factor on U.S. companies’ usage of wearable data often lies within the respective company’s End User License Agreement (EULA). Given the density and length of many EULAs, it appears the relative restriction of each company’s policy could exist anywhere along a wide spectrum of authorized uses, and that many users are unlikely or unwilling to decipher the extent to which their data may be used or sold.¹³⁷

While federal regulation may provide broad lanes for wearable data usage, some U.S. states have implemented regulations of their own, in line with the concepts covered in the GDPR. In 2018, California passed the California Consumer Privacy Act (CCPA). The state law affords Californians the right to know when companies gather information about them and when that information is shared, and the right to either delete such data or explicitly prohibit its sale.¹³⁸ Ahead of its time, the state of Illinois passed the Biometric Information Privacy Act (BIPA) in 2008, which granted similar protections to the CCPA, as well as restrictions on companies selling “or otherwise profiting” from biometric data. Combined with other less expansive regulations in Texas and Washington, these laws may represent an increasing level of regulation on the gathering and use of personal data via wearable devices, a trend which should inform any future strategy aimed and leveraging the increasingly useful technology.

Some employers may rely on the use of voluntary programs to protect against potential liability challenges to workplace wearable programs. By allowing employees to opt in, companies aim to protect themselves against future claims of privacy invasion. However, even programs based on volunteering must exercise caution, especially when

¹³⁶ Greig Paul and James Irvine, “Privacy Implications of Wearable Health Devices,” in *Proceedings of the 7th International Conference on Security of Information and Networks*, SIN ‘14 (New York, NY, USA: Association for Computing Machinery, 2014), 117–21, <https://doi.org/10.1145/2659651.2659683>.

¹³⁷ Syagnik (Sy) Banerjee, Thomas Hemphill, and Phil Longstreet, “Is IOT a Threat to Consumer Consent? The Perils of Wearable Devices’ Health Data Exposure,” SSRN Scholarly Paper (Rochester, NY: Social Science Research Network, September 18, 2017), <https://doi.org/10.2139/ssrn.3038872>.

¹³⁸ “California Consumer Privacy Act (CCPA),” State of California | Office of the Attorney General, accessed October 15, 2018, <https://oag.ca.gov/privacy/ccpa>.

incentives are involved. For instance, after being challenged in court in American Association of Retired Persons (AARP) vs. U.S. Equal Employment Opportunity Commission (EEOC), for offering 30% discount incentives for participation in workplace wellness programs, the EEOC revised rules to eliminate all but “*de minimis*” incentives from such programs.¹³⁹ The rule change was a result of AARP’s argument that significant discounts undermined the need for such programs to be voluntary.¹⁴⁰ Such considerations support the conclusions found by George Dery, in his article published in the Northwestern Journal of Law and Social Policy, that protection against liability potentially fails for many voluntary programs based on the premise that “Employees might consent to wearing such technology due to their need to obtain cash incentives, because of a hope of remaining competitive for promotions, or simply to keep their jobs.”¹⁴¹

One final consideration within the realm of civilian wearable programs pertains to the legal admissibility of data derived from wearable devices during legal proceedings. The first known U.S. legal case in which wearable data was used was in 2015, when Lancaster, Pennsylvania police used data from a Fitbit device to determine that a woman had fabricated a rape report.¹⁴² More recently, in the State of Ohio vs. Ross Compton, the physiological data stored in an arsonist’s pacemaker was used to argue that he had falsified statements about his home burning down in an attempt to conduct insurance fraud.¹⁴³ A Connecticut court allowed Fitbit data to be used to disprove the defense of Richard Dabate, Jr.; the device continued to track his wife’s movement and heart rate for more than an hour

¹³⁹ AARP v. United States Equal Employment Opportunity Commission, No. 1:2016cv02113 - Document 47 (D.D.C. 2017). Justia Law, <https://law.justia.com/cases/federal/district-courts/district-of-columbia/dcdce/1:2016cv02113/182352/47/>.

¹⁴⁰ Hannah-Kaye Fleming, “Navigating Workplace Wellness Programs in the Age of Technology and Big Data,” *Journal of Science Policy & Governance* 17, no. 01 (September 30, 2020), <https://doi.org/10.38126/JSPG170104>.

¹⁴¹ George Dery, “Trading Privacy for Promotion? Fourth Amendment Implications of Employers Using Wearable Sensors to Assess Worker Performance,” *Journal of Law and Social Policy* 16, no.1 (December 1, 2020), <https://scholarlycommons.law.northwestern.edu/njls/vol16/iss1/2>.

¹⁴² Katherine E. Vinez, “The Admissibility of Data Collected from Wearable Devices,” *Stetson Journal of Advocacy and the Law* 4 (2017), <https://www2.stetson.edu/advocacy-journal/the-admissibility-of-data-collected-from-wearable-devices/>

¹⁴³ Maras and Wandt, “State of Ohio v. Ross Compton.”

after he claimed another man murdered her and assaulted him.¹⁴⁴ The use of this information in criminal court proceedings brings to light the additional legal complications that companies may inadvertently encounter in their efforts to utilize wearable devices, as well as potential barriers to acceptance.

The preceding depiction of state and federal regulations and consumer protections provides a backdrop for considering the creation of a service-administered wearables program for active-duty personnel. While many of the aforementioned protections may not specifically apply, much of the legal and regulatory landscape related to wearable devices and data policy is equally uncharted, and evolving at a frenetic pace.

2. Military Considerations

As a military entity, the USCG must consider other unique legal applications that could limit or enable a more robust wearable program within the organization. Among those is the applicability of the Fourth Amendment to military members, particularly as it relates to physiological information gathered by wearable devices. Since 1967, the “Katz Test” has enabled courts to determine if Fourth Amendment protections apply, by determining whether an individual possessed a subjective expectation of privacy regarding the search that was conducted, and whether society would hold that the expectation of privacy was objectively reasonable.¹⁴⁵ This constitutional protection against search and seizure in circumstances when a subject has a reasonable expectation of privacy has long been the subject of debate as it relates to military members. At the time that the Founding Fathers drafted the Bill of Rights, no such protections were afforded to military members. Even today, the Constitution does not explicitly address the applicability of the Fourth Amendment to military members, nor does

¹⁴⁴ David Owens, “Judge Allows Fitbit Evidence into Richard Dabate Murder Trial, Denies Request to Move Trial or Bar Ellington Residents from Jury,” *Courant.com*, January 27, 2020, <https://www.courant.com/news/connecticut/hc-news-dabate-murder-pretrial-motions-20200127-upcgy2lvraibm3induiystbu-story.html>

¹⁴⁵ “Reasonable Expectation of Privacy (REP),” Gonzales and Waddington, Attorneys at Law, accessed March 28, 2021, <https://www.ucmjdefense.com/resources/search-and-seizure/introduction/reasonable-expectation-of-privacy/reasonable-expectation-of-privacy-rep.html>

the Uniformed Code of Military Justice.¹⁴⁶ Regulation of military search and seizure, particularly restrictions on illegally obtained evidence, is found in Article 311 of the Manual for Military Courts-Martial.¹⁴⁷ However, in this section, illegally obtained evidence is deemed inadmissible if:

the accused had a reasonable expectation of privacy in the person, place or property searched; the accused had a legitimate interest in the property or evidence seized when challenging a seizure; or the accused would otherwise have grounds to object to the search or seizure under the Constitution of the United States as applied to members of the Armed Forces.¹⁴⁸

By subjecting the inadmissibility of evidence under military search and seizure to constitutional protections “as applied to members of the Armed Forces” the manual potentially creates a circular reasoning pattern. United States Military Courts’ opinions have been historically torn between the military’s need to ensure good order and discipline for mission effectiveness and the subject’s right to personal protection from search and seizure. For instance, court standings on a service member’s reasonable expectation of privacy in a barracks room have varied, with some applying that expectation to decisions and others assuming that such Fourth Amendment protections were not pertinent.¹⁴⁹ Further, in 1998, the Navy and Marine Corps Court of Military Appeals (NMCCA) found in its decision on *Curry vs. the United States* that a military barracks resident has a “reduced expectation of privacy.” In this case, the United States Court of Appeals for the Armed Forces refrained from commenting on that portion of the subordinate court’s decision, only citing that the NMCCA judge “did not err” in admitting evidence under that standard. Consequently, there remains little certainty as to what a “reduced expectation of privacy” effectively means when potentially applying Fourth Amendment protections to military personnel.¹⁵⁰ In the end, these

¹⁴⁶ Captain James F. Webb, Jr., “Military Searches and Seizures—The Development of a Constitutional Right,” *Military Law Review* 26, Department of the Army Pamphlet 27-100-26 (October 1964), https://www.loc.gov/law/mlr/Military_Law_Review/27607F~1.pdf

¹⁴⁷ Joint Service Committee on Military Justice, “Manual for Military Courts Martial (2019),” accessed March 28, 2021, [https://jsc.defense.gov/Portals/99/Documents/2019%20MCM%20\(Final\)%20\(20190108\).pdf?ver=2019-01-11-115724-610](https://jsc.defense.gov/Portals/99/Documents/2019%20MCM%20(Final)%20(20190108).pdf?ver=2019-01-11-115724-610).

¹⁴⁸ Joint Service Committee on Military Justice, “Manual for Military Courts Martial (2019).”

¹⁴⁹ Major Walter M. Hudson, “A Few New Developments in the Fourth Amendment.”

¹⁵⁰ Major Walter M. Hudson.

decisions leave policymakers wanting. Without additional clarity, either via changes to the Military Rules of Evidence or perhaps Supreme Court decision, the general applicability of Fourth Amendment protections to service members remains questionable, at best.¹⁵¹

These questions acquire a new layer of ambiguity when the applications of privacy protection of military members and the digital world are considered together. Military courts have considered privacy applications within the digital realm, again showing variation with respect to privacy expectations, in deciding the admissibility of files gathered from government computers as in *United States vs. Tanksley*, as well as personal computers within shared government quarters as in *United States vs. Conklin*.¹⁵² In such findings, courts have generally aligned with the previously noted “reduced expectation of privacy” generally afforded to service members.

However, more recent findings in civilian court may further confuse the matter of military privacy expectations with respect to digital information, particularly information held by a third party. In 2018, the Supreme Court decided *U.S. vs. Carpenter*, in which it had considered the admissibility of digital location information automatically gathered from a suspect’s cell phone service provider.¹⁵³ In its 5–4 decision, the Court ruled that Fourth Amendment protections apply to cellular service location information, but offered no test for determining when such protections apply to a third party service provider.¹⁵⁴ At most, the Court gave some insight into how it viewed such information, citing the data’s “depth, breadth, and comprehensive reach, and the inescapable and automatic nature of its collection.”¹⁵⁵ This emphasis on the continuous nature of data gathered by such devices, as

¹⁵¹ Borch, “Does the Fourth Amendment Apply to the Armed Forces?”

¹⁵² *United States v. Tanksley*, No. 99–0666, Crim. App. No. 96–1402, C.A.A.F. 2000, Justia Law, accessed April 2, 2021, <https://law.justia.com/cases/federal/appellate-courts/caaf/99-0666-NA/99-0666-NA-2000-09-25.html>; *United States v. Conklin*, No. 05–0220-AF, Crim. App. No. 35217, C.A.A.F. 2006, Justia Law, accessed April 2, 2021, <https://law.justia.com/cases/federal/appellate-courts/caaf/05-0220-AF/05-0220-AF-2006-07-27.html>.

¹⁵³ Matthew Tokson, “42nd Annual Foulston-Siefkin Lecture: The Next Wave of Fourth Amendment Challenges After Carpenter,” *Utah Law Faculty Scholarship* (2020), 25, <https://dc.law.utah.edu/scholarship/185>

¹⁵⁴ Tokson.

¹⁵⁵ *Carpenter v. United States*, 585 U.S. No. 16–402 (2018), 119. Justia Law, <https://supreme.justia.com/cases/federal/us/585/16-402/>.

well as the somewhat ubiquitous nature of the devices that gather them, may have significant applicability when considering whether the information gathered by wearables is subject to Fourth Amendment protections.

The recent Supreme Court decision in *U.S. vs. Carpenter* in some ways stands in contrast to the Fitbit and pacemaker cases mentioned earlier, with the possible exception that the device users in those cases employed those devices for the explicit intent of gathering and tracking their own data. With that variable in mind, the question of consent becomes primarily important. Previous absences of Fourth Amendment protection on third party information relied on the subject's awareness that such information was gathered by another entity, like bank and phone records.¹⁵⁶ If such consent considerations continue to play a significant role, it stands within reason that Fourth Amendment protections may not be afforded or may be reduced when information is gathered by wearable devices from a subject who signed a terms of use agreement, consenting to be monitored by a commercial third party.

The consideration of this somewhat convoluted applicability of constitutional protections in both the military and civilian contexts sets the stage for a completely novel situation that is potentially inherent to the creation of a military wearable program. What constitutional protections would apply to data gathered from a wearable device worn by a military member as part of a mandatory use program? What about a voluntary program with government-issued devices? These questions demonstrate the uncharted territory into which such a program would be venturing. In such a situation, the legal ambiguity surrounding the program could make gaining the confidence of potential users challenging. If a mandatory program dictates that members should wear their device at all times, on and off duty, in order to provide the most accurate fatigue assessment, can members be sure that is a lawful order? If data gathered by a government-issued wearable could play a role as evidence in an unrelated criminal or civil legal proceeding, would it be admissible? Less extreme, might the organization review data gathered prior to an aviation mishap and use that data to hold an individual accountable under military justice protocols? Again, these hypothetical situations serve to demonstrate that the potential movement into tracking intimate physiological details

¹⁵⁶ Tokson, "42nd Annual Foulston-Siefkin Lecture."

about our service members will require policy solutions that can provide aircrews with an increased level of confidence that they know how their data can be legally used.

One last unique legal concept applied within civil and military aviation bears mentioning at this point. Military and federal courts grant protection to the analysis, investigation, and reports produced by safety investigators and boards under executive privilege. They do this in order to enable investigators to provide open and forthright findings and recommendations, and encourage witnesses to provide full and honest input to investigators, without fear of retribution. Under these policies, senior members of Safety Investigation Boards are able to provide witnesses with a “promise of confidentiality,” assuring the witness that his or her statement will not be disclosed outside the confines of the safety investigation. In doing so, safety programs are able to gather critical safety information that might otherwise go unreported for fear of reprisal. Specifically, safety privileged information cannot be used as evidence to determine a line-of-duty status in any punitive action, in a determination of liability, or as evidence before any other administrative body.¹⁵⁷ This concept may present a unique utility in developing an effective wearable risk assessment program.

3. Social Considerations

In 2014, there were officially more mobile devices than people in the world. By 2017, Internet of Things devices outnumbered mankind.¹⁵⁸ As electronic devices become an increasingly ubiquitous part of everyday life, individuals must determine if and how to incorporate new technologies into their lives. Privacy can play a major role in determining whether or not a person adopts a specific technology or device. One leading adoption model, known as privacy calculus, provides an intuitive portrayal of the risk analysis generally applied by individuals when making this determination. In its simplest version, the model

¹⁵⁷ U.S. Coast Guard, Safety and Environmental Health Manual COMDTINST M5100.47C

¹⁵⁸ Eric Mack, “There Are Now More Gadgets on Earth than People,” *CNET*, accessed September 20, 2021, <https://www.cnet.com/tech/computing/there-are-now-more-gadgets-on-earth-than-people/>; “8.4 Billion Connected Things Will Be in Use 2017,” Gartner.com, accessed September 20, 2021, <https://www.gartner.com/en/newsroom/press-releases/2017-02-07-gartner-says-8-billion-connected-things-will-be-in-use-in-2017-up-31-percent-from-2016>.

states that “if an individual’s perceived benefit is higher than perceived privacy risk, s/he is more likely to adopt the device.”¹⁵⁹ While this validated model provides a useful, simplified framework for predicting at least one aspect of wearable adoption, a number of social and contextual variables play a significant role in an individual’s calculus.

For instance, a 2019 study by Sabine Trepte found that affordances play a significant role in determining how openly a person will share personal information on an online social media platform. After studying the interactions of 128 subjects, the study determined that people were more likely to share such information when other individuals’ actions demonstrated similar behavior, thus indicating that the environment was a place in which such sharing was either safe and/or a social norm.¹⁶⁰ Additionally, a 2020 study by Steven Neville highlighted the role that novel social concepts, like YouTube unboxing videos, play in normalizing consumer acceptance of new and potentially invasive technologies.¹⁶¹ In light of importance that social affordances might play, it becomes necessary to consider the changing social context in which a wearable program would be implemented, along with other determining factors, in order to decide how best to ensure the devices’ successful adoption. Fortunately, there is a useful model for conducting such analysis.

Building on the Technology Acceptance Model introduced in Chapter II, the Unified Theory of Acceptance and Use of Technology (UTAUT), developed by Viswanath Venkatesh et al. in 2003, provides a useful model for predicting user acceptance of new technologies (see Figure 4).¹⁶² Considering the influence of four core determinants of user intention, the model is widely accepted as a foundational tool in the field of technology usage projection.

¹⁵⁹ He Li et al., “Examining Individuals’ Adoption of Healthcare Wearable Devices: An Empirical Study from Privacy Calculus Perspective,” *International Journal of Medical Informatics* 88 (April 1, 2016): 8–17, <https://doi.org/10.1016/j.ijmedinf.2015.12.010>.

¹⁶⁰ Sabine Trepte, Michael Scharkow, and Tobias Dienlin, “The Privacy Calculus Contextualized: The Influence of Affordances,” *Computers in Human Behavior* 104 (March 1, 2020): 106115, <https://doi.org/10.1016/j.chb.2019.08.022>.

¹⁶¹ Stephen J Neville, “The Domestication of Privacy-Invasive Technology on YouTube: Unboxing the Amazon Echo with the Online Warm Expert,” *Convergence*, November 20, 2020, <https://doi.org/10.1177/1354856520970729>.

¹⁶² Venkatesh et al., “User Acceptance of Information Technology.”

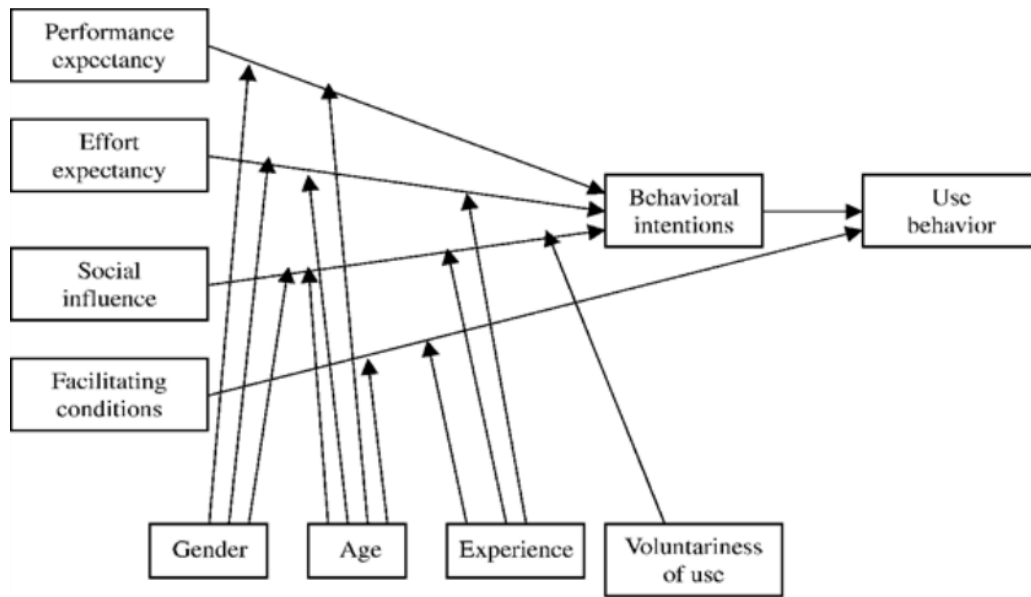


Figure 4. The Unified Theory of Acceptance and Use of Technology (UTAUT)¹⁶³

Since its creation in 2003, the model has undergone several revisions by researchers pursuing a more accurate predictor of technology adoption, either as a general tool or within niche groups and markets.¹⁶⁴ Divine Quase Agozie et al. created one such modification to support their 2020 study of privacy considerations' impact on social commerce use by members of Generation Y (see Figure 5).¹⁶⁵ The adaptation introduced Privacy Concern as a new independent determinant. According to the research team, this variable provided an 11.6% improvement over the baseline UTAUT model.¹⁶⁶

¹⁶³ Venkatesh et al.

¹⁶⁴ Alaa Momani and Mamoun Jamous, "The Evolution of Technology Acceptance Theories," *International Journal of Contemporary Computer Research (IJCCR)* 1 (April 7, 2017): 50–58.

¹⁶⁵ Divine Quase Agozie, Muesser Nat, and Sampson Abeeku Edu "Understanding Privacy-Focused Technology Use Among Generation Y: Its Impact on Behavioural Intention and Actual Use of Social Commerce," in *Handbook of Research on Managing Information Systems in Developing Economies*, ed. Richard Boateng (Hershey, Pennsylvania: IGI Global, 2020), <https://doi.org/10.4018/978-1-7998-2610-1.ch004>.

¹⁶⁶ Agozie, Nat, and Edu.

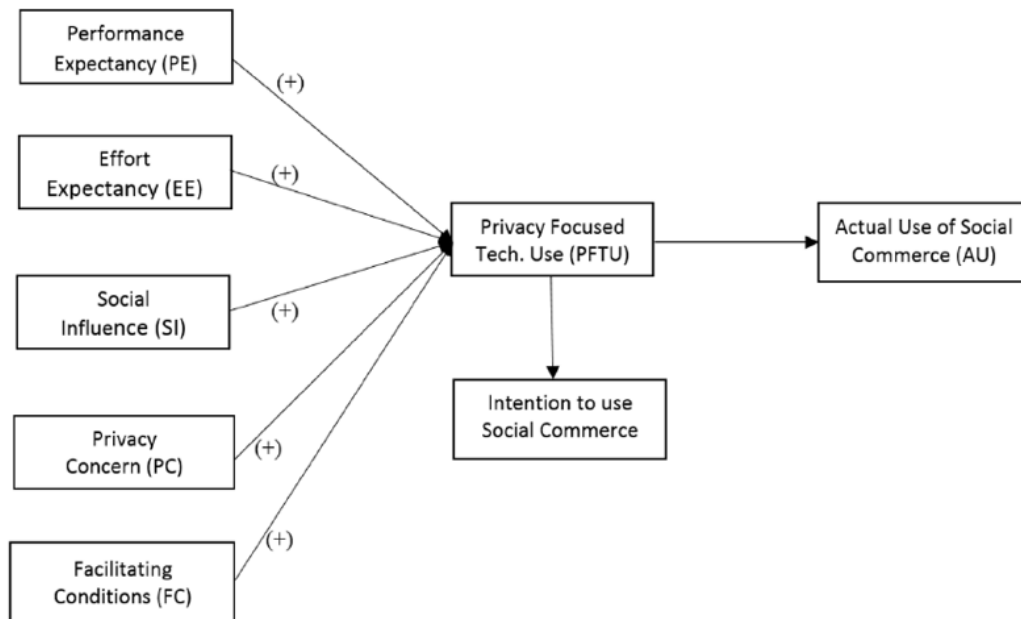


Figure 5. Agozie's Adapted UTAUT¹⁶⁷

The five determinants of this model will provide a theoretical foundation for investigating potential user acceptance of wearables for this study. The model will be employed with one additional modification, as this study's assessment is not focused on the variable of user-controlled privacy focused technology functions (see Figure 6).¹⁶⁸

¹⁶⁷ Agozie, Nat, and Edu.

¹⁶⁸ Agozie Nat, and Edu's study focused on Privacy-Focused Technologies, user interface tools that enable consumers to personally control the degree to which personal information is shared within a digital social networking framework. Because variable privacy settings are not a specific focus of this study, they have been removed from the EUTAUT model.

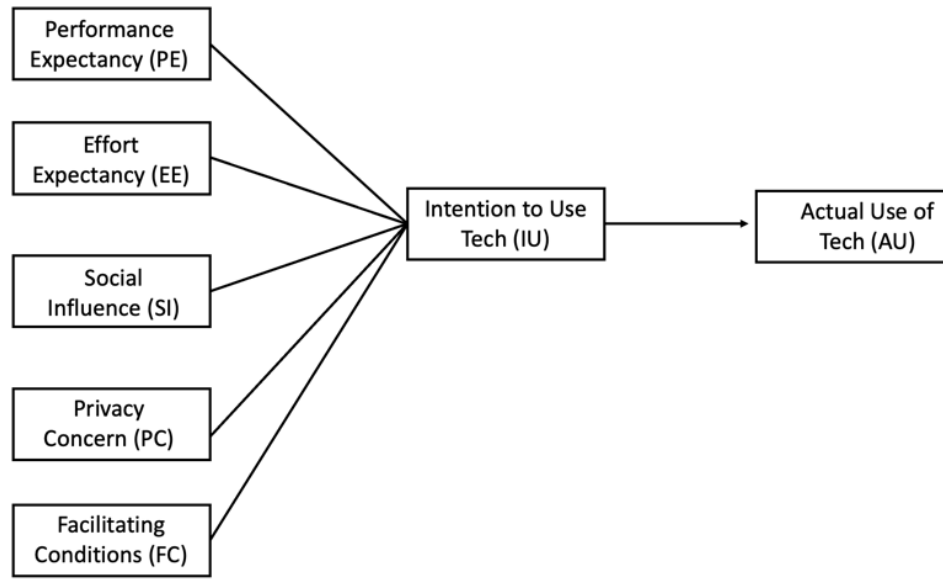


Figure 6. Modified Unified Theory of Acceptance and Use of Technology (MUTAUT) (adapted from Agozie et al.)¹⁶⁹

Performance Expectancy: Perhaps the most fundamental determinant of technology use, individuals tend to employ technologies that they believe will serve their intended purpose, and enable the user to perform a task with increased ease or effectiveness.¹⁷⁰ Numerous studies have shown a positive relationship between performance expectancy and a user’s willingness to accept new technologies.¹⁷¹ As one might intuitively determine upon first considering skydiving, users are not keen to adopt technologies that they do not think will work.

Effort Expectancy: As defined by Venkatesh et al., effort expectancy is “the degree of ease associated with the use of a system.”¹⁷² As one might assume, an increased level of effort correlates with a decreased tendency to adopt a new technology. This tendency has been well documented in analyses of online behavior, where e-commerce, gaming, and social

¹⁶⁹ Agozie, Nat, and Edu, “Understanding Privacy-Focused Technology Use Among Generation Y.”

¹⁷⁰ Venkatesh et al., “User Acceptance of Information Technology.”

¹⁷¹ Agozie, Nat, and Edu, “Understanding Privacy-Focused Technology Use Among Generation Y.”

¹⁷² Venkatesh et al., “User Acceptance of Information Technology.”

networking sites that were deemed easier to navigate showed proportionally higher use than more complicated and less user-friendly.¹⁷³

Social Influence: In line with the original model, social influence represents “the degree to which an individual perceives that important others believe he or she should use the new system.”¹⁷⁴ This variable captures the social norms of a user valuing what others will think if they based on their willingness or lack of willingness to use a new technology. Peer pressure, as a simplified concept, captures the idea that users are more inclined to adopt new technologies if they appear socially acceptable. Perhaps surprisingly, studies demonstrated that social influence had an increased influence on user intention toward use under involuntary circumstances as compared to voluntary situations, particularly in the early stages of the experience.¹⁷⁵

Privacy Concerns: Within an online environment, privacy concerns decrease a user’s willingness to share information and may decrease a person’s willingness to employ an online system. Introduced into the UTAUT by Agozie et al., this determinant accounts for the user’s trust in the security of the online environment, particularly with regard to potential exposure of information that the user intends to retain personal control over. Many scholars assert that trust is at the core of all social interactions, and that individuals are more likely to engage in any given social situation when trust levels are high. Seeing the relationship between potential wearable users and policymakers through a social context, this places privacy—and consequently trust—as one of the fundamental determining factors in whether the adoption of such devices will be successful.

Facilitating Conditions: Conceptually linked with each of the other four factors, facilitating conditions are reflected in “the degree to which individuals believe that appropriate technical and societal structures exist to support their use of technology.”¹⁷⁶ Individuals must be convinced that logistical support and policies exist to make use of a technology feasible

¹⁷³ Agozie, Nat, and Edu, “Understanding Privacy-Focused Technology Use Among Generation Y.”

¹⁷⁴ Venkatesh et al., “User Acceptance of Information Technology.”

¹⁷⁵ Venkatesh et al.

¹⁷⁶ Venkatesh et al.

before they are willing to adopt it. Similar to the way a consumer might not be influenced to buy a product with a 20-year warranty at a “going out of business” sale, facilitating conditions account for the user’s perception that the technology they are considering will be able to be used in the real world. Venkatesh et al. found this determinant to be the least impactful of their original four, in large part because the same factors that create increased facilitating conditions are also accounted for in the other three factors. However, some studies have shown a significant correlation between positive facilitating conditions and user intention to adopt things like interactive whiteboards and mobile technologies.¹⁷⁷

Each of these variables plays a role in an individual’s privacy calculus, determining whether he or she is willing to disclose varied levels of personal information for the actual or perceived benefit garnered through sharing.¹⁷⁸ An analysis of aggregated privacy calculus is a timely inquiry as society adjusts to the impacts of the COVID-19 pandemic. Scholars have noted that impacts like the 2020 pandemic alter the way individuals make decisions based on personal or civil benefit. A 2020 paper by Teagen Nabity-Grover et al. in the *International Journal of Information Management* posited that social media users shifted disclosure decisions from a “self-focus” privacy calculus to an “other-focus” decision framework.¹⁷⁹ Under this new perspective, users are more likely to disclose personal information if they perceive a collective benefit from doing so. Such a perspective provides a useful lens for a potential wearables-based risk-management program, in which individual privacy would be exchanged for the benefit of increased safety for the collective group.

¹⁷⁷ Boštjan Šumak and Andrej Sorgo, “The Acceptance and Use of Interactive Whiteboards among Teachers: Differences in UTAUT Determinants between Pre- and Post-Adopters,” *Computers in Human Behavior* 64 (November 1, 2016): 602–20, <https://doi.org/10.1016/j.chb.2016.07.037>; Raden Agoeng Bhimasta and Budi Suprpto, “An Empirical Investigation of Student Adoption Model toward Mobile E-Textbook: UTAUT2 and TTF Model,” in *Proceedings of the 2nd International Conference on Communication and Information Processing, ICCIP ‘16* (New York, NY, USA: Association for Computing Machinery, 2016), 167–73, <https://doi.org/10.1145/3018009.3018046>.

¹⁷⁸ Tobias Mini, “Privacy Calculus” (Seminar thesis, University of Passau, 2017). https://www.researchgate.net/publication/322900839_Privacy_Calculus

¹⁷⁹ Teagen Nabity-Grover, Christy M. K. Cheung, and Jason Bennett Thatcher, “Inside out and Outside in: How the COVID-19 Pandemic Affects Self-Disclosure on Social Media,” *International Journal of Information Management*, Impact of COVID-19 Pandemic on Information Management Research and Practice: Editorial Perspectives, 55 (December 1, 2020), <https://doi.org/10.1016/j.ijinfomgt.2020.102188>.

C. ACCEPTANCE: USER PERCEPTIONS

This portion of the study set out to assess the technology acceptance of a wearable device aimed at providing quantitative input for preflight risk assessment among USCG aviators. To do so, the experiment used the MUTAUT as a model to evaluate use of a COTS wearable device by 20 USCG aviator participants.

1. Objectives

The MUTAUT defines five specific areas of focus: performance expectancy, effort expectancy, social influence, privacy concerns, and facilitating conditions. This investigation focused primarily on two areas of analysis:

1. Whether the use of the wearable created a change in the wearer's perception regarding the utility of the fatigue/readiness information provided by the device as compared to their own intuitive self-assessment (capturing Performance Expectancy, Effort Expectancy).
2. Whether concerns over data privacy or the visibility of data by supervisors might dissuade potential users from utilizing such a device (capturing Social Influence, Privacy Concerns, Facilitating Conditions).

2. Method

The research experiment employed a commercially available wearable device that collected and analyzed physiological data to determine the wearer's daily physical output and recovery. The Whoop band measured heart rate, movement, and respiratory rate, which it then analyzed via proprietary algorithms to provide the user with simplified sleep, readiness, and activity scores. In addition to this interpreted and simplified data, this study conducted additional analysis on physiological markers including heart rate, sleep, activity, and respiratory information, in an effort to identify correlations between physiological performance and survey feedback.

Participants completed pre- and post-participation surveys via an online platform. Comparison of participant responses captured changes in stated preference toward the utility

of the wearable and identified variables, while analysis of the raw wearable data provided insight into subjects' revealed preferences over time.

Additional analysis of individuals' Whoop data sought to identify behavioral trends (changes in sleep performance and/or readiness scores over time), relationships between predisposition and performance (differences between performance/recovery changes experienced by subjects who did or did not already use some type of wearable device), and correlations between user experience and perception (relationships between improved sleep performance and increased acceptance of the device).

a. Participants

The study involved 20 male active-duty USCG aviators. A breakdown of the demographic characteristics of the participants (including age, aviation specialty, and whether or not they already owned a wearable device) is shown in Table 2. Subjects participated on a strictly voluntary basis. The voluntary nature of this program introduced an implicit bias into the sample under observation. That is, by agreeing to participate, subjects demonstrated a baseline willingness to consider wearable technology's utility within their aviation duties as well as consent to monitoring by the device company and the USCG.

Table 2. Demographic Subgroups

Category	Subgroup	Abbreviation	Percentage
Age	20-29	20-29	30%
	30-39	30-39	55%
	Over 40	40+	15%
Aviation Specialty	Flight Mechanic-Rescue Swimmer	Mech-Swim	45%
	Pilot	Pilot	55%
Currently Own Wearable	Do Not Own	Do Not Own	50%
	Own	Own	50%

b. Study Design

Participants completed an online survey to establish their pre-use preferences, perspectives on the perceived usefulness of the wearable device, their basic demographic

information, and self-assessed technological predisposition. The subjects were then given the opportunity to wear the Whoop band for 30 days without additional intervention. Following the 30th day of use, subjects completed a post-experience survey. Surveys employed both Likert-scaled preference questions, in which subjects indicated perspectives on a 6-point scale, demographic subgroup questions, and text entry questions, in which subjects provided qualitative perspectives and amplifying information.

c. Wearable Device

The study employed the Whoop strap 3.0 wrist-worn wearable device.¹⁸⁰ The Whoop strap collected physiological data, including heart rate, heart rate variability, sleep information, respiratory data, and activity data, and transferred that information to the Whoop application via a Bluetooth connection with the subject's personal smartphone. The cloud-based Whoop Team Dashboard aggregated data from all subjects for analysis at the end of 30 days.

3. Data Analysis

Transformation of Likert-scale data followed accepted statistical principles. Although the specific nominal values within the various 6-point scales changed, the numeric coding remained constant with values suggesting greater acceptance of the device or concept representing a numeric score of six and the most negative responses equating to a score of one. The subsequent analysis of data through JMP Pro 15 and IBM SPSS Statistics version 28 provided a way to calculate descriptive statistics and matched pairs analysis of pre- and post-survey responses. Although the number of participants in the study is small ($n = 20$), the presentation of data follows statistical standards for academic research. Due to the relatively small number of subjects employed in this experiment, this study did not anticipate results that would support statistically significant conclusions. Instead, this study sought to identify descriptive statistics that would provide researchers and policymakers a baseline understanding and a focus for future efforts.

¹⁸⁰ "Meet Your Personalized Digital Fitness and Health Coach," WHOOP, accessed July 17, 2021, <https://www.whoop.com/>.

a. Factors Impacting Intention to Use

Subjects were asked to rate the importance of characteristics in each of the five MUTAUT categories (6-point scale), with 1 having low influence and 6 having high influence on their willingness to use a wearable device. Reported prioritization of factors influencing subjects' intent to use wearable devices for the experiment's stated purpose remained relatively unchanged between pre- and post-surveys. Subjects cited Performance Expectancy and Privacy Concerns as the most influential factors in both instances.

Table 3. Descriptive Statistics: MUTAUT Factors Influencing Intent to Use

Element	Survey	<i>n</i>	<i>M</i>	<i>SD</i>	<i>df</i>	<i>t</i>	<i>p</i> [*]
Performance Expectancy	Pre	20	5.15	0.81	19	-.525	.606
	Post	20	5.25	0.78			
Effort Expectancy	Pre	20	4.90	0.85	19	.224	.825
	Post	20	4.35	1.13			
Social Influence	Pre	20	3.76	1.14	19	-1.00	.333
	Post	20	4.00	1.08			
Privacy Concerns	Pre	20	5.20	1.23	19	.433	.867
	Post	20	5.15	1.13			
Facilitating Conditions	Pre	19	3.73	1.40	18	.266	.531
	Post	19	3.80	1.36			

Note: *95% Confidence interval used for calculating p values.

b. Performance Expectancy

Subjects also answered questions on pre- and post-surveys in which they ranked their relative trust between a wearable device and their own intuition when diagnosing their personal level of fatigue. Low scores represented trust in intuition and high scores signified a trust in the wearable device (6-point scale). Reported trust in the data provided by the wearable device relative to personal intuition increased between the pre- and post-surveys. Within the pre-survey, the reported sample mean ($M = 2.90$) suggested a slight lack of trust in such devices compared to the respondents' own intuition and feelings. Conversely, following the experiment, the mean increased ($M = 3.45$) pointing to an increase in the perceived trust in the wearable devices.

Additionally, two subgroups produced potentially notable differences in the two surveys. First, the pre-survey comparison between the Mech-Swim and Pilot subgroups produced ostensibly identical results (mean responses within 0.02). However, in the post-survey, the Mech-Swim mean ($M = 3.89$) increased more than the Pilot mean ($M = 3.09$). The delta between the two subgroups may reflect the differences in the prior use of wearable devices. Among the Mech-Swim subgroup, six of nine owned such devices prior to the study while only four of 11 within the Pilot subgroup owned one. As such, the results for the subgroups based upon currently owning a wearable device produced a similar dynamic. Respondents who previously owned a similar device ($M = 3.90$) reported a higher level of post-survey trust than those who did not ($M = 3.00$). The collective data support an increase in trust for the wearable's data following its use. Table 4 highlights the data centered on the reported trust in wearable devices.

Table 4. Descriptive Statistics: Trust in Wearables

Survey	Subgroup	<i>n</i>	<i>M</i>	<i>SD</i>	<i>df</i>	<i>t</i>	<i>p</i> *
Pre		20	2.90	0.79			
Post		20	3.45	1.10	1	-1.68	.110
Pre	Mech-Swim	9	2.89	0.60			
	Pilot	11	2.91	0.94	1	0.06	.956
Post	Mech-Swim	9	3.89	0.35			
	Pilot	11	3.09	0.32	1	-1.69	.107
Pre	Do Not Own	10	2.80	0.63			
	Own	10	3.00	0.94	1	0.56	.584
Post	Do Not Own	10	3.00	0.82			
	Own	10	3.90	1.20	1	1.96	.065

Note: *95% Confidence interval used for calculating p values.

c. *Privacy Concerns*

The pre- and post-surveys asked subjects to rate their concerns over access to personal data by an outside commercial source or the USCG. Higher scores (6-point scale) represent an increased level of concern. Reported concerns regarding both commercial and USCG access to subjects' physiological data remained relatively unchanged between pre- and post-surveys. The pre-survey reported sample means for concerns regarding

commercial ($M = 3.81$) and USCG ($M = 3.87$) access to data, as well as the post-survey commercial ($M = 3.81$) and USCG ($M = 3.67$) means suggest a persistent concern regarding data privacy.

Table 5. Descriptive Statistics: Data Privacy Concerns

	Survey	<i>n</i>	<i>M</i>	<i>SD</i>	<i>df</i>	<i>t</i>	<i>p</i> *
Commercial Access	Pre		3.81	1.223	15	.000	1.0
	Post		3.81	1.51			
USCG Access	Pre		3.87	1.72	14	.526	.607
	Post		3.67	1.34			

Note: *95% Confidence interval used for calculating p values.

Comparison of subgroup data reveals no significant variance between Mech-Swim and Pilot groups regarding commercial or USCG data privacy concerns. However, post-survey data suggests a significant difference between age group perspectives, with USCG privacy concerns varying by 1.53 points between 20–29 and 40+ subgroups, and commercial privacy concerns for the same groups showing a 1.0 difference. These data suggest a correlation between increased privacy concerns and older subjects.

Post-survey subjects who reported not using the wearable device as part of their risk assessment also reported higher USCG ($M = 3.63$) data privacy concerns than those who reported integration of the device into their risk analysis ($M = 3.16$). However, an inverse relationship existed between post-survey commercial privacy concerns and wearable use, with wearable users reporting $M = 3.87$ and subjects who did not use the device for risk analysis reporting $M = 3.54$. Qualitative input provided by subjects also provided insight into the reasoning behind potential acceptance barriers as related to privacy. A pilot from the 30–39 age demographic stated, “I absolutely do not want the USCG to have access or hold me accountable for my sleep post mishap.” A flight mechanic, also in the 30–39 age group, who did not use the Whoop band as part of risk analysis noted, “I wouldn’t want any of this data to be used against me for decisions made now or in the future.” Finally, pre- ($M = 3.05$) and post-survey ($M = 2.45$) support for a mandatory wearable program show a decrease, while pre- ($M = 4.10$) and post-survey (M

= 4.05) support for voluntary programs remained ostensibly unchanged. As such, while data did not support conclusive relationships between changes in privacy perspective and device adoption, the persistently high privacy data concerns reported by subjects, as well subject's relatively high pre- and post-survey rankings of privacy as a determinant factor suggest that it may play a role as a barrier to adoption.

Table 6. Data Privacy Concern Descriptive Statistics by Subgroup

Survey	Subgroup	<i>n</i>	<i>M</i>	<i>SD</i>	<i>df</i>	<i>F</i>	<i>t</i>	<i>p</i> *
Post (USCG)	Mech-Swim	8	3.50	1.51	1		-0.07	0.94
	Pilot	9	3.44	1.42				
Post (USCG)	20-29	5	2.80	1.30	2	1.61		0.34
	30-39	9	3.55	1.23				
	40+	3	4.33	2.08				
Post (Commercial)	20-29	6	3.33	1.75	2	0.44		0.64
	30-39	10	3.70	1.15				
	40+	3	4.33	2.08				
Post (USCG)	Used	11	3.63	1.28	1		-0.63	0.53
	Did Not Use	6	3.16	1.72				
Post (Commercial)	Used	8	3.54	1.36	1		0.47	0.63
	Did Not Use	11	3.87	1.64				

Note: *95% Confidence interval used for calculating p values.

d. Sleep Insight

Data revealed the mean average of hours of sleep per night across all subjects to be $M = 6.82$, $SD = 0.64$, $Max = 7.90$, and $Min = 5.56$. While this result suggests better sleep discipline than was observed in the previously mentioned Tufts study survey results, it is important to note that some subjects demonstrated comparatively low average nightly sleep times.¹⁸¹ Three subjects averaged less than six hours of sleep per night ($M = 5.57$, $M = 5.56$, and $M = 5.84$). The three subjects represented one of each age subgroup, a 20–29-year-old flight mechanic, a 30–39-year-old flight mechanic, and a 40+ year old rescue swimmer. Interestingly, two of these three subjects reported previously owning wearable

¹⁸¹ O'Donnell, "Using Heart Rate Variability to Manage Crew Fatigue in U.S. Coast Guard Aircrews."

devices, all three declared a high interest in technology ($M = 4.66$), all three conveyed a high perceived accuracy of the device ($M = 4.66$), and yet all three also reported not incorporating the wearable device into risk-management practices.

The limited data did not reveal a causal relationship between wearable use and changes in sleep score, recovery score, HRV, or nightly hours of sleep over the period of observation. The limited number of subjects and short duration of the study made such results unlikely. Figure 7 visually depicts each subject's daily recovery score over the duration of the experiment, highlighting the absence of correlation between wearable use and improved sleep or recovery over the 30-day period.

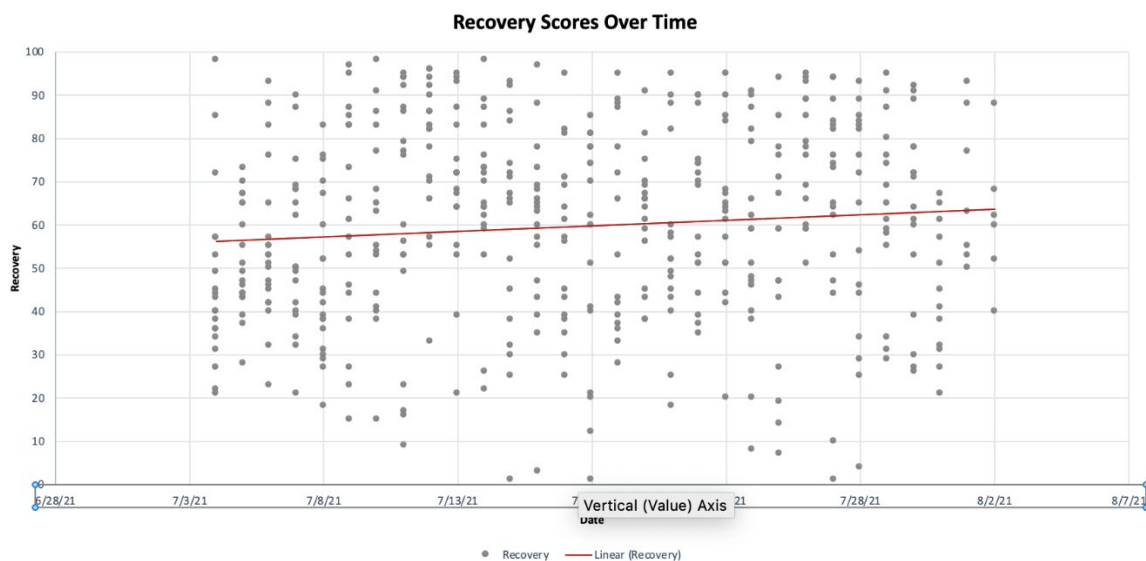


Figure 7. Subjects' Daily Recovery Scores Over 30 Days

It is worth noting that inciting behavioral change in the form of improved sleep was not a primary focus of this examination. Instead, this study set out to determine if and how wearables might inform members when their sleep quality or quantity is lacking, allowing the user to incorporate that knowledge into operational risk decisions. Individual depictions of daily sleep and recovery scores demonstrate the wearables' potential to provide such daily insights. Figure 8 serves as a representative example, showing one subject's daily sleep and recovery scores in a simplified format. Toward that end, the wearable device

appeared to provide useable, relevant data that subjects could incorporate into risk-management decisions. However, the poor sleep performance demonstrated by the three subjects who also chose not to incorporate wearable input into risk-management decisions suggests that other influences beyond individual predisposition and technical accuracy may be necessary to encourage adoption of such devices for the purpose of informing risk-management.

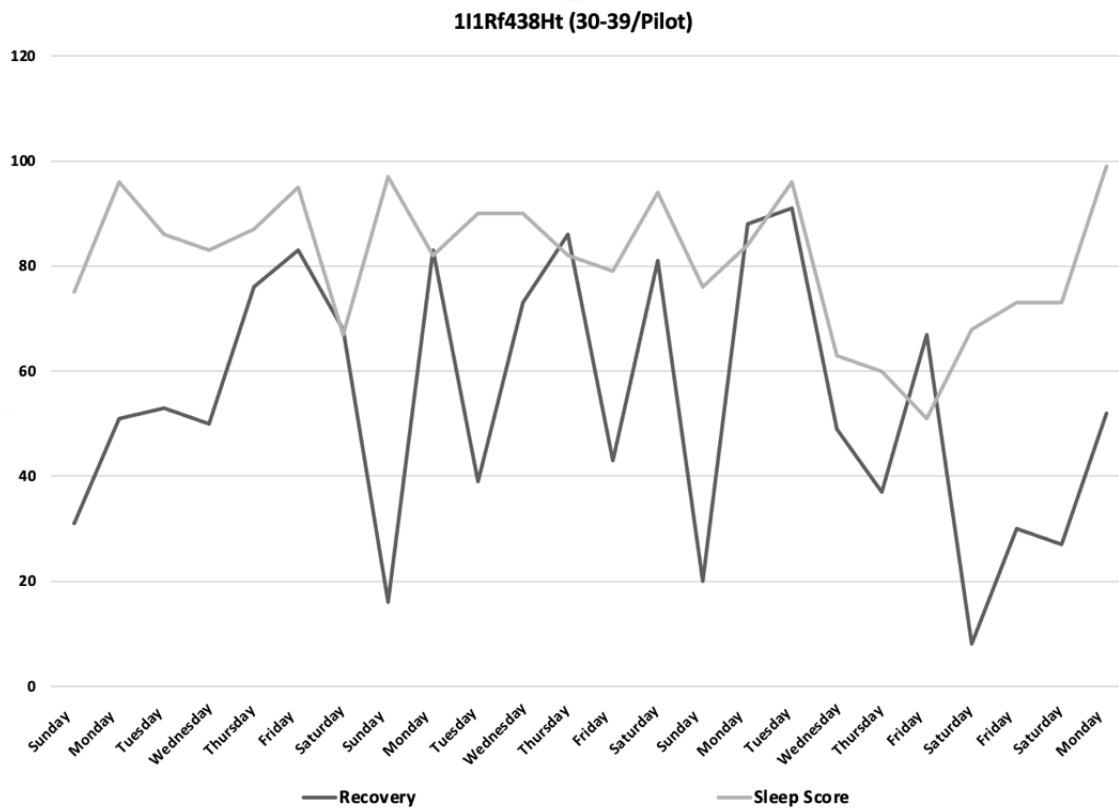


Figure 8. Representative Example of Subject's Daily Sleep and Recovery Scores

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V. CONCLUSIONS AND RECOMMENDATIONS: THE POTENTIAL ROLE OF WEARABLES IN USCG AVIATION RISK MANAGEMENT

A. ACCURACY

Definitive conclusions regarding the accuracy of wearables in aggregate are difficult to support, given the sheer number of devices, the varied physiological markers each aims to measure, and the speed at which new devices are introduced. The aim of this study was not to verify that wearables are accurate. Instead this study attempted to verify, through analysis of existing literature, that at least some wearables are accurate to a degree sufficient for supporting aircrews' ability to better quantify their personal physiological indications of fatigue. Toward that end, existing research supports the conclusion that some wearables do meet this accuracy performance threshold, particularly as applied to sleep measurement. For instance, a May 2021 study by Evan Chinoy et al. analyzed the performance of four commercial sleep trackers as compared to a research-grade actigraphy band and found that "consumer wearables are promising for tracking sleep and wake in real world home conditions."¹⁸² In support of this conclusion, the study cited the following performance of the four wearable devices:

Results Sensitivity (for sleep) and specificity (for wake), respectively:
Actiwatch 2 (0.95, 0.36), Readiband (0.93, 0.43), Inspire HR (0.93, 0.45),
Ring (0.94, 0.41), and Vantage V Titan (0.96, 0.33).¹⁸³

Chinoy et al.'s study also noted that the specificity measured by most wearables actually out-performed the research-grade actigraphy band.¹⁸⁴

With this example in mind, and again noting the frenetic pace of change within this market, this thesis did not validate or recommend devices by name. Instead, policymakers and researchers would do best to reference the most updated validation studies when

¹⁸² Evan Chinoy et al., "275 Evaluation of Multiple Wearable Sleep-Tracking Devices Tested Under Ad Lib Home Sleep Conditions," *Sleep* 44 (May 3, 2021): A110–A110, <https://doi.org/10.1093/sleep/zsab072.274>.

¹⁸³ Chinoy et al.

¹⁸⁴ Chinoy et al.

considering the choice of a specific wearable device, as performance comparison data may be dated even by the time of the publishing of this thesis.

B. AUTHORITY

No legal precedent could be found to prohibit the issuance of wearable devices to aircrew members as a voluntary supplement for risk-management decision making. Additionally, while no such precedent explicitly provided Fourth Amendment protections to active-duty military service members in order to prevent their participation in an involuntary wearable monitoring program, the novelty of such technology indicates that such a program would raise legal questions that have been hitherto untested. Specifically, insufficient data exists to determine the admissibility of wearable data gathered under an involuntary program in administrative or legal investigations. One might speculate that the significant shift towards protecting individual privacy demonstrated in the Supreme Court's *Carpenter* decision would indicate a trend toward increased legal protections for member's privacy. However, the additional consideration of military members' "reduced expectation" of privacy pushes such speculation further into the realm of conjecture. This reality creates a notable risk to the creation of such a military wearables program. That is, the fact that both technological capability and legal applicability are evolving rapidly creates a situation in which policies may become quickly outdated by changing legal restrictions. This places policymakers in a situation where they must decide if such a program warrants investment. In part, any such decision gambles on hope that the legal latitude currently afforded under military applications of the Fourth Amendment will continue if or when those liberties are tested under the unique considerations presented by wearable devices.

From a perspective of application, two general avenues for potential wearable programs appear: mandated and voluntary. A mandatory program that requires 24/7 wearable usage as a condition of employment within a specific military specialty would depend heavily on the military members' reduced expectation of privacy for its legal foundation. While such a program would arguably provide the greatest objective benefit from a risk-management perspective (assuming both that monitoring all members would

provide greater detection of potentially fatigued flyers and that the data gathered from involuntary users would be as accurate as that of voluntary members), it presents the greatest risk of being deemed legally unsupportable once tested.

A voluntary approach would provide a more conservative option for policymakers to test the legal durability of such a novel program. Like similar fitness programs in civilian organizations, the USCG program's legal foundation could be set in an EULA, in which members consent to monitoring as part of the issuance of the device. Doing so would align with the spirit of the Supreme Court's decision in *Carpenter vs. the United States*, as the member would be explicitly stating his or her consent to monitoring, and thereby eliminate (or at least significantly reduce) any expectation of privacy that might otherwise be implied. It should be noted that some vulnerability exists in the potential that the "voluntariness" of the programs might be questioned, as occurred in civilian programs. However, the strength of such assertions would be dependent on the method and scope of a program's specific administration. Additionally, the use of an EULA would allow the USCG to apply the concept of privilege to the information gathered by the wearable, should they choose to do so.

Finally, the control and security of personal data presents a potential liability for the USCG, should it attempt to implement a wearables program. In addition to leveraging the legal protections of a well-developed EULA, the organization would need to make determinations regarding the breadth of access to wearables data. That is, should supervisors, medical practitioners, or operational decision makers be granted access to an individual's data, or should the insight provided to the individual be the avenue through which the organization seeks improvements to risk management? This question presents a similar path toward policy solutions in which both a conservative and aggressive approach would lack legal prohibition. However, like the consideration of voluntary versus mandatory programs, the decision to aggressively share personal data may have additional impacts in the realm of how successfully the technology is accepted by the workforce.

C. ACCEPTANCE

The descriptive statistics provided by the survey data indicated a shift in subjects' trust toward the wearable devices and away from personal intuition for the purpose of evaluating personal fatigue. This may indicate that the quantitative data provided by wearable devices could serve as an improved preflight input for aircrew risk assessment. Additionally, survey input identified data privacy as a key factor in determining user acceptance. Data privacy concerns played a more significant role in older subjects' technology acceptance as compared to younger participants. This may indicate that data privacy will become a less influential factor as older members attrite from the workforce. Finally, the raw sleep data indicated that some subjects averaged sub-optimal levels of sleep throughout the study (below policy requirements), despite having a quantitative depiction of their sleep performance. This draws into question the effectiveness of existing policies at ensuring that aircrew members obtain adequate sleep, and also highlights the potential ability of wearable devices to provide insight into existing aircrew sleep patterns. It also demonstrates that additional policies and strategies might be necessary to facilitate user acceptance and utilization of wearable data, beyond just providing members with wearable devices. While the survey and wearable findings were not statistically significant due to the experiment's sample size, they align with qualitative survey comments, and support continued research in this field.

D. NEXT STEPS

The conclusions supported within this thesis do not provide sufficient grounds to urge immediate establishment of a fleetwide wearables program within the USCG. However, the information gap identified through the analysis of existing mishap data, previous studies of fatigue in USCG aviation (most notably the Tufts study), and the sleep data drawn from this study's experiment clearly demonstrates a need for further pursuit of objective data regarding the prevalence of fatigue within operational aircrews.

As indicated in the previous chapter, the limited pool of subjects restricted the statistical significance of finding within this study. However, when considered within the context of existing research, the data collected through this study supports further

investigation into the need for and potential acceptance of wearable devices within aviation risk management. Researchers should conduct additional analysis on a larger scale to address the following subjects:

- The scale/scope of fatigue within aviation crews. Despite existing policies requiring crews to report to work well rested, just how fatigued are USCG aircrew members? This is perhaps the primary utility that wearables present in the near term: the ability to turn “known unknowns” into “knowns” by providing the first objective measurement of a previously subjective factor. This utility may also span beyond the realm of aviation fatigue, providing training commands like Aviation Survival Technician A-School or Recruit Training Command with insights into the balance of physiological strain and recovery their respective programs place on students.
- The impact of voluntary versus mandatory programs on the acceptance on wearable device by crew members. Will crews simply follow orders and agree to be monitored off duty? This question presents challenges, as it would theoretically require the administration of experiments with mandated use for some subjects.
- The impact of wearable device use on aircrew fatigue over time. Once tracked, will aircrew members achieve reduced levels of preflight fatigue over a protracted timeline (months/years)?

Continued study of this subject will provide a greater understanding of the scale of threat that fatigue presents to aircrews and will assist policymakers in determining how best to implement such a program, should it prove necessary. The following sections provide recommendations for the implementation of a wearables program in light of the legal and social considerations identified by this thesis, using the study’s three-step assessment sub-model.

E. DEVICE SELECTION (ACCURACY)

While analysis of specific device performance falls outside the scope of this thesis, the research did entail a review of recent wearable performance analyses, both as a means of addressing the question of aggregated wearable accuracy as it pertains to the study's sub-model, as well as a means of selecting a device for use in this specific study. Due to the rapid pace at which new commercial fitness wearables are introduced to the market, policymakers should conduct similar research utilizing up-to-date peer-reviewed performance evaluations. In addition to validating a potential device's accuracy, future review should consider the specific requirements of wearable devices aimed at facilitating crew fatigue assessment as well as the device's ease of use. For instance, while EOG data garnered from wearable glasses might provide the most accurate assessment of physiological fatigue, less obtrusive wrist-worn or ring devices using HR/HRV and sleep data tracking may prove more practical in application. Additionally, wearable capabilities should be limited to only those tasks which support the stated purpose of facilitating crew fatigue assessment. Additional capabilities, though appealing, may present vulnerabilities to operational security and user privacy. For instance, device GPS tracking could unintentionally create a data source that provides little to no benefit from a risk-management perspective, but could create significant risk if inadvertently disclosed.

F. PROGRAM SCOPE (AUTHORITY)

Due to the untested nature of legal restrictions surrounding the application of off-duty monitoring of military personnel, early forays into this policy realm should be approached conservatively. Prototype wearable programs should be completely voluntary in nature and administered via unit aviation safety departments. Additionally, the information provided by the wearable should be for the exclusive use of the member to whom the device was issued, and not monitored by a higher USCG authority. Finally, wearable issuance should include a comprehensive EULA between the wearable user and the USCG in addition to EULA(s) between the user and the commercial wearable company. Similar to consent-to-monitoring agreements that authorize members to access government desktop computers, these agreements should outline the extent to which the

individual is agreeing to relinquish expectations of privacy as well the extent to which the data gathered by the device may or may not be shared by the government agency. In addition to providing a less tenuous legal foundation for the wearable program, this voluntary and tempered approach will avoid barriers to acceptance that may exist in the form of privacy concerns and meager support for compulsory use. By avoiding such barriers, this approach could better facilitate the acceptance of this new technology.

Additionally, noting the correlation between users' trust in wearable data and their pre-experiment use of a wearable device, policymakers might consider policies that encourage aircrews to utilize input from devices they already own during preflight risk assessments. As discussed earlier, personal wearable devices are becoming increasingly common, with the number of worldwide Apple watch users exceeding 100 million in 2020.¹⁸⁵ While this strategy presents challenges regarding standardization across varied hardware and software platforms, it may provide a social nudge toward normalizing the use of physiological data in preflight risk discussions at little to no financial cost.

G. TRUST AND PRIVILEGE (ACCEPTANCE)

Should the USCG eventually seek to establish a wearables program in support of aviation risk management, the issue of trust is likely to play a critical role with regard to how effectively the technology is accepted and how successfully it is incorporated into individuals' personal safety practices. Specifically, policymakers must address the role that privacy will play in encouraging or discouraging user acceptance of such a physiologically invasive practice.

While this study's experiment did not provide conclusive data delineating privacy as the most fundamental factor in predicting wearable acceptance, it should again be noted that the subjects who participated created an inherent bias in data by nature of their volunteer status. That is, this pool of subjects was predisposed to accept wearable technology in the proposed form, otherwise they would not have volunteered. Anecdotal

¹⁸⁵ "Above Avalon: Apple Watch Is Now Worn on 100 Million Wrists," Above Avalon, accessed August 14, 2021, <https://www.aboveavalon.com/notes/2021/2/11/apple-watch-is-now-worn-on-100-million-wrists>.

perspectives provided by potential subjects who chose not to volunteer indicated a distrust for submitting to 24-hour-per-day physiological monitoring. Specifically, some personnel declined participation for fear of being deemed unqualified for flight status due to any type of asymptomatic heart issue that could have been detected. While these statements cannot be considered as part of the formal analysis of research data, they are ignored to the detriment of understanding the role privacy may play in successfully implementing a wearable program. Clearly, they lend credence to the idea that trust in the form of user privacy concerns may play an even larger role than this study's data demonstrates, and that such concerns could serve as a significant barrier to user acceptance in any mandated program.

With privacy's critical role in technology acceptance in mind, the USCG should consider policy solutions that would develop user trust and encourage member transparency. One such policy tool, previously discussed as applied by aviation safety personnel, is the concept of privilege. In developing and implementing a wearable program, the USCG should preemptively apply privileged status to data gathered by government-issue wearable devices as part of the service-drafted user agreement. Doing so will encourage device acceptance by eliminating barriers in the same way that the use of privilege enables interviewees to share critical safety information with investigators. With clearly stated policy in place providing limitations on the release of wearable data and protection from the misuse of that data in the form of supporting any administrative or punitive action, users may be more likely to leverage this technology for the policy's stated purpose: to provide the individual with a more objective and quantified method of determining how fatigued they are prior to flight.

While the concept of privilege is not new to aviation safety, the proactive application of legal protection to a data source absolutely is. No such pre-application of the concept to physiological data could be found as part of this study's literature review. However, as noted throughout the course of this thesis, wearable technology has created unprecedented opportunities and challenges through the quality and quantity of previously inaccessible personal physiological information it can now provide. In such an uncharted technological and legal space, unprecedented privacy policies may be most appropriate,

and the most effective at building trust. To be clear, such a change would represent a significant expansion of the concept of privilege as applied to safety information, but it draws on the same principles that historically enabled safety programs to be effective at preventing mishaps: trust. By prioritizing the discovery and sharing of information that can improve aviation processes and prevent mishaps over administrative accountability, the principles of safety privilege enable access to data that might otherwise not be disclosed for fear of retribution. If implemented effectively, the preemptive application of privilege to wearable data could provide aviators with an otherwise inaccessible indicator of their preflight fatigue status. Just like aviators learn to trust the data provided by flight instruments while navigating an aircraft, so they might learn to trust both the objective data provided by a wearable device to gauge their level of preflight readiness as well as the organization that issued it to them.

The concept of trust pervades the conclusions drawn from this study's three sub-model categories. While sufficient research exists to support the idea that some wearables may provide accurate data, policymakers must do their due diligence to ensure that the data from the specific device they choose can be trusted. Although the USCG may possess the legal authority to mandate the use of wearable devices to monitor its members on and off duty, it must balance the benefits of doing so with the trust its members have for the service and the trust it seeks to place in its members. Finally, in order to encourage members to accept this new technology, the USCG must develop policies that will enable members to trust that the private physiological information they provide will be used to improve their safety, and not to facilitate retribution or manipulation. As mentioned above, aviators may prove to be an ideal demographic through which to continue analyzing the potential utility of wearable technology, as they represent a group that has historically learned the value of trusting their flight instruments.

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Naval Postgraduate School
Monterey, California