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Fatigue and management of warfighter mental endurance

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ABSTRACT
Mental fatigue (MF) is a psychobiological state induced by prolonged exertion that has the potential to reduce performance. In military operations, MF coincides with inadequate sleep, circadian disruption and other stressors, further increasing the risk of fatigue-related errors of judgement and reduction in physical and psychological performance. Experienced leaders can detect MF, but multimodal monitoring and assessment technologies still cannot duplicate this capability. Experiments to define signals that cue this human percept could inform future technologies. Countermeasures include engagement strategies, brain endurance training to extend physical endurance, and caffeine and modafinil to temporarily sustain performance. An infrastructure for physiological monitoring and integrated analyses will advance team performance enhancement, along with the use of explainable and interpretable artificial intelligence modelling, refined through iterative experimentation. More precise definitions that distinguish MF from other types of fatigue will help advance the development of monitoring technologies and countermeasures by targeting the right physiological and behavioural metrics.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Mental fatigue (MF) monitoring and management bolsters military performance in continuous operations and extreme environments by directly reducing or managing risk related to physical and mental lapses.

WHAT THIS STUDY ADDS

⇒ Humans can intuitively detect MF, but technology has not yet replicated this human capability.
⇒ Well-designed studies have demonstrated effective countermeasures such as brain endurance training, behavioural engagement, operational scheduling tools, supplements, and stimulants.
⇒ Development of an infrastructure for physiological monitoring, integrated analyses and AI modelling is advancing team performance enhancement.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ More precise definitions that distinguish MF from other types of fatigue will help target the right physiological and behavioural metrics in research studies

INTRODUCTION

Mental fatigue (MF) is a primary concern in military performance and may be a critical determinant of mission success or failure.[1] Fatigue can occur following sustained attention with underload or overload, typical of military operations. For example, friend-foe errors of judgement are attributable to MF and may explain some fratricide events during military operations. In controlled laboratory models of sentry duty, errors increase after 2 hours of sustained attention in well-rested individuals, and caffeine only extends performance for another hour.[2] Extended time-on-task results in peripheral physiological deactivation, explaining lapses of attention in human operators that result in serious military mishaps such as ship collisions and vehicle convoy accidents. It should be noted that these performance failures typically result from a culmination of adverse events and in conjunction with other fatigue factors such as late night circadian cycle timing and inadequate sleep.[3] Without relief, such as with a shift in focus to an alternate task, performance can be disabled for a period of time. SLA Marshall described this problem in terms of '*battle fatigue*' in soldiers subjected to repeated intense emotional loads. Soldiers in the Korean War were trained to flatten against the ground when they encountered hostile fire, suppress the threat and then move again; but, after three episodes of '*flattening*' on a mission, units were rendered combat ineffective for the day due to the sustained emotional load, even after covering only a short distance and receiving no casualties.[4] These examples highlight the significance of MF to military operations.

In this paper, MF is defined as a psychobiological state induced by prolonged exertion that has the potential to reduce performance.[5] Though familiar to the general public, this notion is still much debated within the scientific community and too often confused with sleepiness and drowsiness. MF is physiologically and psychologically distinguished from states produced by inadequate sleep, suboptimal circadian timing and central fatigue (ie, exercise-induced decrease in maximal voluntary activation level). These may be related to MF but do not define the neurophysiological state, and they appear to involve different mechanisms and recovery strategies.[6] For example, MF can be reversed with a change in tasks, while sleepiness is reversed primarily by sleep.[3] Mentally fatigued individuals without central fatigue can still perform maximal exercise and maintain marksmanship

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accuracy.[7] After significant physical exertion, athletes can be physically fatigued but not sleepy or mentally fatigued. Nevertheless, it is important to acknowledge the frequent co-occurrence of MF (caused by prolonged mental demands) and sleepiness (caused by inadequate sleep) in military settings. There is an important interaction between these two conditions that can produce a marked degradation in performance capability.

Detection and prediction of MF is vital to combat developers, mission planners and unit leaders to optimise performance and avoid scheduling individuals at suboptimal capacity. Furthermore, performance limits can be safely expanded through techniques such as brain endurance training, use of pharmaceuticals and through engagement strategies.[8 9] Offsetting MF is advantageous to military forces, allowing increased physical and mental performance in sustained operations, pushing closer to physiological limits in extreme environments, and reducing the frequency of consequential mental lapses and accidents.[10]

This brief review focuses on approaches to detecting and monitoring fatigue states and strategies to extend mental endurance in military operations.

DETECTION OF FATIGUE

Human facial recognition of MF

Effective teams are critical to military performance and part of that effectiveness comes from skilled team leaders being able to intuit the mental readiness status of their individual team members. The specific human cues have not been well defined but appear to involve facial characteristics. Identifying these physiognomic features along with measurable biological and neurophysiological responses associated with MF could help train other humans as well as artificial intelligence (AI) tools in MF assessment. Facial physiognomy has the double advantage of being easy to test experimentally and as an easily implemented technical solution outside of the laboratory. Numerous studies have examined fatigue detection using eye-tracking, physiognomy, contactless cameras, modelling or more broadly AI; however, to date, most of these studies focused on the sleepy and drowsy component of driver fatigue. MF has been reliably produced in laboratory and field studies by increasing task difficulty and/or time-on-task.[11] For example, a prolonged cognitive task (sustained attention during a 45 min psychomotor vigilance task) and an executive process task (45 min Go-No-Go task) were both responsible for a significant increase in perception of effort and a decrease in cognitive performance.

One study, the '*classification of fatigue faces study*' investigated human detection of MF produced by a demanding cognitive task (45 min PVT, Go-No-Go task).[12] Video sequences of subjects were presented to military evaluators who were asked to put them in the chronological order of increasing MF state.[12] In a total of 328 evaluations, the evaluators were able to correctly order the four video sequences 45% of the time (compared with 4% correct ordering that would be obtained in a random sort), and the correct answers are significantly associated with a higher confidence score compared with other answers. The number of facial indicators used (eg, eyes, mouth, head position) affected the ability to correctly order the faces.[12] Further experimental validation of facial indicators of MF, using other models of MF and with evaluators of varying levels of human perception skill, will provide a foundation for the development of MF digital tools.

Can technology detect fatigue as effectively as an experienced NCO?

Detecting MF ahead of a performance failure has been an elusive technological goal in science and engineering. Currently, the military leans on the instinctive ability of unit leaders, and this ability may be further enhanced by learning responses of individuals within the team during stressful military drills. This sets a yardstick for any novel system: it must match or surpass the fatigue-sensing capability of a seasoned non-commissioned officer.

As noted in the previous section, there are numerous fatigue detection systems, primarily targeting sleepiness and drowsiness in vehicle operators.[13 14] However, the lack of robust validation and standard accreditation hampers their efficacy even for this application. Some technologies, like the PERCLOS system, gauge eyelid closures but miss nuances like inattention detected by psychomotor vigilance test (PVT). Commercial attempts, such as the FIT device, lacked sensitivity during sleep studies.[15] The FIT device based its metrics on eye movements and pupil dilation, metrics prone to vast individual variation. A single-channel EEG worn by French military pilots aided in managing MF, during prolonged flights, but only related to monitoring of microsleeps.[16] Predictive modelling still primarily hinges on sleep patterns rather than on MF and is more adept at group-level optimisation than individual performance prediction.

Measuring performance decay in repetitive tasks highlights MF effects over time; for instance, errors during sentry duty simulations spike after about 2 hours of concentration.[2] The neurobiological underpinnings of MF suggest avenues like heart rate variability or electrodermal activity for continuous assessment via wearable technology but will require rigorous testing against valid MF models to ascertain sensitivity and specificity.

Current research suggests that multimodal fusion of sensor data will be needed to gauge operator state, rather than any singular measure. Human assessors intuitively scrutinise facial features and vocal nuances but often also engage in conversation to gauge responsiveness. One proposed model to test this human–AI collaboration is '*Ellie*' a congenial virtual human developed by Rizzo *et al* at the Army Institute of Creative Technologies.[17] Ellie provides an empirical evaluation tool for markers of mental states, and this will support facilitation of human–AI teamwork by technology that adapts to human MF. This represents one aspect of a multicomponent system that combines such online monitoring with biomathematical model predictions, fitness for duty testing and other physiological and behavioural variables to accurately assess military operator state and performance capability.[14] Reaching only slightly further into the future, Vettel *et al* envision a future with 'adaptive autonomy teammates' in the form of humanised technology that uses embedded uniform sensors to continuously monitor neurophysiological status of the team members and dynamically adapt to the needs of the humans.[18]

PROTOTYPES FOR REAL-TIME MONITORING AND PERFORMANCE MANAGEMENT

Military applications: monitoring and fatigue management system for ship crew scheduling

Fatigue monitoring technology can be useful to the military after the details of individual sensor data fusion, team data aggregation, predictive analyses and user presentation are developed and tested. Current technologies available for monitoring sleep duration, quality and timing can provide alertness predictions due to underlying sleep and circadian rhythm disruption that contribute

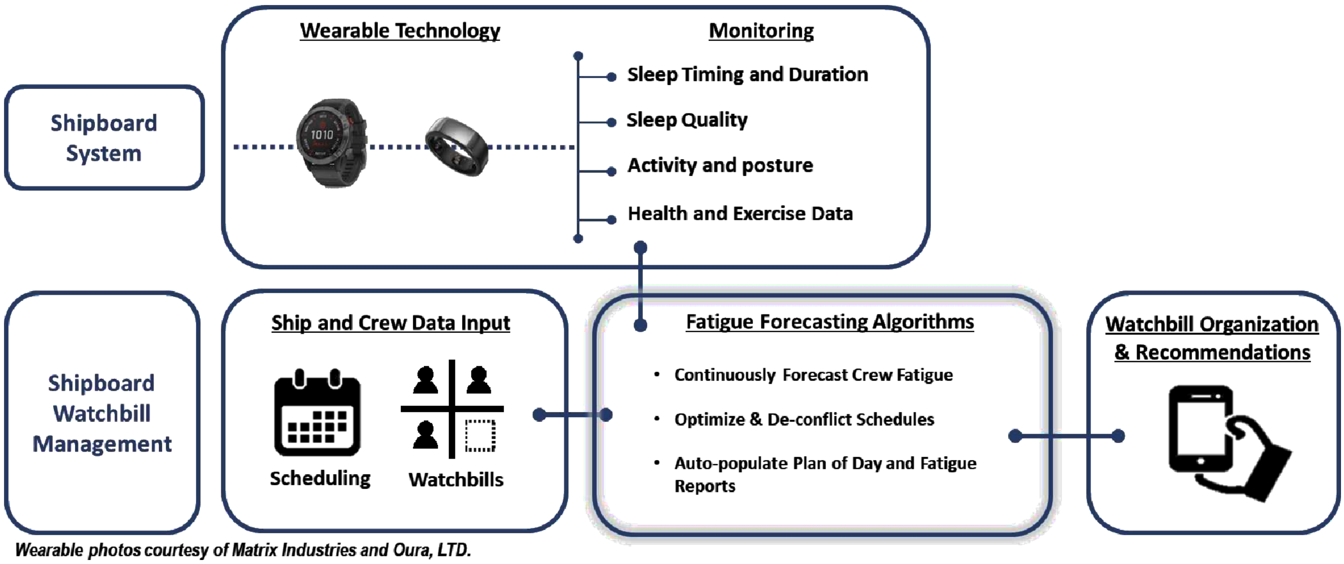

Figure 1 Overview of the Wearable-Enhanced Watchbill Management System.

to fatigue-related accidents. Although no such technology is yet strictly validated for prediction of MF, systems based on sleep status are immediately useful when combined with scheduling tools and build a foundation to add future real-time MF detection systems as they evolve. A recent feasibility study explored the technical feasibility and acceptability of employing continuous physiological monitoring devices worn on the finger or wrist in shipboard settings for acquiring sleep data.[19] The study identified several technical and cyber security barriers to wearable implementation; however, the study supported the utility of wearables and confirmed that the collection of quality and complete data from wearables is possible for operational fatigue risk management.[20] Building on these findings, the Command Readiness, Endurance and Watchstanding (CREW) programme developed an offline end-to-end data infrastructure prototype (CREW ver.1) to acquire sleep data from wearables without requiring a personal smart phone device in the data pipeline. The wearable data is automatically transferred when a sailor comes into proximity of data hubs placed in common areas on the ship. Data is then aggregated, processed and transferred to a Navy watchbill management programme for individual- and group-level fatigue risk assessments. By connecting timely and quality sleep data to watchbill management processes, fatigue risk can be actively monitored and mitigated. An overview of this plan is depicted in figure 1.

CREW ver.1 was tested during a large-scale, multi-domain military exercise, Talisman Saber 2023 (TS23). CREW ver.1 securely captured and moved wearable sleep data without commercial cloud systems to the Optimised Watchbill Logistics (OWL) programme for fatigue risk assessment demonstrations with the ship. A total of 244 sailors wore Perceptive devices, which synchronised with a network of shipboard hubs. On average, 30% of participants were able to synchronise with the network of shipboard hubs each day. Several technical factors (eg, location of hubs) prevented higher rates of successful syncing during TS23, and these findings resulted in refinements in CREW ver.2, which was tested during Trident Warrior 2024 (Rim of the Pacific) and found substantial technical improvements. CREW ver.3 is now exploring additional form factors, data hub locations, as well as the evaluation of the accuracy of fatigue risk predictions in shipboard settings.

STRATEGIES TO EXTEND MF LIMITS

Pharmaceutical mitigation of fatigue-related performance degradation

Intensive research to extend endurance capabilities of soldiers in WWII concluded that amphetamines could motivate soldiers with the perception of alertness but did not prevent actual reductions in physical or psychological performance, while 250 mg of caffeine did actually extend physical and psychological performance for several hours.[21] This dose range of caffeine (200–250 mg) has been repeatedly confirmed as an effective performance-enhancing dose in sleepy or mentally fatigued soldiers. There is an important distinction between working with human biology to achieve maximum potential and trying to exceed normal biological limitations (which typically fails).[22] The history of military amphetamine use to try to extend endurance capabilities highlights some of these risks.[21]

More recently, modafinil, a non-amphetamine stimulant, has been shown to extend mental performance during total sleep deprivation, similar to caffeine and without some of the side effects associated with amphetamine.[23] Modafinil is known to have multiple effects on different brain areas and neurotransmitter systems in the brain. Like amphetamine and methylphenidate, it inhibits dopamine reuptake, underlying its positive effects on human performance. Moreover, besides the dopaminergic effects of modafinil, several non-dopaminergic effects of modafinil have been described (eg, increase of electrical neuronal coupling) that could further explain its efficacy as a wake-promoting and cognitive enhancing substance. Among healthy American and French military pilots, modafinil is legally distributed in situations where pilots are already sleep-deprived, but operational needs require them to continue their mission. Despite this officially regulated off-label use of modafinil, a recent review of the use of modafinil highlighted gaps in the current knowledge of modafinil use (eg, dose-response relationship and long-term effects) and the uncertainty surrounding its risk–benefit profile (eg, overconfidence effects).[24] A recent study of interindividual differences in modafinil sensitivity, both in terms of risks and benefits in military student pilots during extended wakefulness (24 hours), reconfirmed that, in total sleep-deprived conditions, sustained cognitive performance is improved by modafinil use.[25]

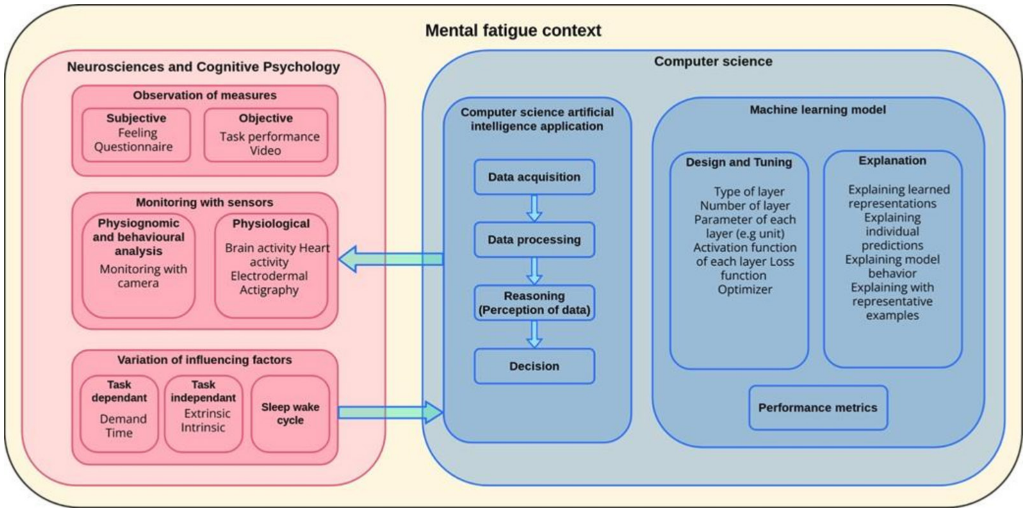

Figure 2 A roadmap for integrating mental fatigue into artificial intelligence models using explainable and interpretable artificial intelligence.

Tyrosine is a dietary supplement that has also demonstrated effectiveness in extending MF limits. Orally ingested tyrosine (8–10 g/day) has been demonstrated to be effective in sustaining performance in a variety of psychologically demanding tasks, stressful field exercises and in sleep-deprived individuals performing a prolonged PVT.[26] Mentally demanding tasks increase turnover of norepinephrine in some parts of the brain, and rodent brain microdialysis studies have demonstrated that greater availability of tyrosine precursor, which crosses the blood–brain barrier, sustains norepinephrine production and prevents cognitive performance declines in high-stress conditions. Despite demonstrated effectiveness, there is no 'caffeine-tyrosine stress bar' available to soldiers.

Brain endurance training

The negative effects of MF have typically focused on investigations of cognitive performance. However, as early as 1890, Professor Angelo Mosso had observed that the muscular endurance of two of his colleagues at the University of Turin declined after spending all morning giving lectures or examining students.[27] More than a century later, these initial observations on the negative effect of MF on physical performance were confirmed experimentally, where a cognitively demanding task for 90 min significantly reduced performance during a subsequent high-intensity aerobic cycling test.[28] This decline in endurance performance was associated with a higher perception of effort in the mentally fatigued condition despite no significant changes in cardiorespiratory and metabolic responses compared with the control condition (watching documentaries for 90 min). Since this seminal experiment, most studies have confirmed the negative effect of MF on endurance performance and extended it to skilled performance, while performance during short maximal physical efforts does not seem to be affected.

More recently, research into the link between MF and physical performance has moved from its negative acute effects to the potential chronic benefits of adding cognitive load to physical training.[29] The hypothesis is that adding cognitive load to physical training (Brain Endurance Training, BET) may induce, over time, superior improvements in soldier or athlete's physical performance compared with standard physical training. Although more research is warranted, most studies published to date show improvements in whole-body and muscular endurance as well as cognitive and skilled performance in active people and athletes who systematically added cognitive load to their physical training.[29] These positive effects of BET seem to be particularly evident in fatigued conditions. For example, in a randomised controlled trial, 24 competitive cyclists performed a 5 min time trial (TT), followed by a 30 min Stroop task, a 60 min submaximal incremental test and a 20 min TT. This test battery was performed before and after 6 weeks of training during which cyclists trained five times/week and completed either cognitive response inhibition tasks (Post-BET group) or listened to neutral sounds (control group) after each training session.[30] While changes in 5 min TT performance did not differ between groups, 20 min TT performance improved significantly more in the post-BET group than in the control group. If confirmed in military settings, these findings suggest that BET may be a strategy to improve resistance to both physical and MF in soldiers and other military operators.

Other countermeasures

Endurance performance is limited by MF but can be substantially extended by motivational self-talk[31] and other practical psychological interventions used by athletes.[8] Some forms of music (eg, exciting or personal preferences), odours (eg, peppermint, cinnamon) and vibrotactile stimulus have also been shown to effectively counter MF.[9] A wide variety of strategies for engagement can be highly effective in extending mental endurance. In the example of SLA Marshall's observed performance reduction during repeated movement under fire, they determined that each man lost the sense of presence of their fellow soldiers, and a partial remedy was for squad leaders to re-establish personal contact with each soldier down the line.[4] In addition to the importance of this social contact, morale, cohesion and esprit provide powerful motivators that can mitigate fatigue through increasing motivation to achieve the team's goals.[32]

FUTURE RESEARCH: QUANTITATIVE MODELLING OF MF USING INTERPRETABLE ARTIFICIAL INTELLIGENCE (XAI) MODELS

Traditional contactless modelling that integrates video stream with face detection, extraction of parameters and reasoning faces several challenges.[33] Until now, the absence of a clear definition of MF was responsible for AI models poorly suited to detect and model mental state. Most of the time, they were able to detect sleepiness and/or drowsiness using specific markers such as PERCLOS.[34 35] To bridge the gap between current models of contactless and the detection of clear MF states, we propose an integration of this clearer definition of MF into AI models using explainable and XAI.[33–35] This can be achieved using XAI, a set of techniques that better explain how the model decision works. XAI will integrate new knowledge and a clearer definition of MF into the training and learning processes.

A good modelling approach requires both mathematical and computer modelling approaches based on explainable learning models (ELM) that enable humans to know how the reasoning module of the AI operates and quantified and well-designed experimental data (with a proper definition of MF).[35] Using ELM to extract concepts learnt by the model and highlight them during prediction could allow us to compare MF markers/modifications identified by modelling with those identified by human experts[11] and discover new markers not used by humans. These improvements, based on a dialogue between neuroscience and computer science, could lead to more accurate and reliable models of MF (figure 2).[35]

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