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Abstract

Extreme work environments are inherently stressful and involve challenging working and living conditions. In contexts ranging from space exploration to disaster response, people must sustain performance under pressure, and function with limited resources. In this paper we develop the concept of endurance for extreme work environments, which we define as the capacity to sustain performance at high levels for safe and effective operations over extended durations (e.g., a mission, operation, deployment, or expedition). We integrate diverse streams of literature (e.g., work stress, recovery, and sleep) to describe endurance in terms of short – and long-term energy management processes as individuals interact with their work-life system (i.e., work, non-work, and sleep environment). We conclude with practical and theoretical implications for a better understanding of endurance, such as considering multiple time perspectives, and the role that researchers, practitioners, and organizations can play in optimizing endurance in the field.

Keywords: dynamics, extreme teams, field research, human performance, operational readiness, pattern, resilience, sustained performance, time, within-person

Endurance in Extreme Work Environments

Space shuttles, submarines, and polar stations are vastly different settings, but all share an emphasis on safety with a high cost of failure. Workers in these environments experience chronic exposure to high and sustained levels of stress, providing real-world opportunities to investigate the limits of human performance. A better understanding of human performance in extreme work environments is important from two perspectives. First, in extreme work environments, poor performance can have catastrophic consequences for the team, organization, customers, and the broader community. Second, insights derived from extreme work environments are increasingly relevant to work features in modern work environments such as unpredictable patterns of activity and rest, intensification of work, and managing complexity and uncertainty. For example, automation, robots, and artificial intelligence are removing routine aspects of some roles, while increasing the complexity and uncertainty of the remaining work (Griffin et al., 2019; Parker & Grote, 2020). Moreover, technology is increasing around-the-clock activity in many industries, which places more emphasis on the human capacity to sustain performance over long periods (Krueger, 1989). Therefore, it is not surprising that there is growing interest in understanding how humans perform in extreme environments (Bell et al., 2018; Driskell et al., 2018).

Extreme work environments require workers to sustain optimal physical and psychological states such that they are ready to respond effectively to routine demands and unanticipated challenges across an extended duration. This duration can range from weeks and months (e.g., a submarine deployment) to years (e.g., the spaceflight to Mars) (Brasher et al., 2010; Flynn-Evans et al., 2016). In this article, we extend our understanding of the factors that inform performance by developing the concept of endurance for extreme work environments. To date, endurance has typically been studied in the context of sports and refers to the capability to resist physical fatigue while engaging in exercise for a prolonged duration (Sjostrom et al., 1987).

We begin by providing an overview of extreme work environments and defining the concept of endurance. We then show how endurance provides additive explanatory value relative to extant constructs such as grit and resilience. Next, we integrate diverse bodies of literature to explain how endurance is shaped within constrained and demanding environments. We focus on processes of energy management across work, non-work, and sleep life domains (i.e., a work-life system) and consider how an interplay between short- and long-term dynamics impact endurance. We conclude by discussing implications for research and practice.

Defining Endurance

For extreme work environments, we define endurance as an individual's capacity to sustain performance at high levels for safe and effective operations over the extended duration of a mission, operation, deployment, or expedition. Our concept of endurance extends current approaches to work performance to capture the overall performance requirements of humans in extreme environments. In our paper we use the term 'mission' to encompass the various types of long-term goal-driven events such as expeditions (e.g., arctic expeditions), operations (e.g., counter terrorist operations), and deployments (e.g., combat deployments).

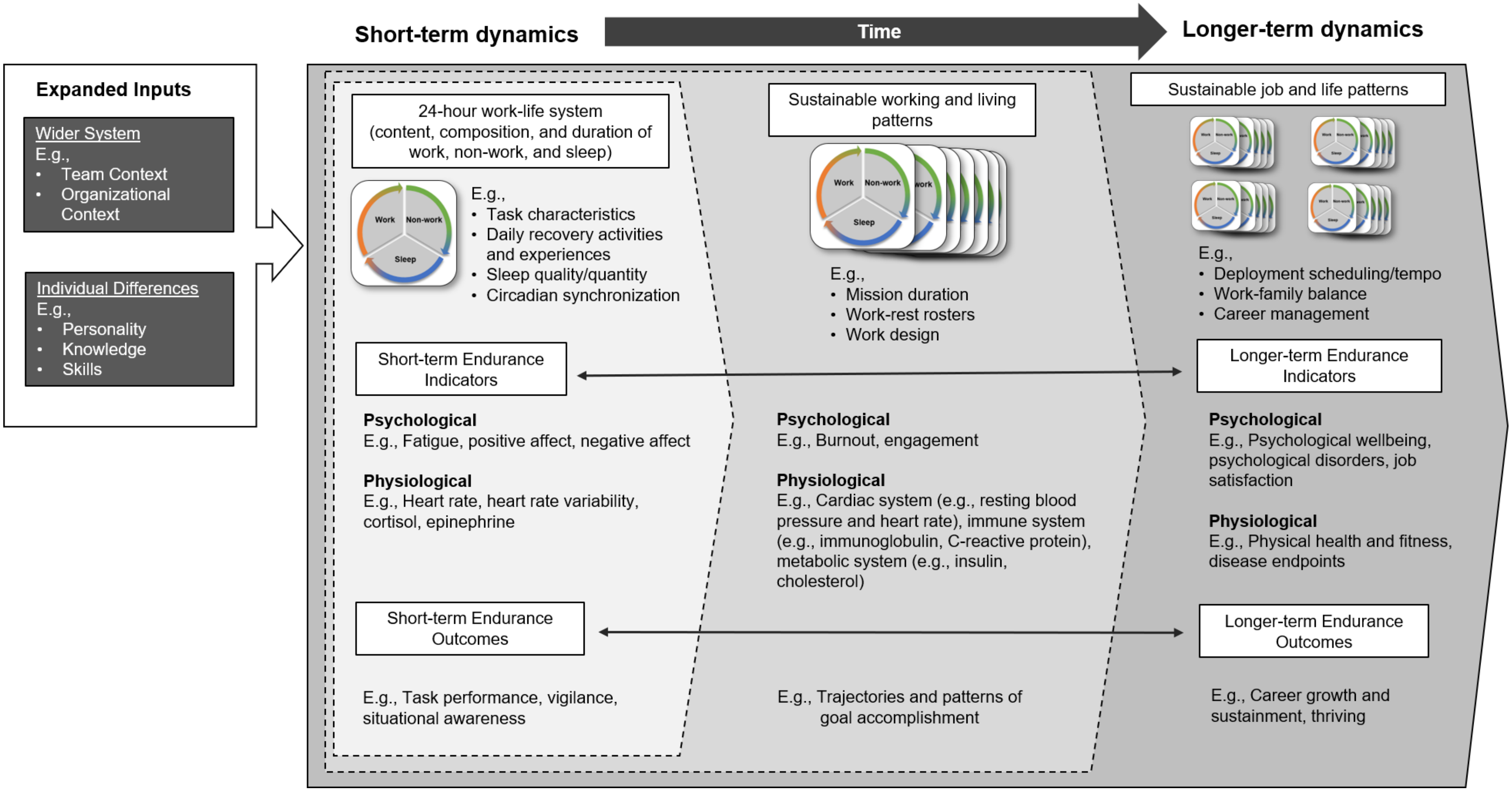
Endurance emphasizes high performance because in extreme work environments such as spaceflight (Salas et al., 2015), high altitude mountaineering (Wickens et al., 2015), Special Forces operations (Urban, 2012), and polar workgroups (Leon et al., 2011), workers must perform safety critical tasks and activities over a long duration mission. Task demands evolve rapidly in these environments and failure to perform optimally—even for short periods—can result in mission risks and failure (Wickens & Huey, 1993). The exact standard of what constitutes ‘high’ or ‘optimal’ performance varies depending on the context. For example, the type of performance required during a high intensity combat situation will differ to the performance required during a prolonged and monotonous vigilance task.

Performance and safety are both important elements of endurance. In some contexts, high performance can come at costs to safety (Jiang & Probst, 2015). However, the need for individuals to maintain their own safety and the safety of others is imperative to mission success in many extreme work environments, where threats to human lives can be immediate and significant. For example, submarine command teams must achieve mission objectives while also ensuring the safety of their own submarine and the safety of surrounding vessels (Stanton & Roberts, 2018).

An individual’s underlying *capacity* for high performance is also central to our definition of endurance because extreme work environments require workers to maintain ongoing operational readiness to respond to unpredictable events. Operational readiness in a traditional military sense refers to a state of being able to react, respond, and carry out tasks at the required performance level (Cosenzo et al., 2007). It describes a latent potential for performance, as opposed to the observed actions, or ‘doing’ of performance (Roe, 2014).

We present a general model of endurance in Figure 1 depicting outcomes, indicators, and work-life patterns that constitute endurance. Temporal factors are inherently important in our model which differentiates short-term and long-term dynamics (Griffin & Clarke, 2011). A dynamic work-life system (i.e., work, non-work, and sleep experiences and activities) operates at multiple levels over time to affect psychological and physiological indicators of endurance. Outcomes related to endurance are also conceptualized at multiple levels, depending on the time frame of reference (e.g., task performance on a single day vs. a pattern of goal accomplishment over a several month-long mission). The dynamic process of energy management is central to our model and involves individuals adjusting their psychophysiological states in response to stressors and changes in their environment, for instance, expending energy to respond to demands and replenishing energy to reduce fatigue. The specifics of the processes are addressed in subsequent sections.

Figure 1. A temporal framework to understand the factors that impact and predict endurance.



Distinguishing Endurance from Related Constructs

Before presenting details of the endurance process, we consider how endurance is distinct from related constructs such as grit and resilience. First, grit is a personality trait defined as passion for and perseverance toward long-term goals (Duckworth et al., 2007). As such, the focus of grit is on the role of stable individual differences in how an individual approaches long-term challenges (i.e., between-persons approach). By contrast, endurance emphasizes the dynamic interaction between an individual and their daily experiences (i.e., within-persons approach), although the extent to which individuals can endure in extreme work environments is likely driven by trait levels of grit. For instance, trait grit predicts retention and performance in military training programs (Maddi et al., 2017).

Resilience is another concept that is relevant to long-term functioning and performance in extreme work environments. Resilience is conceptualized as an emergent outcome and refers to the process of ‘bouncing back’ from adverse events (Hartwig et al., 2020). Defined in this way, resilience focuses on the specific temporal period *after* a triggering adverse event or chronic sequence of stressors that individuals and teams must respond to and recover from (Hartwig et al., 2020). Resilience plays an integral role in endurance, with individuals needing to be resilient and robust to the potentially significant adverse events they might face on long-duration missions. However, endurance focuses more broadly on complete trajectories of performance across an entire mission, which includes patterns leading up to and following potential acute and chronic stressors.

As summarized in Table 1, endurance is best viewed as an integrative concept that captures the dynamic processes through which humans not only survive but perform over the course of an inherently stressful and complex mission (Driskell et al., 2018). Endurance encompasses both short-term performance variability and long-term performance trajectories.

Table 1. Differentiating endurance from related constructs

	Constructs		
Characteristic	Endurance	Resilience	Grit
Explores high performance under adverse and stressful conditions	✓	✓	✓
Focus on person-environment interactions	✓	✓	✗
Described by short-term dynamics (e.g., processes that unfold daily)	✓	✓	✗
Described by long-term dynamics (e.g., processes that unfold over weeks - months)	✓	✓	✗
Focus on whole-of-mission trajectories of performance	✓	✗	✗

The Dynamics of Endurance

Performance, and the factors that impact performance, are dynamic and can fluctuate over time (Roe, 2014). For example, performance has been found to change in response to factors such as contextual workplace conditions, and individual level differences (Alessandri et al., 2015). Recent research suggests that a within-person approach is most useful for understanding ongoing change in an individuals' states and behaviors as they interact with the environment across periods such as hours, days, and weeks (McCormick et al., 2020). This approach contrasts with conventional between-persons research that focuses on static questions regarding stable constructs, and highlights differences between people. In the following sections we detail the within-person processes and mechanisms underlying endurance over short and longer periods of time. To set the stage, we first explain processes of energy management, and how they support performance in demanding contexts.

Energy Management

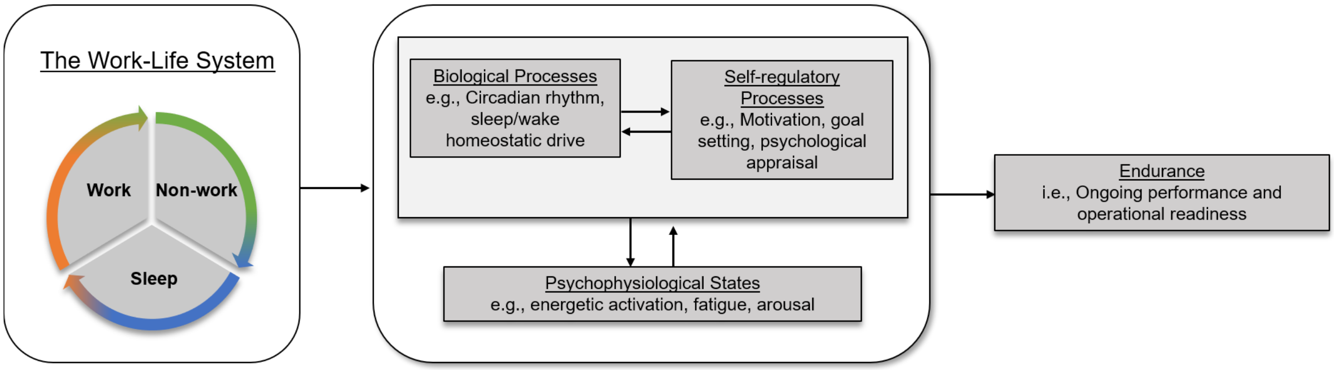
Energy management is the process of balancing energy expenditure in response to stressors and demands, with recovery through processes of rest, sleep, and detachment (Meijman & Mulder, 1998). Over time, endurance is the successful management of these processes to maintain high levels of performance and safety.

Many studies concerned with human energy at work adopt the perspective of the Effort-Recovery (E-R) model (Meijman & Mulder, 1998) or its variations. The E-R model proposes that energy expenditure in response to work demands causes stress-related psychophysiological load reactions which are reversed by periods of recovery (Rau & Triemer, 2004). If adequate recovery does not occur, an individual may start the next working period in a suboptimal state, meaning compensatory effort is required to perform. This effort can lead to accumulation of fatigue and negative health outcomes (Demerouti et al., 2009).

Recent research suggests the E-R model does not adequately explain the dynamics of energy expenditure and replenishment (Zijlstra et al., 2014). For instance, certain experiences during work (e.g., flow) can generate positive moods that help maintain short-term energy levels and overrule fatigue effects, and enjoyment of work tasks can have protective effect even if recovery is limited (Demerouti et al., 2012). Conversely, recovery outside of work can be hindered by work-related rumination (Querstret & Cropley, 2012). Therefore, it is not entirely clear when stress ends, and recovery starts. For extreme work environments where there is substantial blur between work and non-work domains, both in terms of physical space and time, it is critical to identify and understand the mechanisms underlying energy expenditure and energy restoration. A better understanding of these mechanisms will inform the specific factors that detract from or support an individual's ongoing capacity to perform.

We propose that effective energy management facilitates endurance by enabling the psychophysiological states that sustain performance across the changing demands of the external environment. We depict the main elements and processes involved in energy management in Figure 2. Psychophysiological states (e.g., fatigue, arousal) are shaped by biological processes such as circadian rhythms and sleep/wake cycles; and self-regulatory processes such as motivation and goal setting (Zijlstra et al., 2014). Endurance involves successful short- and long-term energy management over a sustainable pattern of work, non-work, and sleep.

Figure 2. Model of energy management processes



The Role of Biological and Self-Regulatory Processes

Drawing on recent approaches toward energy regulation (Zijlstra et al., 2014), we propose that endurance involves the interaction of biological rhythms and goal-driven self-regulation processes through which people upregulate or downregulate their psychophysiological state to respond to demands and changes in the external environment. We describe these two aspects of endurance below.

First, humans have evolved several biological patterns and rhythms which support homeostasis through physiological regulation and modulate basic energetic activation. For instance, one of the most important of these internal biological processes is the circadian rhythm, otherwise known as the 'biological clock'. Human energy levels and alertness fluctuate in a predictable pattern over the course of a 24-hour day, and a large part of this pattern is determined by the circadian rhythm (Dijk & Czeisler, 1995). This timekeeping system governs many physiological parameters such as core body temperature and metabolism (Buxton et al., 2012; Wright et al., 2002). These biological processes are modulated to varying extents by the external environmental (Wright et al., 2013). For example, circadian rhythms are disrupted due to the changes in light when travelling across multiple time zones.

Second, humans have the capacity to engage in more conscious goal-driven self-regulation to muster additional energy in line with psychological appraisal of the environment and the self (Neal et al., 2017). Self-regulation encompasses the various ways in which people modify their thoughts, feelings, and behaviors to reach a desired end state or goal (Gross, 2015). Situational demands can mean an individual's current psychophysiological state deviates from the state required, for example, they need to be more energetic, vigilant, or relaxed, depending on what they perceive is required in that moment. When the required state is one of higher energetic activation, individuals can actively upregulate to a higher energetic state by mobilising compensatory effort to increase attention and focus (Hockey, 1997; Kahneman, 1973). For example, a night shift worker may be in a state of heightened sleepiness during their circadian low (03:00 am - 05:00 am) (Gander et al., 2011) and so must upregulate their energy and exert effort to compensate for their current state of fatigue. Similarly, there are times when the required state is one of lower energetic activation. For example, an individual ruminating after work about unsolved work problems may need to downregulate their psychophysiological state by engaging in activities (e.g. mindfulness exercises) to detach from work, which enables better sleep quality (Hülsheger et al., 2014; Querstet et al., 2017).

Goal-driven self-regulation can be viewed as a process of making choices that involve an interaction between a person and their environment (Neal et al., 2017). Although individuals choose how to spend their time, how much effort to exert, and what strategies to employ; constraints in the environment determine the goal-related choices that are available. Consider a sonar operator in a surface vessel or submarine who must remain vigilant for many hours to detect low-probability signals (Mackie et al., 1994). Although the requirement to focus attention and remain alert over a prolonged period has been found to be fatiguing (Warm et al., 2008), the high-risk environment means they must continue to invest as much effort and energy as required (or as possible) to meet the goal of keeping the vessel and crew safe. Workers in conventional environments have more flexibility to adopt self-regulatory strategies which includes disengaging attention from the primary task and switching to a secondary task momentarily (Ariga & Lleras, 2011), or redirecting attention towards internal thoughts such as through mind-wandering (Thomson et al., 2015).

Energy Management within an Interconnected Work-Life System

We next consider how energy management processes evolve over time across the three life domains (work, non-work, and sleep), creating a ‘work-life system’. Past research indicates that activities and experiences that occur in one domain within a work-life system can have flow-on effects to other domains (Crain et al., 2018). In extreme work environments where work, non—work, and sleep are often tightly coupled, this can have important implications for endurance, as ineffective energy management in any single domain can have carry-over effects that impact ongoing performance.

Experiences across work, non-work, and sleep domains (see table 2 for a summary) have been shown to impact common psychological and physiological states (Crain et al., 2018). For instance, fatigue is a common outcome investigated across work ergonomics (Young et al., 2015), recovery research (Demerouti et al., 2009), and sleep science (Dawson & McCulloch, 2005). As such, research is increasingly recognizing dependencies and interactions among work, non-work, and sleep, (Crain et al., 2018). For example, the amount and quality of sleep affects every day waking experiences at and away from work, with lack of sleep being associated with perceptions of stress (Minkel et al., 2012), and decreased cognitive functioning (Cohen et al., 2010). Similarly, work and non-work activities impact the ability to obtain optimal sleep. For example, work deadlines or social activity limiting the hours available for sleep (Basner et al., 2014).

Table 2. Illustrative experiences and activities across a work-life system

Key Life Domain	Illustrative experiences and activities
Work	• Task workload (e.g., cognitive and attentional load, Hancock & Matthews, 2019) • Job characteristics (e.g., job demands and resources, Bakker & Demerouti, 2014)
Non-work	• Type of recovery activity (e.g., leisure vs. obligated duties, Sonnentag, 2001) • Type of recovery experience (e.g., psychological detachment; relaxation; mastery; control, Sonnentag & Fritz, 2007)
Sleep	• Sleep quality/quantity (Barnes et al., 2016), sleep hygiene (Miller et al., 2011), circadian rhythms (Folkard, 1990)

An understanding of carry-over effects within the work-life system of an extreme environment is critical, because in these contexts, work, non-work, and sleep are often highly interconnected. Highly interconnected domains in a work-life system with little redundancy or flexibility mean disruptions can have an immediate and pervasive impact, with ripple effects throughout the entire system (Perrow, 1999). That is, extreme work environments have little redundancy because workers have less flexibility and choice with energy management strategies (e.g., they must perform optimally during work for safety reasons). The consequences and carry-over effects of ineffective energy management in one domain (e.g., insufficient sleep) have more direct and far-reaching implications, as workers continually compensate to maintain high performance. To illustrate, we consider work, non-work, and sleep in space and undersea missions, where operations represent a tightly coupled work-life system with little flexibility

(Landon et al., 2019). We consider each element of the work-life system (work, non-work, and sleep) sequentially below.

In space and undersea missions, the safety critical and unpredictable nature of work, means crew members must be ready to perform, and upregulate if necessary, not only during scheduled work hours, but also during non-work and sleep time (Flynn-Evans et al., 2016; Moffitt, 2008). Requirements include being ‘on-call’ to respond to critical events and incidents 24-hours a day, as well as undertaking obligatory tasks that occur outside of scheduled work hours, such as maintenance of systems, participation in drills, and meetings (Shattuck & Matsangas, 2017). Fatigue from extended periods of work present a serious risk, as a crew or team must be self-reliant for the duration of an undersea or space mission, given the difficult or impossible option of extracting existing personnel or inserting backup personnel once the mission has started (Brasher et al., 2010).

Non-work time is important for psychological detachment from stressful work periods but can be hard to obtain in space and undersea missions, meaning stress from work demands spills over to non-work time (Sonnentag & Fritz, 2015). The “letting go” of work-related thoughts and activities required for psychological detachment implies not only refraining from performing work-related tasks, but also mentally disconnecting from work (Sonnentag & Fritz, 2015). However, being constrained to work and live in close physical proximity to one’s workplace has been found to predict poorer psychological detachment and a reduced capacity for recovery (Searle, 2012). Moreover, psychological detachment is increased through engagement in enjoyable leisure activities such as exercise and joint activities with others (Feuerhahn et al., 2014; Hahn et al., 2012). With limited space, time, and choice of leisure activities impeding psychological detachment, workers are at risk of experiencing high levels of strain and negative affective states after a stressful workday (e.g., work-related rumination) that prevents effective recovery (Sonnentag, 2018).

Last, despite the critical role of adequate sleep for optimal human functioning, sleep is often the first domain to suffer in an extreme work environment (Miller et al., 2008). Sleep plays an important part in returning psychophysiological states to baseline, with humans requiring on average 8–8.5 h of sleep per night (Watson et al., 2015). However, factors such as operational pressures, uncomfortable sleeping environments, and a 'can (and will) do' attitude towards meeting work goals mean sleep loss and/or deprivation is a common occurrence in extreme environments (Moffitt, 2008). For example, astronauts typically obtain less than 6 hours of sleep per day (Barger et al., 2014), with sleep being disrupted by suddenly shifted work operations, uncomfortable ambient temperatures, and an absence of circadian cues such as light cycles (Stuster, 2010).

As our examples illustrate, there is a high potential for carry-over effects within a constrained extreme environment. These effects highlight a need to consider how elements of the entire work-life system interact over time to affect energy management, and ultimately, the capability to endure.

Designing a Work-Life System to Optimize Endurance

We propose that organizations and individuals can optimize endurance by designing a work-life system that integrates across work, non-work, and sleep components. Designing a work-life system for optimized endurance requires individuals and organizations to actively shape and manage the content, composition, timing, and environment of work, non-work, and sleep components to reduce or prevent negative carry-over effects that otherwise contribute to an accumulation of fatigue and strain.

A work-life system designed to consider the interconnected nature of work, non-work, and sleep allows for more sustainable patterns of energy management, and reflects taking a systemic approach to reducing the degree to which individuals need to compensate across the demands of a mission. Although compensation efforts are a critical component in energy management, repeated short-term compensation in response to environment challenges leads to accumulation of strain and fatigue that impairs functioning and performance over longer periods (Ford et al., 2014; McEwen, 2007). For example, although 24-hour sleep-deprived individuals may be able to maintain safety-critical task performance for a period using compensatory strategies (Hockey et al., 1998), chronic sleep loss has cumulative detrimental effects that are not easily reversed by short-term strategies, such as taking a single extended sleep (Cohen et al., 2010).

A systemic approach to mitigating a build-up of strain and fatigue is critical because the highly interconnected nature of extreme work-life systems means fatigue and strain can rapidly carry-over and accumulate from one working period to the next (Hockey, 1997). Additionally, there is less opportunity in extreme work environments to reverse any build-up of strain and fatigue. For instance, in the common working week pattern of five days of work and two days of rest, the weekend provides opportunity for respite to occur (Fritz et al., 2010). By contrast, extreme work environments often involve continuous work operations (i.e., 24/7), sometimes without weekends - for example, submarine crews are expected to work on a rotating shift schedule continuously for weeks to months before a dedicated rest period (Brasher et al., 2010; Moffitt, 2008).

Models of stress such as the allostatic load (AL) model (McEwen, 2007) specify that sustained exposure to stressors and/or sustained activation even when stressors are no longer present results in more permanent psychophysiological changes (e.g. elevated cortisol levels, hypertension) which impair functioning (e.g. increased sleep disturbances) as the body treats the stressful state as the new 'set point' (Selye, 1955). Over time, these changes decrease an individual's capacity to cope with future stressors. By designing a work-life system to minimise negative carry-over effects from the onset of a mission, organizations and individuals can reduce or mitigate the risk of a vicious and unsustainable cycle of ongoing compensation, where extra effort has to be exerted at the beginning of every new working period to prevent performance breakdown (Hockey, 1997).

Organizational and individual strategies for optimizing endurance

Organizations and individuals can leverage different strategies to design work-life systems for endurance and protect against the accumulation of strain and fatigue (Crain et al., 2018). In extreme work environments, organizations largely determine environmental constraints such as the physical working and living environment, the work design, and the degree of autonomy afforded to workers (Landon et al., 2019). A key strategy that organizations can implement is the design of work/rest schedules in line with criteria that support endurance across a whole work-life system. Work/rest schedule design is concerned with the daily structure and timing of work, non-work, and sleep elements across a mission. These schedules are critical in many extreme environments where work shifts need to support a platform (e.g., ship, submarine) to operate for 24-hours a day, while allowing individuals time for other duties, rest, and sleep (Colquhoun, 1985).

Although the design of work/rest schedules is not a new topic, an integrated work-life system approach is often missing. For example, while there is a large body of research on work/rest schedules in the offshore oil/gas industry, the majority focus on sleep-related issues

(Riethmeister et al., 2019), with few studies accounting for work stressors or recovery opportunities (Parkes, 2017). Indeed, the offshore process industries still operate rosters that involve contracted 12-hour working shifts, and factors such as worker exposure to overtime are often not considered (Parkes, 2017).

Designing a work/rest schedule according to endurance criteria allows organizations to integrate human biological needs (e.g. sleep and recovery) with mission workload requirements as shaped by operational needs and constraints. For example, sleep criteria can include (a) allowing for an 8-hour block of uninterrupted sleep per 24-hour period (Watson et al., 2015) and (b) allowing for night-shift workers to have a circadian synchronised sleep period, which involves employing light-management techniques (Boivin & James, 2005). In terms of criteria for non-work, this may include allowing workers enough time to transition between work and sleep periods. For instance, an adequate amount of time should be factored into a schedule to allow for 'winding down' prior to sleep to maximize sleep quality/duration, as well as to mitigate the temporary effects of sleep inertia on work performance (i.e., grogginess and disorientation) after waking up (Tassi & Muzet, 2000). For work criteria, although these will be shaped by mission operational requirements, these criteria should aim to protect against excessive worker fatigue. For example, scheduled work periods should not be longer than 8-hours of continuous work, as extended work shifts (e.g. 12-hour shifts) are associated with greater fatigue and decrements in performance capacities and alertness, particularly where high workloads are concerned (Bendak, 2003; Macdonald & Bendak, 2000). We also note that work criteria such as working hours, will be related to and impacted by the number, skills, and experience levels of personnel an organization deploys on a mission, as any additional/unexpected increase in demands must be absorbed by existing workers. Therefore, for a work/rest schedule to be operationally feasible, organisations are required to consider task allocations among team members and expected projections of workload to ensure teams set out from the beginning of a mission with sufficient levels of personnel to support around-the-clock work shifts.

Individual workers also shape the design of their work-life system when they interact with their environment on a day-to-day basis (Neal et al., 2017). Individuals optimize endurance and reduce negative carry-over effects by actively choosing what, when, and how they engage in activities and strategies that assist in regulating their energetic state effectively, whether this is a state of higher energetic activation to deal with high workloads, or a state of relaxedness and calmness for sleep and energy restoration. For example, how an individual integrates physical exercise as a non-work activity within their work-life system will have implications for endurance. Physical exercise is an important non-work activity that facilitates psychological detachment (Feuerhahn et al., 2014; Rook & Zijlstra, 2006). However, potential carry-over effects must be considered. For example, engaging in high-intensity exercise ≤ 1 hour before bedtime can lead to sustained physiological activation (e.g., elevated heart rate) which can disrupt the onset of sleep (reducing total time slept) (Oda & Shirakawa, 2014). To optimize the benefits of physical activity for psychological detachment, workers would be best placed to engage in high-intensity exercise directly after work, or failing this, light exercise preceding a sleep period. This pattern creates the best opportunity for obtaining an adequate amount of sleep, which prepares the individual to deal with the demands of the next working period (Cohen et al., 2010).

Discussion

In this paper we have introduced ‘endurance’, a conceptualization of performance that expands upon traditional approaches and is suited to understanding the unique demands of extreme work environments. We have explained, with focus on processes that unfold over a mission, how endurance is the capacity to sustain high performance over an extended duration. Drawing on diverse perspectives of work stress, performance, and physiology, we have argued that an endurance-approach to performance is needed to understand how an individual sustainably manages energy across daily work, non-work, and sleep experiences. In the face of long-term stress and limited opportunity for respite, endurance depends on avoiding accumulation of strain, as this leads to negative changes in mental and physical health, which affects future readiness to perform. Below, we discuss how this theoretical approach can be applied to support researchers and practitioners.

Research Implications

The concept of endurance has important implications for how researchers approach long-term performance in complex and uncertain work environments. We highlight two themes for future research.

Temporal Perspectives

The concept of endurance highlights the importance of understanding performance and functioning as it unfolds within individuals in their natural environment across short- and long-term timeframes (Klonek et al., 2019). In ideal circumstances, workers would be able to perform optimally daily and endure, however, these two situations are not synonymous. Factors that enable workers to perform in the short-term might have different implications for long-term endurance. For example, Grech et al. (2009) found that the relationship between workload and fatigue changed over consecutive days during a naval mission, such that at the beginning of the mission, low workload was associated with fatigue, however at the end, high workload was associated with fatigue. This is relevant to extreme work environments because demands such as workload are often variable and unpredictable across a mission. Additionally, there is currently limited understanding about how ongoing combinations of stressors (e.g., lack of sleep in combination with high workloads) impact workers over longer durations (i.e., over several months) in an operational environment. Future research would benefit from exploring relationships and implications over different timeframes, with attention paid to longer time windows (e.g., 'mission', 'deployment', 'assignment' or 'roster'), as well as shorter-term fluctuations in dynamic states (Klonek et al., 2019).

One approach to advancing temporal research involves using intensive longitudinal data (ILD) to study within-person processes as they unfold over time (Hamaker & Wichers, 2017). New techniques to analyzing ILD such as continuous-time dynamic modelling and dynamic structural equation modeling examine how a preceding state of the system (e.g., a person) gives rise to a subsequent state and interactions between variables (Driver & Voelkle, 2018; Hamaker et al., 2018). These techniques extend on conventional approaches (e.g., growth modeling) which typically focus on concurrent relationships between variables, rather than their dynamic interplay over time. For example, an interesting application of ILD is looking at inertia, or otherwise referred to as autoregressive effects. To date, inertia has typically been explored in the research of affect and is defined in this context as how much carry-over an emotion has from one moment to the next (Albers & Bringmann, 2020). This may be a valuable avenue for understanding endurance. Detecting a certain degree of inertia or change in inertia in indicators such as mood or fatigue, could provide insight into trajectories of endurance and how factors in a work-life system affect an individual's ability to regulate their state.

A related future direction is to extend the temporal frame over a job/career, i.e., endurance across multiple missions (the right-hand portion of Figure 1). While a detailed discussion of endurance over a job/career is beyond the scope of this paper, we propose this perspective involves exploring how even longer-term processes and work/rest patterns over multiple years impacts outcomes such as retention, career development, and long-term health. For example, how much time does an individual require following a mission to recover sufficiently before the next mission? Relevant factors include how strenuous the previous mission was, how intense the upcoming mission is predicted to be, and what work-life looks like in-between missions (Castro & Adler, 1999). Additionally, work-related factors such as enriched work design (e.g., work that involves challenge, feedback and high-level skill use) and fulfilling career pathways (e.g., opportunities for personal and professional development) can facilitate overall job satisfaction and organizational commitment (Parker, 2014).

Adopting a Holistic Work-life System Approach

Endurance emphasizes a whole work-life system approach towards exploring human performance and functioning. Modern work is characterized by significant blurring between work, non-work, and sleep due to factors like technological advances, work intensification, and the proliferation of a 24/7 society. Despite this, little research adopts an integrated approach towards work, non-work, and sleep (for an exception see Crain et al., 2018). Organizational research, in particular, focuses on the work-nonwork interface, often neglecting sleep, despite its role in effective human functioning, worker safety, and performance (Crain et al., 2018). Future research may benefit from adopting a more a holistic approach by examining how work demands and respite activities affect functioning and performance throughout the whole work-life system.

For the purpose of brevity, we have focused on individual level endurance and the immediate ‘work-life system’ in this paper, however, it is important to acknowledge that the individual sits within several systems, as depicted in the top left of Figure 1 (i.e., team and organizational context). Many factors across these systems have implications for endurance. For example, effective leadership in an extreme team may buffer stressors specific to work tasks and support a positive social climate that encourages effective teamwork under difficult circumstances (Zaccaro et al., 2009). Training is also another important element. Specialized stress training that focuses on contextual factors (e.g., organizational, environmental, and task demands) that are imposed upon the team may help counter the negative effects of extreme conditions on team performance (Driskell et al., 2018).

Applied Research to Inform Practical Interventions

In addition to theoretical directions, it is important to explore how endurance can be practically investigated and optimized in real-world settings, both for extreme contexts and conventional work environments. Following from our earlier discussion on endurance criteria in the design of work/rest schedules, we now concentrate on how researchers and practitioners can conduct applied research to inform these criteria and interventions.

Although some endurance criteria are straightforward to specify, for example, it is widely known that adults should obtain 8-hours of sleep for optimal performance, health, and wellbeing (Watson et al., 2015), this is not always the case. Often, organizations have limited insight into how individuals or teams work and live within an extreme environment, and/or there is limited existing research that provides actionable recommendations. This is where applied research conducted in real-world settings is important, as it allows for the capture of the complex factors that shape performance in extreme environments, which in turn generates context-specific recommendations to organizations (Bell et al., 2018). For example, even in a laboratory study where work tasks can be closely simulated, it is not practicable to replicate accumulative mission-level effects such as long-term sleep deprivation and isolation from loved ones due to ethical and logistical constraints (among others). In the following we briefly discuss some challenges and opportunities associated with applied research and offer an example from our research.

Applied research that examines individuals and teams in extreme environments is not without challenges. First, access is a major obstacle. Even where access to is possible, it is often limited, as research goals cannot interfere with operations (Driskell et al., 2018). Additionally, it is not uncommon to rely on self-directed measurement protocols in settings where researchers cannot be present due to limited space and/or dangerous conditions (e.g., submarines, war zones). This raises questions as to how researchers can design measurement protocols that are robust, yet simple and flexible for minimal participant burden.

There are several ways researchers can tackle the challenges of field research. One promising avenue is wearable sensor technologies (Ganster et al., 2018). An increasing number of wearable devices are now equipped with sensors that allow for continuous measurement of the environmental context (e.g., audio/video streams) and physiological indicators (e.g., stress and health via heart rate variability). Second, where traditional experience sampling methodologies are too burdensome in a high-risk operational setting, researchers should consider using single-item measures (Fisher et al., 2016). Although multiple-item measures are traditionally preferred, single-item measures done systematically using validated items may increase response rates and minimize respondant burden (Fisher et al., 2016). This is pertinent if the intent is to capture dynamic fluctuations over time which requires high-frequency assessments (e.g., several times a day) (Kozlowski & Chao, 2018). Lastly, a useful complementary method is to draw on qualitatively rich sources of data such as case studies and focus groups studies. This can be a useful step in understanding the context, before diving into the often expensive and ‘one-shot’ opportunity to collect field data. For further discussions on conducting applied research in dynamic and complex contexts, we refer readers to Kerrissey et al. (2020) and Bell et al. (2018).

Our research team has utilized several of the above-mentioned methods (among others) as part of a large-scale research program which aims to inform and optimize submariner endurance within a future submarine platform design, intended to replace an existing fleet of submarines in the next several decades (See Boeing et al., 2020; Wilson et al., in press). Existing literature offers limited guidance, with submariners facing several relatively unique operational constraints, such as tight limits on crew sizes, confined and isolated spaces (Brasher et al., 2010), and limited exposure to sunlight which has uncertain impacts on circadian processes (Bass & Lazar, 2016). Therefore, to develop appropriate endurance criteria to guide organizational interventions in a submarine context, it was critical to gather field data representative of the challenges inherent in a submarine work-life system.

As an initial step prior to collecting field data, the research team conducted qualitative research, which included desktop research (e.g., existing case studies/reports) and focus groups with submariners to understand the key features and constraints of the context. This data informed the development of a measurement protocol suited for ILD collection during live submarine operations, which consisted of wearable devices (i.e. actigraphy), daily diary surveys, and work/rest event logs, enabling measurements at varying resolutions (e.g., minute-to-minute sleep/wake data to twice daily workload ratings) (see Wilson et al., 2021). A subset of the data including sleep/wake, fatigue and workload measurements was analyzed with the Fatigue Impairment Predictions Suite (FIPS) (Wilson et al., 2020), which is an open-source framework that allows organizations, practitioners, and researchers to implement biomathematical models of fatigue (BMMs). BMMs are a family of dynamic phenomenological models that predict the neurobehavioral outcomes of fatigue (e.g., sleepiness, performance impairment) based on sleep/wake history (Dawson et al., 2017). Using this modelling tool, we compared hour-to-hour changes in submariner fatigue across different work/rest schedules. Drawing on these submarine-specific insights, as well as the multidisciplinary literature presented herein, we developed a comprehensive set of criteria for submariner endurance. These criteria have since been used to evaluate and inform staffing requirements for the future submarine platform, as well as develop recommendations for how technical components such as automation capability and platform habitability (e.g. bunking spaces, leisure spaces) should be designed to support endurance (see Boeing et al., 2020).

Conclusion

The concept of endurance provides insight on how individuals withstand variable and unpredictable stressors while sustaining performance and readiness over a long duration mission. Endurance focuses on dynamic changes in an individual's capacity to perform as they interact with their work-life system over short- and long-term timeframes. Given the changing nature of work, which is characterized by increased uncertainty and complexity due to advanced technology, we hope that the endurance concept will facilitate momentum in adopting an integrated approach towards understanding human performance and long-term wellbeing in not only extreme work environments, but also increasingly demanding conventional work environments.

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The Authors declare that there is no conflict of interest

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