The Effect of Motor, Cognitive, and Combined Fatigue on Motor Performance and Learning, and Transfer.

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Dedication

To my loving wife, Maddy, thank you for your patience, strength, and sacrifice that made this dream a reality. Your love and support have been the fuel that carried me through long nights, uncertain moves, and the weight of balancing professional ambition with personal responsibility. From the demands of military life to the quiet challenges behind the scenes, you stood beside me, not just as a loving spouse but as a source of strength, grace, and unwavering belief. I am thankful that our children witness firsthand what it means to lead with courage, pursue dreams passionately, and support those we love unconditionally.

To our three children, Finn, Rory, and Luca, thank you for keeping life interesting and full of joy. You've provided the balance and perspective I needed during this challenging endeavor. While you may not grasp it yet, your genuine curiosity reminds me why learning matters, your laughter lifts me through the hardest times, and your endless smiles make even the most exhausting days' worth it.

To my parents, whose unwavering support throughout my life's adventures has been the foundation upon which I have built my aspirations. Mom, thank you for being the calm strength and steady voice of reason that anchored me through life's journey. Your quiet confidence, patience, and unwavering belief have shaped not just this work, but the person I've become. Dad, thank you for demonstrating, through action, what it means to commit fully, show up every day, and embrace vulnerability in pursuing something greater. Together, your continued presence, belief in me, and constant encouragement are the epitome of what it means to be parents who are truly present and supportive of their children. This accomplishment is the foundation of everything you gave up so I could pursue my wildest dreams, which were many.

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This dissertation is a culmination of the support, mentorship, and love I have received from so many. I am forever grateful to each and every one of you who have played a pivotal role in this journey. Thank you!

ABSTRACT

This dissertation aimed to synthesize existing literature on acute state motor and cognitive fatigue within a military population. Significant effort has aimed to explore the underpinnings of human fatigue, how it is perceived and appraised, and subsequent impacts on motor performance capabilities. Despite extensive exploration, a notable gap exists in exploring the combined effects of fatigue on subsequent motor performance within a controlled laboratory setting. To our knowledge, no study has examined the interaction between performance and learning under a state of combined fatigue, nor the transferability of skills acquired in practice to combat-specific environments.

Study one served as a foundational study and aimed to compare the effects of isolated fatigue (motor, cognitive fatigue) and combined fatigue on subsequent motor performance. In support of previous findings, results demonstrated that isolated motor and cognitive fatigue resulted in slower anticipatory reaction time. Notably, findings demonstrated the compounding effect of simultaneous motor and cognitive fatigue, resulting in performance deterioration that exceeded the additive effects of isolated fatigue alone.

Study two aimed to extend these findings by examining whether the observed effects would generalize to the military population, enhancing the ecological validity and increasing the applicability to real-world military operations. Consistent with study one, results demonstrated decreased military marksmanship performance following isolated motor and cognitive fatigue. Additionally, results demonstrated a negative, additive effect on marksmanship accuracy and effect when compared to isolated fatigue.

Study three aimed to expand these results further by exploring the impact of fatigue during practice on skill performance, acquisition, and transfer to real-world combat tasks. Results indicated that practice that incorporates similar demands of the performance environment resulted in improved skill acquisition and transfer. For instance, participants who practiced under fatigued conditions outperformed those who trained without fatigue when assessed during retention and transfer testing conducted under fatigue. These findings suggest that skill learning and transfer are context-dependent and contingent on the similarity of training to performance environments.

This dissertation not only contributes to the mechanistic influence of fatigue, but more importantly, demonstrates the importance of nesting task-specific training to improve motor performance, learning, and transfer.

Keywords: fatigue; human performance; transfer of training; synthetic training environments; military marksmanship; motor skill; motor learning

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INTRODUCTION

Demands of the Military Environment

Warfare has long been associated with prolonged, challenging environments that necessitate continuous and efficient performance for operational success. Combative military environments demand the rapid integration of high-level technical, tactical, physiological, and cognitive processes. For many military missions, servicemembers must accomplish these processes while carrying substantial loads and maintaining vigilance of their surroundings.

Phased military operations require extensive planning and preparation, detailed rehearsals, and seamless execution. Throughout each phase, Soldiers are exposed to increased cognitive stress, heightened vigilance, danger to self and others, sleep deprivation, arousal fluctuations, and potentially stressful events (Hancock & Hoffman, 1997; Harris et al., 2005). Extended phases (e.g., military sustained operations) require continuous effort and often test the limit of human capabilities (Johnson et al., 2001). Moreover, as the battlefield and our adversaries advance technologically, prolonged military operations necessitate continuous monitoring and deliberate execution of missions on a dynamic battlefield. The demands often lead to various forms of fatigue throughout the armed forces (Caldwell, 2005).

Empirical Studies of Fatigue in the Military

The Armed Forces are particularly interested in the prevention of performance degradation due to fatigue, as contested military environments necessitate high-level physiological and cognitive performance. Soldiers are required to plan, rehearse, and complete mission objectives following prolonged weighted foot marches through challenging terrain intensified by an environment replete with imminent danger. The compounding effects of these demands may negatively impact Soldier performance and overall mission success, thus necessitating increased scientific inquiry to better understand how to offset these adverse effects. To navigate the consequences of prolonged military operations, robust efforts have been implemented across the military to uncover the foundations of isolated and multi-modal fatigue and its impact on mental and physical performance. The following section will provide research on the various modalities of fatigue and their relationship to military performance.

Motor Task-Induced State Fatigue

The physical demands of warfare are immense, often requiring Soldiers to sustain high-level physical performance in extreme operational environments. Despite substantial advances in equipment and training programs, the burden of the external load has increased over time (Knapik et al., 2004). As Dean and Dupont (2008) described, military doctrine outlines appropriate weight limits that an individual Soldier is recommended to carry while in the field. A Fighting Load (FL) is the lightest load package, commonly encompassing a weapon system, military uniforms, body armor, helmet, equipment harnesses, water, and appropriate ammunition. Approach March Load (AML) requires increased ammunition, a shoulder-worn military backpack with sleeping equipment, or any additional equipment necessary for the mission. The heaviest equipment package, the Emergency Approach March Load (EAML), requires additional equipment and large rucksacks carried for long distances (20 km/day) due to challenging terrain. The total weight of an EAML payload can exceed 54 kg per Soldier. Despite these recommendations, a study consisting of 16 military operations in Afghanistan reported that United States Soldiers commonly carry 28.61 kg during active engagements (FL), 45.95 kg while approaching missions (AML), and 59.76 kg for longer missions (EAML) (Dean & Dupont, 2008). Furthermore, additional occupational demands such as manual labor, casualty evacuation, and reacting to enemy forces often require high aerobic and neuromuscular fitness (Larrson et al., 2020). The physical demands, coupled with decreased recovery periods, have garnered significant scholarly inquiry in the pursuit of understanding fatigue's foundations and mechanistic influences.

Due to their increased occurrence in past military conflicts, various load carriage events have served as the predominant vehicle for exploring the impact of physically demanding tasks on military performance. Leveraging ecologically valid tasks, military leaders may better understand how assigned personnel may perform in contested military environments. Overwhelmingly, studies consistently demonstrate that fatigue induced by physically demanding military tasks, such as load carriage events, results in decreased marksmanship performance. Gil-Cosana and colleagues (2019) investigated the impact of carrying different military equipment on shooting performance, in which thirty-nine males in the Spanish Army completed a three-phase study in which participants completed an unweighted, light military equipment condition (10.3kg) and a heavy military equipment condition (19.5kg). A shooting task, encompassing five engagements to a 15-meter target, was conducted before and immediately following the assigned fatigue condition. Despite load conditions, participants demonstrated a significant reduction in overall marksmanship performance following a 3km walk test. These results are consistent with additional work demonstrating decreased shooting performance following aerobic events (Ito et al., 1999), physically demanding military tasks (Jaworski et al., 2015; Dias et al., 2005), exhaustive upper extremity exercise and obstacle tasks (Evans et al., 2003), and exhaustive whole-body exercise and torso loading (Frykman et al., 2012). The existing research on this topic consistently demonstrates that physical fatigue has a negative impact on motor skill execution within a military context.

Cognitive Task-Induced Fatigue

In addition to physical demands, warfare's cognitive demands are similarly challenging. These demands are often categorized as active (e.g., continuous engagement in motor or cognitive tasks) or passive (e.g., prolonged observation with minimal motor or cognitive engagement) and often occur in various environments, ranging from geographically separated command posts to the battlefield front lines. The unpredictable and fluid nature of military operations dictates round-the-clock assessment, planning, and implementation of mission tasks; tasks that expose Soldiers to volatile environments saturated with inherent danger, requiring extended periods of alertness, vigilance, and decision-making. Further complicating these demands, technological advancements and adversarial capabilities have resulted in substantial changes in modern military operations. Future military conflict is anticipated to be fully connected and synchronized across multiple domains (i.e., land, sea, air, space). This synchronization has led to an emerging propensity towards increased information availability and degrees of freedom across technological solutions. These advancements, combined with the well-established mental demands of military operations, have given rise to an influx of scholarly inquiry.

Barlett (1942) published one of the earliest known studies demonstrating the adverse effects of prolonged mental effort on military pilot performance. He emphasized the importance of distinguishing between fatigue induced by challenging physical tasks and that resulting from tasks requiring prolonged concentration coupled with an advanced degree of skill. During the

Cambridge Cockpit Studies, participants were asked to manipulate various controls in response to changes in aircraft instrumentation during simulated flight tasks lasting between two and seven hours. Barlett reported that as fatigue increased, participants demonstrated increased lapses in alertness and deterioration of motor and cognitive skills. Furthermore, as flight time increased, participants reported increased discomfort, accepted lower performance standards, failed to interpret instrument readings correctly, and performed numerous task responses out of sequence (Barlett, 1942).

More recent inquiries have begun to focus attention on the impact of cognitive fatigue on subsequent motor and cognitive performance and have yielded mixed results. For example, Head and colleagues (2017) used a dissociated approach in which participants completed a mentally fatiguing task prior to a simulated marksmanship task. In that study, participants completed a 49-minute Sustained Attention to Response Task (SART) prior to a shoot, no shoot marksmanship tasks. While having a limited effect on marksmanship accuracy, hit percentage, and precision were similar to those of a control condition. However, participants demonstrated significantly higher overall errors of commission when they were cognitively fatigued. Furthermore, Head et al. (2017) reported a decrease in overall reaction time for the mental fatigue condition. Although there is limited research examining the effects of cognitive fatigue on motor performance within a military population, the existing research demonstrates that being cognitively fatigued negatively impacts motor behavior.

Combined Motor and Cognitive Task-Induced Fatigue

Prolonged military operations require Soldiers to cyclically perform complex tasks in challenging environments, often with minimal time to recover (Belenky et al., 1987; Krueger, 1989). Research has consistently demonstrated that prolonged, intense cognitive and motor tasks can impair muscle activation pathways (Pageaux et al., 2015), feedback mechanisms (Jia et al., 2022), and the overall integrity of the central nervous system (Metha & Parasuraman, 2013; Tornero-Aguilera et al., 2022). Furthermore, prolonged physically and mentally demanding tasks have also been associated with decreased psychophysiological and cognitive function, including, but not limited to, vigilance (Lieberman et al., 2005), reaction time (Lieberman et al., 2005), working memory (Harris et al., 2005), effort perception (Marcora, 2009), and self-regulation and control (Englert, 2016; Wagstaff, 2014).

While exploring the impact of prolonged military operations, Lieberman and colleagues (2005) investigated the effect of 53 hours and 73 hours of physically and mentally demanding military tasks with limited food across two studies. For Study I, thirty-one male Army rangers completed a five-day study encompassing pretesting, 53 hours of continuous activity mirroring the demands of combat, and post-field testing. Activity included extended foot marches with heavy equipment loads, parachute jumps, small boat navigation, and exposure to simulated weapons fire and explosions. Cognitive and mood assessments (e.g., visual reaction time, scanning visual vigilance testing, working memory testing, and mood profiles) were captured before, during, and after field activities. Compared to pre-field testing, participants undergoing 53 hours of continuous activity demonstrated significantly degraded performance with slower reaction time and errors, and decreased visual vigilance, working memory, reasoning, and mood states. For Study II, sixteen male Navy sailors completed a week-long study encompassing pre-testing, 73 hours of continuous activity, and post-testing. Over the 73 hours, participants were exposed to “sustained sleep deprivation, in combination with extensive environmental, physical, and psychological stress” (Lieberman, 2005, p. 7). Similar to the previous study, cognitive and mood assessments were captured before, during, and after field activities. When compared to pre-testing, participants demonstrated significant deterioration of choice reaction time, visual vigilance, working memory, and attention. Additionally, all mood states (i.e., tension, depression, confusion, vigor, fatigue, and anger) were negatively impacted across all subscales. Furthermore, when mood state was compared across studies (e.g., 53 hours vs. 73 hours), significant declines were found between the duration of sustained operations. In summary, Leiberman et al. (2005) examined the effect of physically and mentally demanding tasks during two prolonged duration military operations (e.g., 53 and 73 hours). Over the course of both operations, military personnel demonstrated significant cognitive and mood deterioration (i.e., impaired reaction time, working memory, attention, and mood states), with greater decline observed in the longer 73-hour operation.

Expanding the length and assessment of continuous military operations, Castellani and colleagues (2006) explored the effect of sustained operations (i.e., 84 hours) on physical and behavioral performance. Thirteen military members completed a two-phase study consisting of 84 hours of testing with no scheduled military activity (i.e., control group) and 84 hours of testing and sustained military operations. During the sustained operations phase, participants completed approximately 49 hours of combat-specific military tasks, 28 hours of traditional physical and mental tasks, and an average of 6.2 hours of sleep. Physical and behavioral measurements were captured at consistent, pre-determined intervals for the control and sustained operation phases. Physical measures included maximal strength, power, repetitive lifting (i.e., work production), obstacle course, grenade throw, marksmanship, and wall building. Behavioral measures included visual vigilance, reaction time, working memory, motor learning, and attention. Following 84 hours of sustained operations, participants demonstrated a significant deterioration in physical performance with a decrease in mean jump power and work production. However, no significant differences were found for bench press power, marksmanship proficiency, grenade throws, and wall-building following 84 hours of sustained operations. Behaviorally, participants exposed to 84 hours of sustained operations demonstrated a significant decrease in performance in visual vigilance, reaction time, working memory, and motor learning. Tests assessing motor learning, attention, and short-term memory via a repeated acquisition task were unaffected by sustained operations. In summary, Castellani et al. (2006) investigated the effect of 84 hours of sustained military operations on physical and cognitive performance when compared to a rested control. Results demonstrated mixed results, with significant reductions in physical performance (e.g., jump power, work production) and cognitive measures (e.g., visual vigilance, reaction time, working memory), while other physical (e.g., bench press, marksmanship) and cognitive tasks (motor learning, attention) remained unaffected.

Theoretical Structure for Fatigue Studies

Despite an increase in scholarly work, theoretical models explaining fatigue processes and underlying mechanisms remain under scrutiny. Due to conflicting definitions and their multi-faceted nature, scholars have long suggested abandoning terminology associated with fatigue (Muscio,1921), while others have more recently called for a unified approach (Enoka & Duchateau, 2008; Behrens et al., 2023). Despite fatigue's complexity, several theories have been applied to uncover the underpinnings of fatigue and its impact on motor and cognitive performance. Numerous theoretical frameworks have been leveraged throughout the literature to discern the complex interplay between physiological, sensory-perceptual, and psychological processes, resource-based judgments, and overall perception or feelings associated with fatigue (Boksem & Tops, 2008; Peng et al., 2018; Enoka & Duchateau, 2008; Behrens et al., 2023). Similarly, various taxonomies and models have been offered to explain the mechanisms causing performance deficits in motor or cognitive performance when individuals are fatigued (Enoka & Duchateau, 2008; Behrens et al., 2023; McMorris, 2018; Evans et al., 2016; Morcora, 2009). The various models used to explain fatigue will be reviewed in the following section.

Unitary Models of Capacity

While numerous theories have been applied to understand the effect of fatigue, Kahneman's unitary resources theory (**Figure 1**) offers a rationale for a potential deficiency in allocating sufficient attentional resources for task completion (Kahneman, 1973). Kahneman (1973) proposes that humans have a limited amount of attentional resources available to freely allocate for task completion, in which the allocation of attentional resources is driven by task demand. The total available attention resource pool is said to be affected by numerous factors: (1) arousal, (2) enduring dispositions, (3) momentary intentions, and (4) evaluations of demands on capacity. The available pool of resources is flexible; however, as task demand increases, so does the need for increased resource allocation, thus limiting additional resource availability. While not directly proposed in this model, the mechanistic influences of fatigue are present in the miscellaneous manifestations of arousal. Kahneman's theory suggests that an individual's

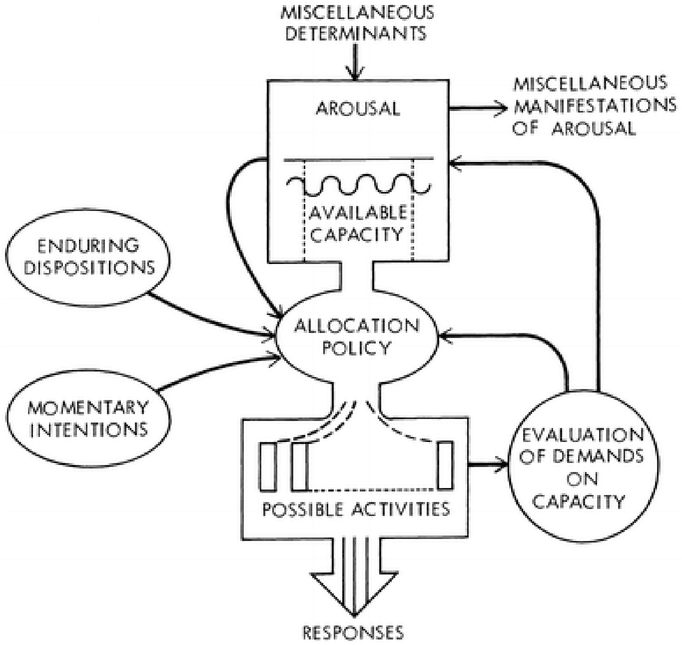


Figure 1. Kahneman's Unitary Capacity Model of Attention.

evaluation of task demands provides cyclical feedback, resulting in the modulation of arousal. As physiological and psychological fatigue increases, individual arousal levels decrease, thus limiting the available capacity to allocate attentional resources to motor and cognitive tasks. Kahneman (1973) proposed that numerous tasks can occur simultaneously as long as demand does not exceed available capacity. Structural or capacity interference may occur when competing demands exceed available resources, resulting in deteriorated performance.

Multiple Resource Models of Capacity

Contrary to trends noted by Kahneman, Wickens (1980) proposed that attentional resources are separated into multiple, distinct resource pools capable of being accessed simultaneously without interference. He advocated that resources are represented by the combination of four “defined", separate dimensions **(Figure 2**).

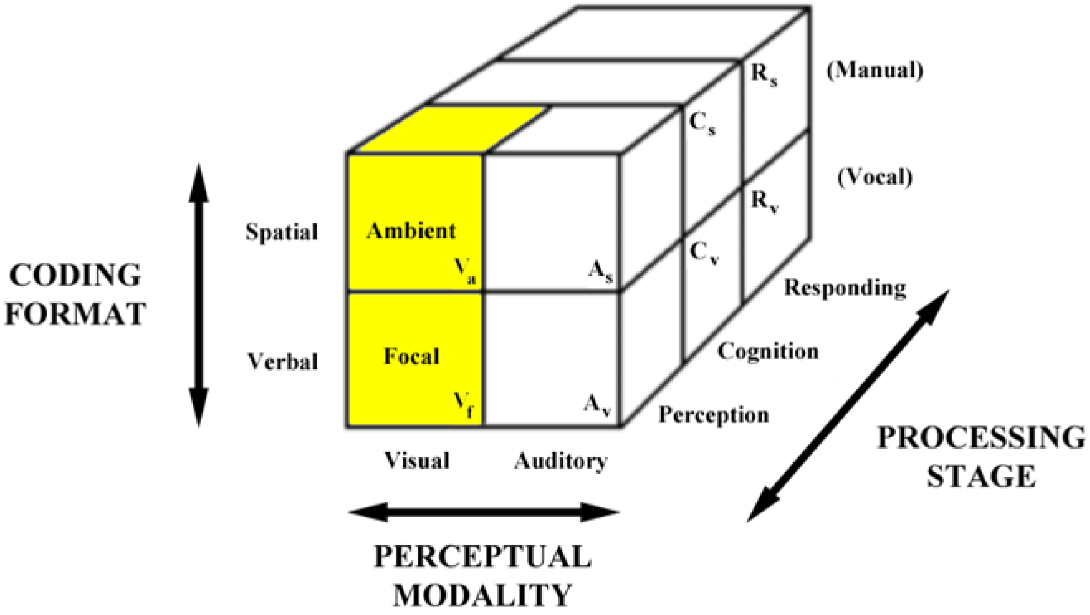


Figure 2. Wickens 4-D Multiple Resource Model.

The stages of processing dimension suggest that perceptual and cognitive tasks utilize distinctive resources, separate from the resources modulating the selection and execution of a given task. Second, the code of processing dimension specifies that verbal/linguistic activity utilizes resources different from spatial activity. Third, the modalities dimension asserts that auditory and visual perception utilize separate, distinct resources. Lastly, the latter added dimension of visual channels suggests that focal (i.e., object recognition, high acuity tasks) and ambient (i.e., peripheral, perception of orientation and movement) vision utilize different resources. Wickens (2008) further explained the interplay, suggesting that time sharing of resources will be more efficient if tasks utilize different levels within each dimension. This brings a noteworthy distinction between the Kahneman and Wickens models, as the Wickens model proposes that as one resource pool, or coding format, experiences fatigue (i.e., cognitive fatigue), a separate resource pool (i.e., manual) would maintain available resources for task execution. If achieved efficiently, the Wickens model predicts a minimal decrement in performance as long as time sharing of resources occurs in different dimensions. From this idea, concern arises from the absence of a central mechanism to prioritize resources when dimension overlap occurs (Hancock et al., 2007). These, among other concerns, deepen our understanding of the challenges surrounding models of attention capacity and their association with the mechanistic substructures of fatigue.

Psychophysiological Explanations

Research investigating the psychophysiological role of fatigue has garnered significant interest in recent years. Corollary discharge, feedback mechanisms, motivation, knowledge of demands, and previous experience highlight agreement between theories (Noakes, 2012; Marcora, 2000). However, differences arise within the models on how feedback is relayed, processed, and acted upon by a central governor mechanism.

Stemming from the previous work of Angelo Mosso and A.V. Hill, the central governor theory (CGT) offers an explanation of fatigue founded on the ideals of maintaining homeostasis (Noakes & Marino, 2009). Proponents of the CGT state that an individual’s physiological state is monitored continuously, and if a threat of damage is identified, the brain will terminate or regulate a given activity before homeostasis is endangered (Noakes, 2012). During the activity, efferent signals initiate action. Consequently, afferent signals provide feedback to a central programmer or governor, which adapts future efferent commands based on known or predicted endpoints of activity (Noakes, 2012). These assertions are substantiated by empirical data (Kay et al., 2001; Amann et al., 2006). Furthermore, this process is believed to occur subconsciously, in that the “subconscious brain informs the conscious brain” of the perception of effort and makes adjustments, based on feedback and motivation, to maintain homeostasis (St. Clair & Noakes, 2004, p. 801). Despite the perception of effort being a hallmark of both theories, Marcora (2009) proposes that the perception of effort is dependent on corollary discharge. As an individual engages in demanding tasks, effort is consciously detected, and action is determined by motivation, knowledge of task demands, knowledge of remaining task demands, and previous experience with the task (Marcora, 2010). Despite differences, both Noakes (2012) and Marcora (2009) believe that motivation, afferent feedback mechanisms, knowledge of task demands, and prior experience shape perceptions and effects of fatigue on motor and cognitive performance.

Taxonomy of Human Fatigue and Performance

The various psychophysiological processes that predictably occur during intense and prolonged motor and cognitive tasks have the potential to negatively impact motor and cognitive performance. Throughout the literature, these processes are commonly categorized using the umbrella term fatigue. Various disciplines and theories have focused on specific mechanistic influences (Enoka & Duchateau, 2016; Venhorst et al., 2018), resulting in numerous definitions of fatigue. This focused attention often results in downplaying the dynamic interaction between subjective and objective changes in performance, as well as individual psychophysiological adjustments to task demands and subsequent perceptual, affective, and cognitive responses (Behrens et al., 2023). Various frameworks have been proposed in response to the highlighted ambiguity of fatigue definitions and mechanistic influences (Enoka & Duchateau, 2016; Kruger et al., 2013; Behrens et al., 2023). For this dissertation, Behrens et al. (2023) components of state fatigue (**Figure 3**) will serve as the working foundation for scientific inquiry. This will allow distinct hypotheses testing regarding objective motor and cognitive performance (e.g., motor and cognitive performance fatigue) and subjective reports of motor and cognitive fatigue (e.g., perceived motor and cognitive fatigue).

Summary and Future Directions

The dynamic landscape of modern warfare underscores the necessity of understanding, preventing, and mitigating the impacts of fatigue on Soldiers. The United States Military is deeply invested in advancing fatigue research, as high-level physical and mental performance is required in highly contested operational environments. In order to meet these demands, the optimization of Soldier performance remains a top priority. As part of this objective, providing realistic training opportunities will be crucial in facilitating Soldier performance, expedited learning of warfighting tasks, and transfer to real-world operational environments; environments requiring Soldiers to perform efficiently across complex performance domains under various states of fatigue. In order to meet these demands, the development,

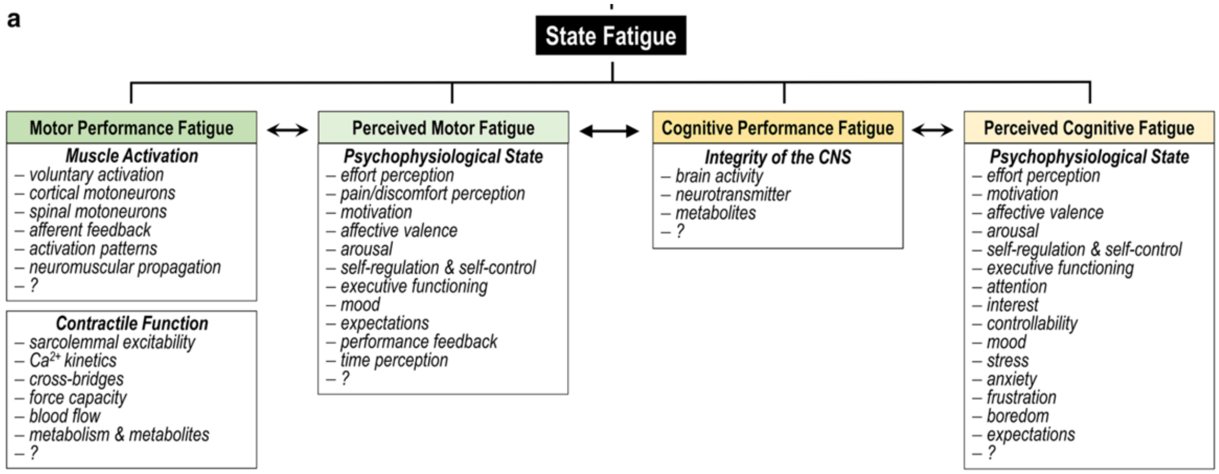


Figure 3. Behrens et al., 2023 Fatigue Framework.

implementation, and analysis of training will play a vital role in skill acquisition and transfer of learning in contested combat environments.

Previous work has demonstrated that learning new skills is highly specific, and training should replicate the sensory and perceptual characteristics (Proteau, 1992), environmental conditions (Wright & Shea, 1991), and cognitive processes found within the performance environment (Lee, 1988). In order to enhance Soldier skill performance and learning, real-world training should incorporate similar visual (e.g., target recognition, enemy movement tracking), auditory (e.g., gunfire sounds, commands from teammates), tactile (e.g., weight of equipment, weapon system recoil), and proprioceptive (e.g., body position when shooting, balance while carrying a heavy load) characteristics. Additionally, training environments should include features of the performance environment to optimize learning effects (Shea & Wright, 1995). This could include the incorporation of fatigue in marksmanship training, execution of military tasks in a confined space (e.g., a dimly lit building), or completing military objectives with teammates. Lastly, training should include similar cognitive processes within the contextual environment (e.g., rapid decision-making, response inhibition, selective attention).

While extensive research has been conducted on physical and mental fatigue in separate and isolated contexts, a notable gap exists in exploring the effect of simultaneous physical and mental fatigue on subsequent military performance in a controlled laboratory setting. To further understand the impact of fatigue on military performance, future research should examine the effect of simultaneous, multi-modal fatigue on military task execution. Additionally, studies should investigate incorporating multi-modal fatigue in practice settings and its impact on military performance, learning, and transfer to real-world combat environments.

While training in the physical world remains vital, advances in virtual environments (e.g., synthetic training environment [STE]) allow military personnel and leadership to bypass the inherent constraints of real-world training (e.g., funding, safety, time, logistics). Furthermore, due to their controlled nature, STEs offer the opportunity to collect rich data across multiple performance domains (e.g., technical, tactical, physiological, cognitive) while mitigating the risk of injury and typical constraints of military training. More importantly, STEs allow for the development and implementation of virtual military activities within practice, which mirror tasks found on the battlefield. Previous research has demonstrated the positive effects of training, which incorporates realistic exposure to performance-specific tasks and environments in virtual reality, on the transferability to performance contexts (Gray, 2017). Using Thorndike's identical elements theory, it is hypothesized that the degree of successful transfer depends on the level of related (i.e., identical) elements (e.g., motor, cognitive, visual), similarities in the environmental context in which the skill is being executed (Thorndike, 1914) and the availability of similar information throughout practice. STEs afford the opportunity to combine virtually generated targets with physically and mentally demanding tasks commonly found in military environments. The opportunity to develop and implement such environments may optimize training conditions using validated motor learning principles, allowing further investigation to explore the adaptability of what was learned during training and how it transfers to real-world environments (Weiss et al., 2014; Wulf, 2007).

This dissertation will examine the effects of motor, cognitive, and combined fatigue on motor and cognitive performance in a simulated environment. Specifically, this dissertation will consist of three distinct studies. Experiment one investigated the foundations of fatigue by exploring the effect of motor, cognitive, and combined fatigue on subsequent performance in a non-military setting to establish a theoretical model for future military-focused testing. Additionally, this initial study examined the perceived workload associated with performance under each fatigue condition. Experiment two explored fatigue’s impact on motor and cognitive performance using an ecologically valid methodology. This study investigated the effect of military-specific motor, cognitive, and combined fatigue on marksmanship performance. Additionally, experiment two examined the perceived workload associated with performance under each military-specific fatigue condition. The purpose of the proposed third experiment was fourfold: 1) to investigate the effect of combined fatigue on military performance within a simulated combat environment, 2) to investigate the effect of training with and without fatigue on military skill learning, 3) to investigate the effect of training with and without fatigue on transfer to a military-specific task, and 4) to investigate the effect of training with and without combined fatigue on the perception of workload during transfer to a military-specific task.

CHAPTER ONE EXPERIMENT ONE: EFFECT OF PHYSICAL, MENTAL, AND COMBINED ACUTE STATE MOTOR AND COGNITIVE FATIGUE ON SUBSEQUENT MOTOR PERFORMANCE AND WORKLOAD

Abstract

Understanding the impact of fatigue on motor performance is intricate and is influenced by a range of factors encompassing individual differences, task-specific demands, and contextual elements. While extensive research has been conducted on mental and physical fatigue in isolation, a notable gap exists in exploring the combined effects of motor and cognitive fatigue on subsequent motor performance within a controlled laboratory setting. Therefore, the present study aimed to explore the combined effects of motor and cognitive performance fatigue on subsequent motor performance. Twenty-eight participants (*M* age = 20.96 ± 1.62 years, male = 9) completed a three-day study consisting of baseline assessments followed by three randomized experimental conditions: physical fatigue (i.e., isometric grip strength task), mental fatigue (i.e., incongruent Stroop task), and combined fatigue (i.e., combined mental and physical fatigue). Each fatigue condition was followed by an anticipatory reaction time task to assess motor performance. A two-way repeated measures ANOVA revealed significant main effects for time and condition; however, they were superseded by the time-by-condition interaction, F(2,54) = 74.14, p = <.001, η=.733. Post-hoc testing revealed significant post-fatigue differences in anticipatory reaction time between the physical and combined fatigue conditions, p <.001. Additionally, significant differences were found between mental fatigue compared to combined fatigue, p <.001. These findings suggest that simultaneous exposure to motor and cognitive fatigue exacerbates deficits observed in the isolated fatigue conditions but, more importantly, leads to a compounded performance decline that exceeds their individual effects.

Introduction

Fatigue has been extensively studied and is often debated as a physiological state, a perceived emotion or feeling, and a homeostatic mechanism crucial in the prevention of injury. The last few decades have seen an increased emphasis on exploring the underpinnings of human fatigue, how it is perceived and appraised, and subsequent impacts on motor performance capabilities. Historically, fatigue has served as an umbrella term for any reportable decrease in physical or mental capacity arising from an increase in the real or perceived difficulty of a particular performance context (see Abd-Elfattah et al., 2015). Due to its complex nature, fatigue has been operationally defined and categorized differently depending on the studied population and the tasks on which fatigue could influence mental and physical demands. This fragmentation has led to a broad scope of conditions and effects resulting from various types of fatigue. In recent years, there has been a call for succinct terminology to appropriately categorize and define fatigue within the human performance literature (Behrens et al., 2023; Enokea & Duckateau, 2016; Kluger et al., 2013). This has resulted in a taxonomy that has been modified, updated, and streamlined over the last ten years (Behrens et al., 2023) and will serve as the foundation for the current inquiry into the intersection of anticipatory reaction time and combined state fatigue.

Understanding the impact of fatigue on motor performance is intricate and is influenced by a range of factors encompassing individual differences, task-specific demands, and contextual elements. Motor Performance Fatigue and Perceived Motor Fatigue have been extensively studied with notable comprehensive reviews (Behrens et al., 2023; Enoka & Duchtea, 2008; Enoka & Stuart, 1992; Gandevia, 2001). Inquiry into motor performance fatigue resulting from acute, maximal force production and prolonged physical exertion has garnered significant attention with findings demonstrating that mental fatigue reduces force production and torque (Baudry et al., 2007), power (Pageaux & Lepers, 2016), and aerobic and anaerobic endurance (Gierczuk et al., 2012), while also slowing response time (Rodrigues et al., 2022; Sant' Ana et al., 2017). Research has also explored the intricacies of the modulating factors of motor fatigue and their impact on performance, with findings demonstrating that moderate physical exertion improved cognitive performance, while low and high-intensity physical exertion did not (Tomporowski & Ellis, 1986).

Similarly, research has shown that cognitive performance and perceived cognitive fatigue can significantly influence subsequent motor performance and overall health and well-being (Habay et al., 2021). Cognitive performance fatigue has been behaviorally associated with changes in balance and postural control, decreased endurance performance (Pageaux et al., 2014), balance and postural control (Mehta & Parasuraman, 2013), pain tolerance (Boat & Taylor, 2017), muscle activation patterns (Pageaux et al., 2015), fine motor control (Duncan et al., 2015), and overall sports performance (for a review see Yuan et al., 2023). Furthermore, cognitive fatigue is also associated with decreases in executive functioning (Boskem et al., 2006), slowing of reaction time on various cognitive tasks (Mockel et al., 2015), and greater medical error rates (McCormick et al., 2012; West et al., 2009). Furthermore, perceived cognitive fatigue has been subjectively associated with increased feelings of tiredness (Boksem & Tops, 2006), decreased motivation (Boksem et al., 2006), and interrupted reward structures (Van Der Hulst & Geurts, 2001).

While extensive research has been conducted on mental and physical fatigue in isolation, a notable gap exists in exploring the combined effects of motor and cognitive fatigue on subsequent motor performance within a controlled laboratory setting. Much of the current literature explores the isolated effects of fatigue on subsequent motor performance, thus failing to capture the complex reality where multiple types of fatigue frequently coincide. Therefore, the present study aimed to explore the combined effects of motor and cognitive performance fatigue on subsequent motor performance. For this study, the exploration of fatigue used the taxonomy proposed by Behrens et al. (2023), which operationally defines motor and cognitive fatigue as a psychophysiological condition that is characterized by a decrease in motor or cognitive performance and produces an increased perception of fatigue (Behrens et al., 2023). More specifically, in the present study, we defined motor performance fatigue as a decrease in force production capability within the neuromuscular system in the context of a prolonged motor task. Cognitive performance fatigue is defined as a decrease in an objective cognitive performance measure in the context of a prolonged or intense cognitive task.

Experiment 1 Research Purpose and Predictions

The purpose of this study was to explore the isolated and combined effects of fatigue on anticipatory reaction time. Based on previous research exploring the effect of isolated fatigue on performance, it was hypothesized that:

1. Isolated motor fatigue will result in a slower anticipatory reaction time compared to baseline.
2. Isolated cognitive fatigue will result in a slower anticipatory reaction time compared to baseline.
3. Combined fatigue will result in a slower anticipatory reaction time compared to baseline.

4. Combined fatigue will have a compounding effect, producing a slower anticipatory reaction time compared to baseline and isolated fatigue.
5. Participants would report higher NASA-TLX Scores for the combined fatigue condition compared to each isolated fatigue condition.
6. Participants would report higher rates of perceived exertion for the combined fatigue condition compared to each isolated fatigue condition.

Method

Participants

An a priori power analysis was performed using G*Power 3.1.9.6 to ensure the study was adequately powered. Based on the G*Power calculation (alpha = .05, power .90), the projected sample size required was approximately N=26 using a within-between-subjects comparison. A total of *N* = 28 (*M* age = 20.96 ± 1.62 years, male = 9) undergraduate and graduate students were recruited from academic courses at the primary institution to participate in this study. Participants were informed they would be completing a fatiguing task but were naïve to the purpose of the study. Before enrollment, participants were briefed on inclusion and exclusion criteria and signed an informed consent previously approved by the local Institutional Review Board (#UTK IRB-23-07438-XP). All participants were considered eligible based on the following criteria: (1) ability to read and speak the English language; (2) ability to distinguish between the primary colors of red, blue, green, and yellow; and (3) have not sustained an injury to their dominate hand, wrist, or elbow within the last six months.

Task and Apparatus

Anticipatory Reaction Timing

Anticipatory reaction time was captured using the Bassin Anticipation Timer (BAT) (Model 35575, Lafayette Instrument Company, USA). The BAT utilized a runway of lights on a linear track 3.58 meters in length. The track was placed on a tabletop and was situated at the midline of the participant standing on pre-marked placements approximately 30.5 cm from the tabletop. The runway lights illuminate sequentially in the direction of the participant. Participants were asked to anticipate the timing of the light sequence and depress a handheld trigger with their thumb when the light sequence arrived at a predetermined target light at the end of the runway. The absolute error of each trial, regardless of whether it was early or late, was captured in milliseconds.

Fatigue Protocols

The protocols to induce fatigue were computer-based and consisted of mental, physical, or combined fatigue tasks lasting approximately 30 minutes. Each block was explicitly designed to align with the timing of the other fatiguing protocols, which are described in the following section.

Mental Fatigue: Incongruent Stroop Task

For the mental fatigue condition, participants completed an incongruent Stroop task of 776 trials over 30 minutes, segmented into 97 blocks of 8 trials each. Congruent and incongruent trials were set to appear equally (50%) across the task. A color word (e.g., green, blue, yellow, red) was presented in a specified font color (e.g., green, blue, yellow, red). The trial was congruent if the meaning of the color word and the font color were identical. For example, the word red was printed in red font. However, the trial was incongruent if they differed. Participants were asked to identify and verbally respond to the font color (e.g., green, blue, yellow, red) of the color word on the screen. The accuracy of the response was recorded throughout.

Physical Fatigue: Repetitive Isometric Maximal Grip Strength

Participants completed a repetitive maximum isometric grip protocol using a MicroFet handheld dynamometer, which consisted of 96 grip trials over 30 minutes on setting II to align with previous protocols exploring maximal isometric grip strength (Firrell & Crain, 1996). Specifically, participants were instructed to hold the dynamometer with their elbow at approximately 90 degrees without resting it on the chair or any body part for the testing phase. Participants were instructed to "squeeze the handle of the dynamometer as hard as you can for each trial." Similar instructions were given on trials 25, 50, and 75. The protocol began with instructions regarding the task, followed by two practice trials, and then participants completed 96 testing trials over 30 minutes. Maximum force and timing of force production measurements were captured as the dependent measures for each trial.

Combined Fatigue: Incongruent Stroop Task and Repetitive Isometric Maximal Grip Strength

For the combined fatigue task, participants completed the mental and physical fatigue tasks simultaneously. Over 30 minutes, 776 Stroop trials and 97 isometric grip trials were completed. The task was broken into 97 blocks, each consisting of eight consecutive Stroop trials and one grip trial. Instructions for the combined physical and mental fatigue setting were identical to those delivered in the separate fatigue conditions described above. Accuracy of response, maximum force production, and timing of force production were recorded for every trial.

Psychological Scales: NASA-Task Load Inventory

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) is a multi-dimensional workload measure comprised of six subscales (i.e., mental demand, physical demand, temporal demand, performance, effort, frustration) and has demonstrated good reliability, $\alpha = 0.71 – 0.81$ (Hart & Staveland, 1988). NASA-TLX was administered using the NASA-TLX iPad application. Participants were asked to rate their perceived workload on a scale of 0-20 anchored by bipolar descriptors (i.e., low/ high). Each of the six subscale scores was digitally multiplied by five to transform data into a hundred-point scale for a possible total of 100 points. Subjective workload was measured at posttest following each fatigue protocol.

Procedure

The study design included three sessions over approximately five days ($M = 5.14$). The administrative tasks of exclusion criteria screening, informed consent, and study overview were completed on day one. Following administrative tasks, participants were familiarized with the testing protocol, research equipment, and baseline assessments for the anticipatory reaction time and isometric grip strength tests. Anticipatory reaction time testing via the Bassin Timer (Model 35575, Lafayette Instrument Company, USA) consisted of two practice trials with performance feedback and five baseline trials without feedback. Isometric grip strength testing via a MicroFet Handheld Dynamometer consisted of five baseline maximal grip force trials lasting two seconds, followed by approximately 10 seconds of rest. Participants were instructed to "squeeze the handle of the dynamometer as hard as you can" during each grip strength trial.

Following baseline testing, participants were randomly assigned to a counterbalanced fatigue condition sequence (i.e., mental, physical, combined) using a balanced Latin square method. During testing, participants were seated approximately 91.44 cm from a computer screen set at eye level. They received instructions via the screen for the task to be completed before being given the opportunity to ask questions. During each testing condition, participants completed a computerized fatigue protocol lasting approximately 30 minutes. Following each fatigue protocol, participants completed posttest anticipatory reaction time testing via the Bassin Timer. Similar to baseline testing, participants completed two practice trials with 100% feedback, followed by five testing trials without feedback. Finally, participants completed the NASA-TLK after the posttest.

On days two and three, participants completed baseline anticipatory reaction time testing, the subsequent computerized fatigue protocol based on a counterbalanced order, posttest anticipatory reaction time testing, and the NASA-TLX. A schematic representation of the testing protocol is shown in **Figure 4**.

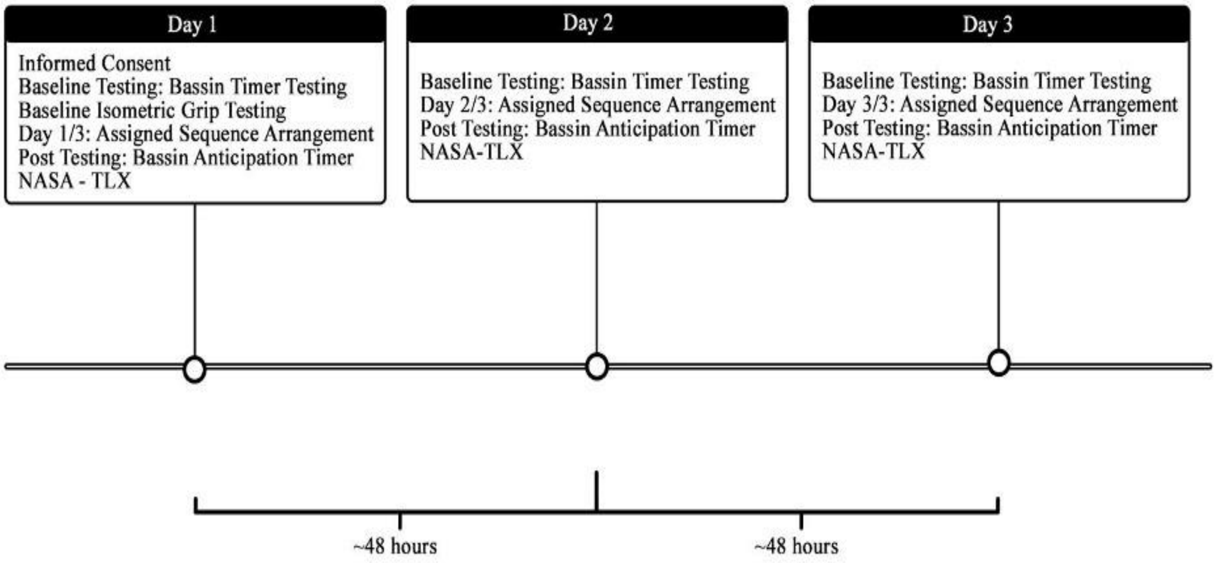


Figure 4. Schematic representation of the experimental design.

Data Analysis

All data validations and statistical analyses were performed with IBM SPSS Statistics (v28, IBM Corp., Armonk, NY). Before conducting the primary analyses, data were screened for irregular values and outliers, revealing two potential outliers via visual boxplot analysis; however, removal via trimming did not substantially alter variable significance. Thus, these data were retained for all future analyses. Assumptions of normality and heteroscedasticity were tested. When normality was violated, degrees of freedom were corrected using Greenhouse-Geisser estimates when necessary. To explore the effect of fatigue on anticipatory reaction time, a 2 (Time: baseline, posttest) x 3 (Condition: physical fatigue, mental fatigue, combined fatigue) repeated measures analysis of variance (ANOVA) was used to compare performance at the two points during each fatigue protocol (i.e., visits). Bonferroni-corrected degrees of freedom were applied during post-hoc testing, and the statistical significance threshold was set at α=.05 for all analyses. Partial eta-squared (η^2) effect sizes for omnibus ANOVAs and Cohen's *d* simple effects for pairwise comparisons were also determined.

Results

Anticipatory Reaction Time

Results from the two-way repeated measures ANOVAs demonstrated a statistically significant main effect for Condition, $F(2,54) = 34.48$, $p <.001$, $\eta^2 = .546$, and Time, $F(1,17) = 38.11$, $p < .001$, $\eta^2 = .585$; however, they were superseded by the time-by-condition interaction, $F(2,54) = 74.14$, $p = <.001$, η=.733. No significant differences as a function of Condition at baseline. Post-hoc decomposition of this interaction revealed the combined fatigue conditions resulting in significantly slower anticipatory reaction time compared to the isolated mental (M_{diff}

= .011 seconds [.007, .015], *d=3.417*) and physical fatigue conditions (M_{diff} = .012 seconds [.007, .017], *d=3.728*). The results of this analysis are reported in **Figure 5**. Descriptive statistics (mean + standard deviation) for anticipatory reaction time and workload data for NASA-TLX subscales are presented in **Table 1**.

NASA-TLX Workload Scores

A repeated-measures ANOVA was performed to evaluate the effect of each fatigue condition on NASA-TLX Workload Scores. Results from the repeated measures ANOVAs revealed a statistically significant main effect for self-reported *mental demand*, F(1.521,41.71) = 240.02, p =<.001, η^2 =.899, *physical demand*, F(1.449, 39.132) = 218.46, p =<.001, η^2 =.890, *temporal demand*, F(2,46) = 17.31, p=<.001, η^2 =.391, *effort*, F(2,54) = 8.66, p =<.001, η^2 =.243, and *frustration*, F(2,54) = 9.76, p <.001, η^2 =.265. Pairwise comparisons indicated that mental

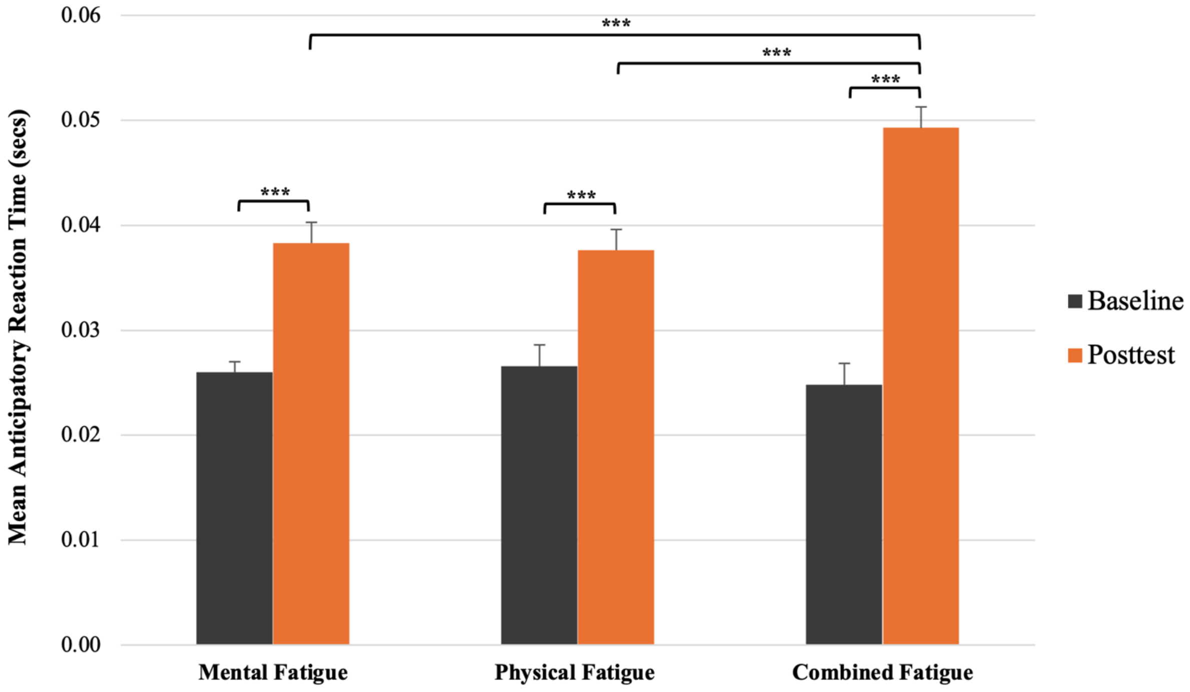


Figure 5. Mean anticipatory reaction time by condition and time.

*** p <.001.

Table 1. Anticipatory reaction time and workload data (mean = standard deviation) by time and condition.

	Mental Fatigue		**Physical Fatigue**		**Combined Fatigue**	
	Baseline	**Posttest**	**Baseline**	**Posttest**	**Baseline**	**Posttest**
Anticipatory Reaction Time (sec)	0.03 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	0.05 ± 0.01
Subscales						
Mental Demand	-	77.50 ± 17.87	-	11.25 ± 6.75	-	74.11 ± 20.32
Physical Demand	-	5.54 ± 6.29	-	75.54 ± 11.57	-	69.11 ± 23.96
Temporal Demand	-	55.54 ± 27.67	-	30.71 ± 22.01	-	51.96 ± 25.22
Performance	-	34.64± 23.61	-	31.61± 15.40	-	38.57 ± 21.72
Effort	-	63.93 ± 18.38	-	62.32 ± 17.35	-	75.36 ± 12.09
Frustration	-	45.71 ± 27.88	-	27.68 ± 24.59	-	50.89 ± 30.82

and combined fatigue increased mental demand compared to physical fatigue (*p's* <.001). No differences were found between the mental and combined conditions (*p*=.520). As for self-reported physical demand, pairwise comparisons indicated that the physical and combined fatigue conditions increased physical demand compared to the mental fatigue conditions (*p*'s <.001). No differences were found between physical and combined conditions (*p* = .299). Comparisons for self-reported temporal demand indicated mental and combined fatigue conditions increased temporal demand as compared to the physical fatigue condition (*p's <.001*). No differences were found between mental and combined conditions (*p* = .827). For self-report of effort required, comparisons revealed the combined fatigue condition required increased effort as compared to the mental (*p* = .005) and physical fatigue (*p*<.001) conditions in isolation. No differences were found between mental and physical conditions (*p*=1.00). Comparisons of self-reported frustration revealed that the mental and combined fatigue conditions increased levels of frustration as compared to the physical fatigue condition (*p* = .002, .004, respectively). No differences were found between mental and combined fatigue conditions (*p* = .982). Lastly, no differences were found in self-reported measures of performance between conditions.

Experiment 1 Brief Discussion

The present study examined the isolated and combined effects of fatigue on anticipatory reaction time. It was predicted that exposure to isolated mental, physical, and combined fatigue would result in depressed anticipatory reaction time when compared to baseline performance. Additionally, it was hypothesized that exposure to mental and physical fatigue simultaneously would result in slower anticipatory reaction time change scores when compared to baseline and isolated fatigue conditions. These findings contribute to a growing body of literature demonstrating that exposure to mental and physical fatigue independently depresses anticipatory reaction time. Additionally, it begins to shed light on the need for increased scholarly inquiry into the effects of combined fatigue. The findings of experiment 1 are discussed in the following sections.

Performance Variables

Isolated Physical and Mental Fatigue

Prior investigations on the effect of isolated fatigue have demonstrated its negative effect on motor performance. Consistent with previous findings, results from this study demonstrate the negative effect of isolated mental and physical fatigue on anticipatory reaction time (Boksem et al., 2006; Mockel et al., 2015). The observed slowing of anticipatory reaction time suggests that isolated fatigue impairs motor and cognitive processes involved in the timing and execution of anticipatory motor tasks.

Combined Physical and Mental Fatigue

The most notable finding of the current investigation is the significant increase in anticipatory reaction time following the combined fatigue condition. This result supports the hypothesis that exposure to multiple types of fatigue has a compounding effect on performance. The compounding effect may be due to the simultaneous demand on available attentional resources (Kahneman, 1973), resulting in depletion, thus leading to a subsequent decline in motor and cognitive task capability. The lack of significant differences in anticipatory reaction time change scores between isolated fatigue conditions suggests that decreases in performance caused by physical and mental fatigue are comparable when assessed in isolation. However, the differences between the effects of isolated and combined fatigue on anticipatory reaction time change scores highlight the importance of considering the interaction between different types of fatigue when assessing performance in real-world contexts, where multiple types of fatigue often co-occur.

Theoretical and Practical Implications

These findings have several notable implications for the understanding of fatigue and its impact on motor and cognitive performance. These findings support common resource pool theories in which structural or capacity interference occurs when competing demands exceed available resources, resulting in deteriorated anticipatory reaction time performance (Kahneman, 1973). Additionally, the findings of this study contradict multiple resource theories (i.e., multiple, distinct resource pools capable of being accessed simultaneously without interferences [Wickens, 2008]) due to the negative, compounding effect found when mental and physical fatigue occurred simultaneously. Furthermore, the current investigation underscores the need for an integrated approach to studying fatigue, which explores the complex interplay of multiple fatigue conditions. This approach is particularly relevant to a variety of contexts such as sports, military, medicine, and occupational settings where individuals are subjected to both physically and mentally demanding tasks simultaneously.

Future Directions

While the results of this study provide significant insights into the effect of fatigue on performance, a significant gap remains in the exploration of fatigue using ecologically valid, real-world tasks and environments. Thus, future studies should explore the effects of combined fatigue on a broader range of real-world motor and cognitive tasks within occupations that commonly experience multiple types of fatigue simultaneously (e.g., military, medical, aviation, manual labor). Due to the unique contribution of these findings, future research should begin to explore the underlying mechanisms that contribute to the compounding effect of multiple types of fatigue experienced simultaneously. Understanding the physiological and cognitive processes that are conjointly affected could inform the development of mitigation strategies and interventions that prevent or delay the deterioration of motor and cognitive performance.

Conclusion

The results of this study demonstrate that exposure to mentally and physically demanding tasks independently impairs anticipatory reaction time, and their combined effects lead to even greater impairments. These findings highlight the importance of considering the interaction between exposure to different types of fatigue in both research and practical applications. By adopting a more integrated approach, it may be possible to develop effective interventions to maintain or enhance performance in demanding environments.

CHAPTER TWO EXPERIMENT TWO:

EFFECT OF PHYSICAL, MENTAL, AND COMBINED ACUTE STATE MOTOR AND COGNITIVE FATIGUE ON SUBSEQUENT MOTOR PERFORMANCE AND WORKLOAD

Abstract

In modern warfare, Soldiers are expected to execute a wide range of complex tasks under significant physical and mental fatigue. To enhance motor performance and future Soldier success, the military must appraise and integrate performance expertise alongside emerging technological systems to develop training solutions capable of delivering results on the battlefield. While existing literature provides a promising future for this line of inquiry, a significant gap exists in the impact of combined fatigue on task performance, learning, and transfer to real-world environments. More specifically, no study has explored the complex interplay of performing and learning under combined fatigue, nor the transfer of learned skills to combat-specific environments. Thus, this study aimed to examine the effect of combined fatigue on military marksmanship performance, learning, and transfer to combat-specific environments. Participants (N=28; M age = 22.04 ± 3.22 years, male = 20) were United States Army and Air Force Reserve Officers' Training Corps (ROTC) cadets. Volunteers completed a three-day study encompassing a physical, mental, and combined fatigue protocol followed by a three-part marksmanship task (i.e., precision, discriminatory reaction, speed, & accuracy). Marksmanship tasks were completed using the InVeris Squad Advanced Marksmanship Simulator, which leverages non-immersive virtual reality and wireless weapon technology to replicate the form, fit, and function of live weapons used by the United States Military. Results from the two-way repeated measures ANOVAs demonstrated a statistically significant main effect for condition on marksmanship precision ($p < .001$), discriminatory reaction time ($p=.002$), and efficiency ($p < .001$). Additionally, results revealed a statistically significant main effect for self-reported mental demand ($p=<.001$), physical demand ($p=<.001$), temporal demand ($p=.014$), effort ($p=<.001$),

frustration *(p=<.001)*, and rate of perceived exertion *(p=<.001)* when fatigued. The findings of this study demonstrate the independent and combined effects of motor and cognitive fatigue on military marksmanship performance. Furthermore, these findings highlight the need for comprehensive training programs across disciplines (i.e., sports, military, aviation, medicine) that address the challenges of combined fatigue while facilitating motor and cognitive performance, retention, and transfer of learning to real-world environments.

Introduction

Warfare is a multifaceted human endeavor that requires the harmonious synchronization of mental and physical performance in the most demanding environments. To enhance motor performance, our military must appraise and integrate performance expertise alongside emerging technological systems in order to develop training solutions capable of delivering results on the battlefield. To combat this challenge, an increase in scholarly work has emerged, leveraging synthetic training environments to explore the effects of fatigue in tactical settings. Understanding the impact of fatigue on motor and cognitive performance is complicated and is influenced by a range of factors encompassing individual differences, task-specific demands, and contextual elements. Within a military environment, research exploring the effects of performing physically demanding tasks has demonstrated reductions in military rifle marksmanship (Jaworski et al., 2015), vigilance, working memory, reaction time (Lieberman et al., 2005), and increased physiological strain (Yanovich et al., 2015). Similarly, research has shown that cognitively demanding tasks are behaviorally associated with depressed reaction time (Buckley et al., 2022), decreases in discriminatory reaction control (Head et al., 2017), fine motor control (Duncan et al., 2015), and overall physical performance (Marcora et al., 2009). While extensive research has been conducted on physical and mental fatigue in separate and isolated contexts, a notable gap exists in exploring the effect of simultaneous physical and mental fatigue on subsequent motor performance within a military population. Therefore, this research study aimed to explore the combined effects of motor and cognitive performance fatigue on subsequent military marksmanship performance.

Experiment 2 Research Purpose and Predictions

The purpose of this study was to explore the isolated and combined effects of fatigue on military marksmanship performance. Based on previous research exploring the effect of fatigue on performance, the following hypotheses were tested:

1. Isolated motor fatigue will result in decreased marksmanship accuracy, as measured by mean radial error, when compared to baseline.
2. Isolated cognitive fatigue will similarly result in decreased marksmanship accuracy, as measured by mean radial error, when compared to baseline.
3. Combined motor and cognitive fatigue will result in decreased marksmanship accuracy, as measured by mean radial error, when compared to baseline.
4. Simultaneous, combined motor and cognitive fatigue will have a negative, compounding effect on marksmanship performance, resulting in significantly decreased marksmanship accuracy as measured by mean radial error change scores when compared to baseline and isolated fatigue.
5. Simultaneous, combined motor and cognitive fatigue will have a negative, compounding effect on marksmanship performance, resulting in decreased discriminatory reaction

control and increased reaction time change scores when compared to baseline and isolated fatigue.

6. Simultaneous, combined motor and cognitive fatigue will have a negative, compounding effect on marksmanship speed and accuracy performance change scores, resulting in slower time and increased shots required for completion when compared to baseline and isolated fatigue conditions.

Method

Participants

An a priori power analysis was performed using G*Power 3.1.9.6 to ensure the study was adequately powered. Based on the G*Power calculation (alpha = .05, power .90), the projected sample size required was approximately N=24 (*M* age = 22.04 ± 3.22 years, male = 20) using a within-between-subjects comparison. Participants were recruited from the Army and Air Force Reserve Officers Training Corps (ROTC) to participate in the study. Participants were informed that they would use a non-immersive virtual reality marksmanship simulator and complete a physical and mentally demanding task; volunteers of this study remained naïve to the purpose and goals of this study. The University of Tennessee Institutional Review Board (UTK IRB-23-07904-XP) approved all methods and documents prior to study initiation. All participants completed an informed consent prior to study initiation.

Task and Apparatus

The data collected during each phase of testing took place in a climate-controlled research laboratory with appropriate safety equipment.

InVeris Squad Advanced Marksmanship Trainer (SAM-T)

All marksmanship tasks were completed using the InVeris SAM-T. The United States Military commonly uses the InVeris SAM-T to conduct non-immersive marksmanship training to provide realistic training in a safe and controlled environment. InVeris systems use infrared and wireless weapon technology (i.e., BlueFire) to deliver precise and robust data capture. Bluefire weapons replicate the form, fit, and function of live weapons used by the United States Military. Participants used Bluefire M4/M4A1 Rifles equipped with Aimpoint Patrol Rifle Optic Red Dot Reflex Sight and Blue Force Gear Standard Issue Vickers Sling for all tasks. A ceiling-mounted projector and shot detection camera were set 5.5 meters from the screen per the manufacturer’s specifications.

Motor Fatigue Task

To induce motor fatigue, participants completed a 30-minute, 3.22km weighted foot march on a powered NordicTrack (Commercial 1750) treadmill. The treadmill speed was programmed at 6.5 km per hour at a two percent incline. The United States Military commonly uses this pace and incline to assess Soldiers' foot march proficiency over a distance ranging from 9.67 km to 19.32km. Participants were outfitted with military uniforms and equipment, including a rucksack (20.4 kg), ammunition vest, helmet, eye protection, and gloves. Participants wore a Polar H10 chest heart rate monitor. A maximum safe heart rate was calculated for each participant, and participation was stopped immediately if the participant’s heart rate exceeded the identified limit.

Cognitive Fatigue Task

To induce isolated cognitive fatigue, participants completed a novel Stroop and Flanker task that was projected on a wall approximately 5.5 meters in front of the participant.

Participants completed 600 trials (i.e., 300 Stroop & 300 Flanker) over 30 minutes. Each cue was presented randomly at one of five locations on the screen **(Figure 6**). For the Stroop task, a color word (e.g., green, blue, yellow, red) was presented in a specified font color (e.g., green, blue, yellow, red). Identical to experiment 1, the trial was congruent if the meaning of the color word and the font color were identical, whereas the trial was incongruent if they differed. Participants were asked to identify and verbally respond to the font color (e.g., green, blue, yellow, red) of the word presented on the screen. For the flanker task, five arrows were presented in a horizontal row on the screen in front of the participant. Each cue consisted of a target stimulus (i.e., center arrow direction) and two adjacent flanker arrows on the left and right of the target stimuli. The trial was congruent if the center arrow and adjacent arrows pointed in the same direction (e.g., > > > > >), whereas the trial was incongruent if the arrow direction differed (e.g., > > < > >). Participants were asked to verbally respond, trial by trial, to the direction of the center arrow and ignore the adjacent distractor flankers. Participants were provided verbal and written instructions prior to the initiation of the task. For all Stroop and Flanker cues, the number and congruency of cues were set to 50%, and each cue was presented on the screen for 1000ms with a 2000ms pause between trials. The accuracy of responses was recorded for each Stroop and Flanker cue.

Combined Fatigue Task

To induce combined motor and cognitive fatigue, participants completed the motor and cognitive fatigue tasks simultaneously. Consistent with the isolated fatigue tasks, participants completed a 30-minute, 3.22 km weighted foot march in combination with the novel Stroop and Flanker task. The treadmill speed was programmed at 6.5 km per hour at a two percent incline. For all Stroop and Flanker cues, the number and congruency of cues were set to 50%, and each cue was

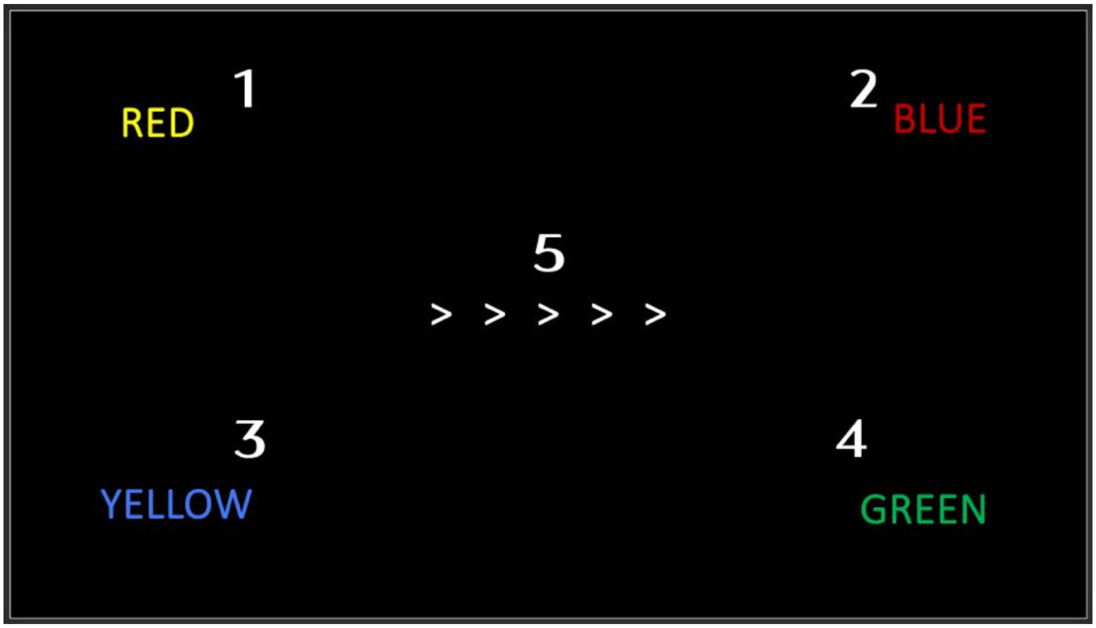


Figure 6. Possible locations of Stroop and Flanker cues.

presented randomly on the screen for 1000ms with a 2000ms pause between trials. The accuracy of responses was recorded for each Stroop and Flanker cue.

Marksmanship Tasks

Participants used Bluefire M4/M4A1 Rifles equipped with Aimpoint Patrol Rifle Optic Red Dot Reflex Sight and Blue Force Gear Standard Issue Vickers Sling for all tasks. Each task was individually programmed (e.g., targets, distance, timing) using InVeris software authoring capabilities and was presented on a simulated live-fire range environment. Prior to each engagement sequence, the following instructions were verbalized: “Lock and load one magazine, move the selector switch from safe to semi, and watch your lane.” Following completion of the engagement sequence, the following common military fire range instructions were verbalized: “Cease fire, cease fire, cease fire,” “Soldiers, clear weapons, drop magazines, place the weapon on safe, and lock the bolt to the rear.”

300-meter grouping task

The 300-meter grouping task used a standardized 25 m grouping target consisting of a single silhouette with a known center point **(Figure 7a)** and is standardized as part of the preparation of Army live-fire marksmanship tasks. Prior to task initiation, participants were informed that they would be completing a shooting task that mirrored the zeroing procedures used to prepare for live-fire range qualification operations. Participants were provided verbal and written instructions and offered an opportunity to ask questions. The 300-meter grouping task required five engagements to the center of a standardized military target. Targets were individually presented on the screen at predetermined, random locations. Once engaged (i.e., shot), the target would disappear, and a new target would appear on the screen. The task concluded when all five targets had been engaged. In order to assess performance, mean radial error (cm) and engagement time (seconds) were captured.

Discriminatory reaction task

The discriminatory reaction task used a custom E-Silhouette target (**Figure 7b**) that consisted of six icons (i.e., squares, triangles, circles) presented in various orientations and colors. Each icon had a number located in the center of the shape, ranging from one to nine. Upon task initiation, a visual, written cue was presented at the top of the screen for 4000 ms. Following a 3000 ms pause, the discriminatory reaction task target appeared on the screen in a predetermined, random location. Using the prior visual cue information, participants had to locate and identify the correct icon, color, and number combination, then engage the identified target with two consecutive shots. Each discriminatory reaction task target was visible for 5000 ms. Once engaged, the target disappeared, and a 2000 ms pause separated the subsequent visual

Figure 7. Marksmanship targets. 300-meter grouping target (a), Discriminatory reaction target (b), Speed and accuracy targets(c).

cue and shuffled the discriminatory reaction task target combination. A total of 10 cue and discriminatory reaction task target combinations were completed. Performance was assessed through total score, which was determined by how many successful engagements occurred out of 20 unique targets. Additionally, individual discriminatory reaction task target engagement time (i.e., seconds) was recorded for each trial.

Speed and accuracy task

The speed and accuracy task used static and moving targets ranging from 50 m to 250 m in distance from the participant. The task **(Figure 7c)** consisted of five static 50-m targets, one 150-m silhouette target that moved horizontally, and six static 250-m silhouette targets. Participants were informed that each target required an undisclosed number of successful engagements for it to disappear. Specifically, participants were instructed to continuously engage the target until it disappeared. Performance was assessed through the total number of shots and total time (i.e., seconds) required for completion.

Self-Report Measures

Workload

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) is a multi-dimensional workload measure comprised of six subscales (i.e., mental demand, physical demand, temporal demand, performance, effort, frustration) and has demonstrated good reliability, $\alpha = 0.71 – 0.81$ (Hart & Staveland, 1988). NASA-TLX was administered using the NASA-TLX iPad application. Participants were asked to rate their perceived workload on a scale of 0-20 anchored by bipolar descriptors (i.e., very low/ high). Each of the six subscale scores was digitally multiplied by five to transform data into a hundred-point scale for a possible total of 100 points.

Perceived Exertion

The Borg Rating of Perceived Exertion (RPE) Scale-10 (Borg CR-10) was used to measure Soldiers' perceived exertion during marksmanship tasks. Specifically, Soldiers rated their perceived exertion on a scale of 0 to 10, with 0 representing "no exertion at all" and 10 representing "maximal exertion."

Procedure

This study used a within-participant, counterbalanced method using a Latin square design. Each participant completed three visits, with seven days between visits (see **Figure 8**). On day one, participants reviewed and signed the informed consent and were randomly assigned to one of three fatigue condition sequences (i.e., motor, cognitive, combined fatigue). The researcher then provided verbal and written instructions on the pretest marksmanship tasks, fatigue condition, and posttest marksmanship tasks. Additionally, participants were fitted for all

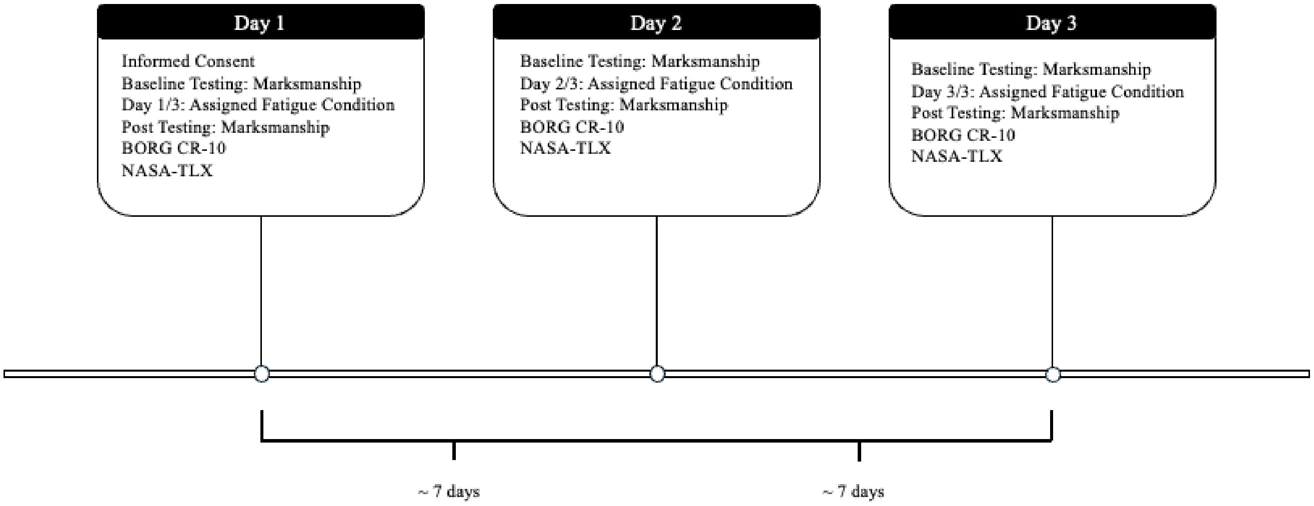


Figure 8. Schematic representation of the experimental design.

military equipment, including a weapon system, rucksack, ammunition vest, eye protection, and gloves. Once complete, participants completed the marksmanship pretest. Prior to the motor and combined fatigue tasks, participants completed a five-minute warm-up consisting of familiarization with walking on a treadmill at an assigned pace with a rucksack and weapon. Following warm-up (if assigned), participants completed their assigned fatigue task and marksmanship posttest task in succession. Upon completing the marksmanship post-test, participants completed the Borg CR-10 scale and the NASA-TLX.

For days two and three, the researcher provided verbal and written instructions on the marksmanship and fatigue task and fitted participants for military equipment. Once complete, participants completed the pretest, warm-up (if assigned), fatigue condition, posttest, Borg CR-10, and NASA-TLX, which were identical to day one.

During the experiment, the following dependent measures were measured: 300 m grouping radial error (cm), 300 m grouping engagement time (seconds), discriminatory reaction task total score (out of 20), discriminatory reaction task response time (seconds), speed and accuracy task total shots, and speed and accuracy task total time for completion (seconds). To ensure adequate fatigue, heart rate was measured using a Polar H10 chest strap, and total Stroop and Flanker error rates were captured.

Data Analysis

All data validations and statistical analyses were performed with IBM SPSS Statistics (v29, IBM Corp., Armonk, NY). Before conducting the primary analyses, data were screened for irregular values and outliers. Assumptions of normality and heteroscedasticity were tested. When normality was violated, degrees of freedom were corrected using Greenhouse-Geisser estimates if necessary. To explore the effect of fatigue on marksmanship performance, a 2 (Time: baseline, posttest) x 3 (Condition: physical fatigue, mental fatigue, combined fatigue) repeated measures ANOVA was used to compare performance. To explore the effect of fatigue on perceived workload, a one-way ANOVA with repeated measures was used to compare subjective ratings post-fatigue. Bonferroni-corrected degrees of freedom were applied during post-hoc testing, and the statistical significance threshold was set at $\alpha=.05$ for all analyses. We also determined partial eta-squared (η^2) effect sizes for omnibus ANOVAs and Cohen's *d* simple effects for pairwise comparisons.

Results

Performance Variables

300 m grouping task, mean radial error

Results from the two-way repeated measures ANOVAs **(Figure 9**) demonstrated a statistically significant main effect for Condition, $F(2,46) = 21.02$, $p < .001$, partial $\eta^2 = .478$, and

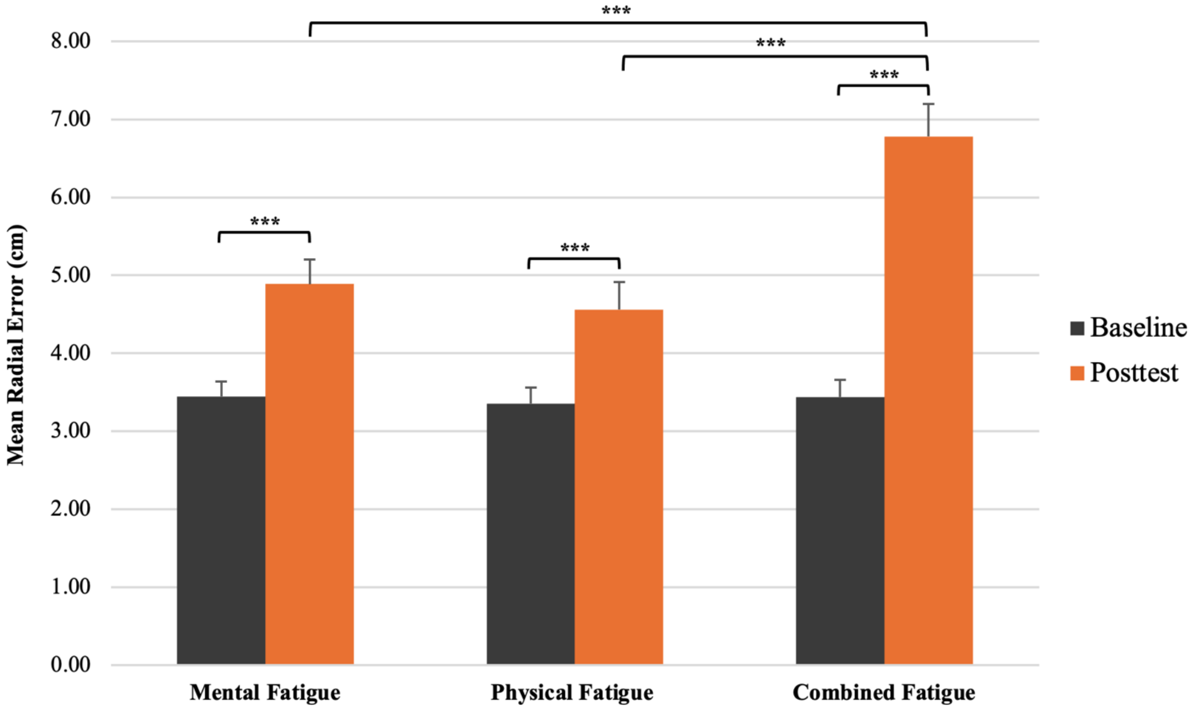


Figure 9. Mean radial error (cm) between conditions and time.

Time, $F(1,23) = 76.69$, $p < .001$, partial $\eta^2 = .769$; however, they were superseded by the time-** p <.01, *** p <.001 by-condition interaction, F(2,46) = 20.00, p = <.001, η=.465. No significant differences as a function of Condition at baseline (p =1.00). Post-hoc decomposition of this interaction revealed the combined fatigue conditions resulting in significantly lower accuracy score compared to the isolated mental ($M_{\text{diff}} = 1.89$ [1.16, 2.63], *d=2.086*) and physical fatigue conditions ($M_{\text{diff}} = 2.23$ [1.24, 3.20], *d=2.451*). Descriptive statistics (mean + standard deviation) for anticipatory reaction time and workload data for NASA-TLX subscales are presented in **Table 2**.

Discriminatory reaction task, total score

Results from the two-way repeated measures ANOVA (**Figure 10**) demonstrated a statistically significant main effect for Condition, $F(2,46) = 3.42$, $p = .041$, partial $\eta^2 = .129$ and

Table 2. Marksmanship scores and workload data (mean + standard deviation) by time and fatigue condition.

	Mental Fatigue		Physical Fatigue		Combined Fatigue	
Accuary Task	**Baseline**	**Posttest**	**Baseline**	**Posttest**	**Baseline**	**Posttest**
Accuracy (cm)	3.45 ± 0.93	4.88 ± 01.53	3.36 ± 1.00	4.56 ± 1.75	3.44 ± 1.07	6.78 ± 2.05
DRT Total Score (out of 20)	15.29 ± 2.61	12.42 ± 3.23	15.75 ± 2.07	12.42 ± 2.98	15.67 ± 2.32	10.29 ± 2.07
DRT Response Time (sec)	1.99 ± 0.39	2.24 ± 0.55	1.90 ± 0.42	2.18 ± 0.44	1.92 ± 0.33	2.32 ± 0.55
SAT Shots (#)	28.67 ± 6.32	33.21 ± 7.52	29.79 ± 7.07	34.58 ± 7.36	28.63 ± 6.29	41.08 ± 9.16
SAT Time (sec)	35.10 ± 6.59	40.45 ± 7.57	33.43 ± 7.50	40.38 ± 8.20	32.36 ± 5.19	48.64 ± 9.03
Subscales						
Mental Demand	-	56.46 ± 21.29	-	37.50 ± 25.28	-	73.13 ± 13.25
Physical Demand	-	14.17 ± 17.36	-	75.63 ± 13.30	-	77.29 ± 14.37
Temporal Demand	-	43.75 ± 25.25	-	44.79 ± 30.56	-	61.25 ± 25.16
Performance	-	25.83 ± 17.61	-	37.08 ± 18.76	-	31.04 ± 17.38
Effort	-	42.92 ± 26.90	-	74.25 ± 15.11	-	77.92 ± 13.67
Frustration	-	28.33 ± 24.52	-	38.13 ± 20.21	-	52.29 ± 19.05
BORG CR-10	-	3.25 ± 1.82	-	6.50 ± 1.59	-	6.63 ± 2.30

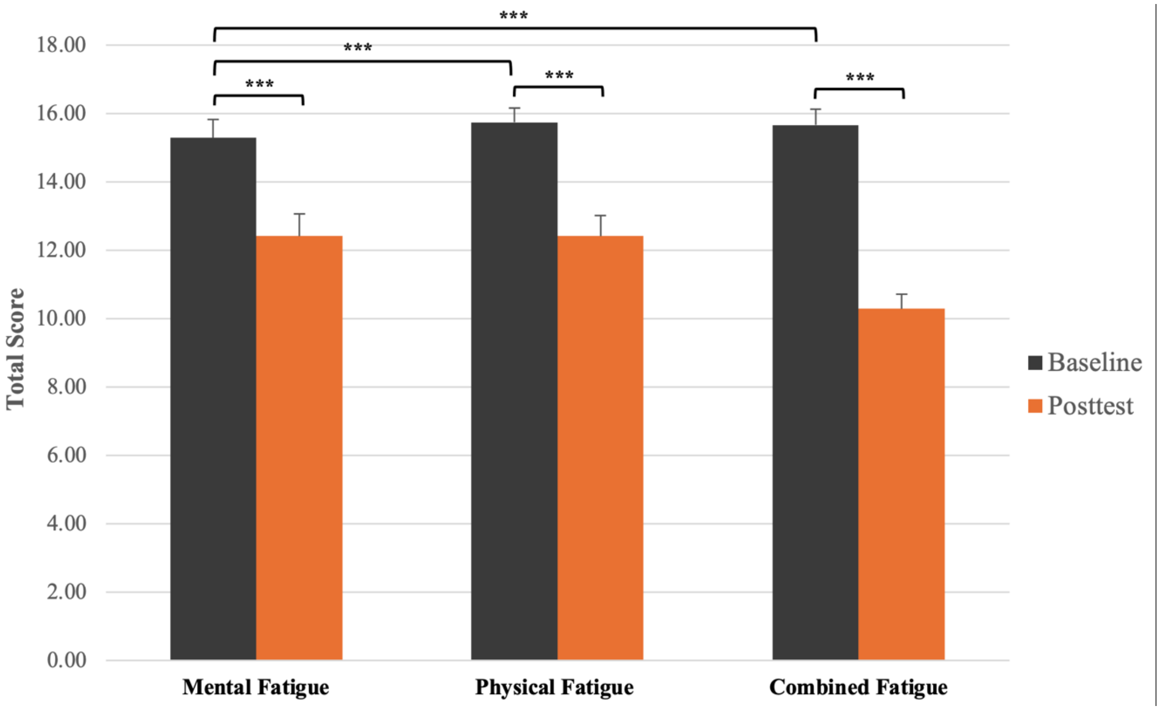


Figure 10. Average discriminatory reaction task scores between conditions and time.

Time, $F(1,23) = 339.46$, $p < .001$, partial $\eta^2 = .937$; however, they were superseded by the time-

*** $p <.001$. by-condition interaction, F(2,46) = 9.70, p = <.001, η=.297. Post-hoc testing revealed no significant differences as a function of Condition at baseline. Decomposition of this interaction revealed the combined fatigue conditions resulting in significantly discriminatory reaction scores compared to the isolated mental ($M_{\text{diff}} = 2.21$ [.586, 3.83], $d=1.371$) and physical fatigue conditions ($M_{\text{diff}} = 2.21$ [.485, 3.93], $d=1.371$). Descriptive statistics (mean + standard deviation) for anticipatory reaction time and workload data for NASA-TLX subscales are presented in **Table 2**.

Discriminatory reaction task, response time

Results from repeated measures ANOVAs (**Figure 11**) demonstrated a statistically

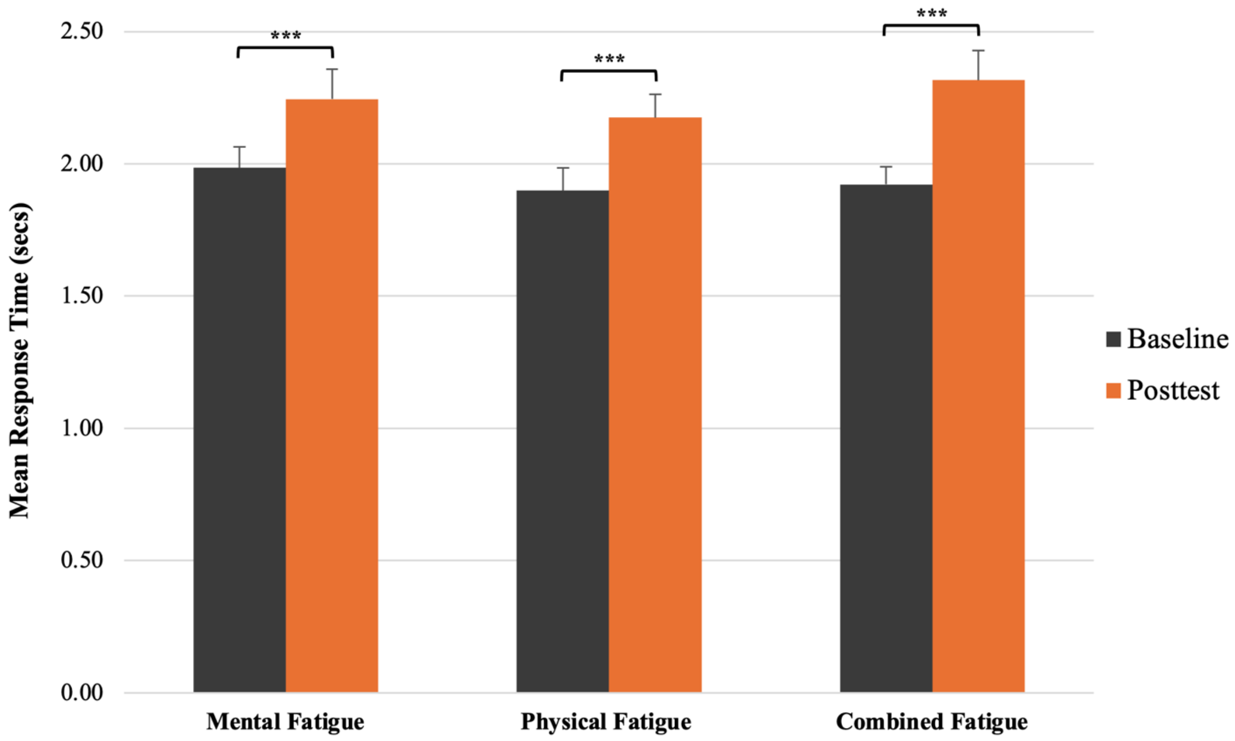


Figure 11. Average response time scores between conditions and time.
*** p <.001.

significant main effect for Time, $F(1,23) = 43.063$, $p < .001$, partial $\eta^2 = .652$. Post-hoc testing revealed no significant differences as a function of Condition at baseline. Multiple comparisons found significant differences in baseline and posttest performance for each condition. Following mental, physical, and combined fatigue, significant differences were found in response time compared to baseline (p=.001, <.001, <.001, respectively). Descriptive statistics (mean + standard deviation) for anticipatory reaction time and workload data for NASA-TLX subscales are presented in **Table 2.**

Speed and accuracy task, total time to completion

Results from the two-way repeated measures ANOVA (**Figure 12**) demonstrated a statistically significant main effect for Condition $F(2,46) = 4.13$ $p = .022$, partial $\eta^2 = .152$ and

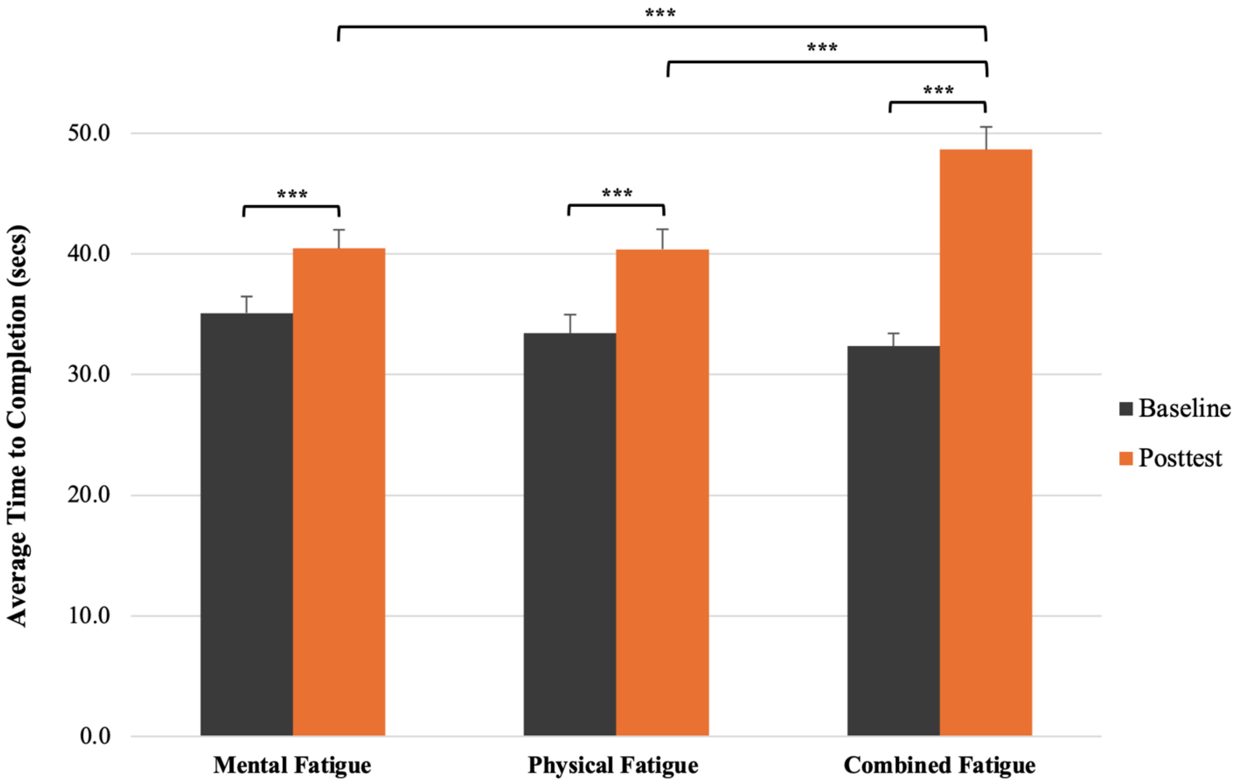


Figure 12. Average time to completion between conditions and time.
*** *p* <.001.

Time, *F*(1,23) = 102.68, *p* < .001, partial η^2 = .817; however, they were superseded by the time-by-condition interaction, F(2,46) = 45.22, p = <.001, η=.663. No significant differences as a function of Condition at baseline (*p* =1.00). Post-hoc decomposition of this interaction revealed that the combined fatigue conditions required significantly more time to complete the task compared to the isolated mental (M_{diff} = 8.19 [3.46, 12.92], *d=2.692* and physical fatigue conditions (M_{diff} = 8.26 [4.35, 12.16], *d=2.716*). Descriptive statistics (mean + standard deviation) for anticipatory reaction time and workload data for NASA-TLX subscales are presented in **Table 2**.

Speed and accuracy task, shots required for completion

A two-way repeated measures ANOVA **(Figure 13**) demonstrated a statistically significant main effect for Condition, *F*(2,46) = 3.71, *p*=.032, partial η^2 = .139, and Time, *F*(1,23) = 205.741, *p* <.001, partial η^2 = .899. however, they were superseded by the time-by-condition interaction, F(2,46) = 36.00, p = <.001, η=.610. No significant differences as a function of Condition at baseline (*p* =1.00). Post-hoc decomposition of this interaction revealed the combined fatigue conditions required significantly more time to complete the task compared to the isolated mental (M_{diff} = 7.88 [2.56, 13.19], *d=3.036*) and physical fatigue conditions (M_{diff} = 6.50 [2.39, 10.61], *d=2.505*). Descriptive statistics (mean + standard deviation) for anticipatory reaction time and workload data for NASA-TLX subscales are presented in **Table 2**.

Workload Scores

A repeated-measures ANOVA was performed to evaluate the effect of each fatigue condition on NASA-TLX Workload Scores and Rate of Perceived Exertion. Results revealed a statistically significant main effect for self-reported *mental demand*, F(2,46) = 15.645, *p* =<.001, η^2 =.397, *physical demand*, F(2,46) = 310.63 *p* =<.001, η^2 =.931, *temporal demand*, F(2, 46) = 4.71, p=.014, η^2 =.170, *effort*, F(2,46) = 36.04, *p* =<.001, η^2 =.610, *frustration*, F(2,46) = 15.014, *p* =<.001, η^2 =.395 and rate of perceived exertion. F(2,46) = 29.67, p <.001, η^2 =.563. Pairwise comparisons indicated the combined fatigue condition increased mental demand as compared to mental (*p* =.003) and physical fatigue conditions (*p* <.001). Additionally, significant differences were found between the mental and physical conditions (*p* =.025). As for self-reported physical demand, pairwise comparisons indicated that the physical and combined fatigue conditions increased physical demand compared to the mental fatigue conditions (*p* <.001). No differences were found between physical and combined conditions (*p* =1.00). Comparisons for self-reported temporal demand indicated that combined fatigue conditions increased temporal demand

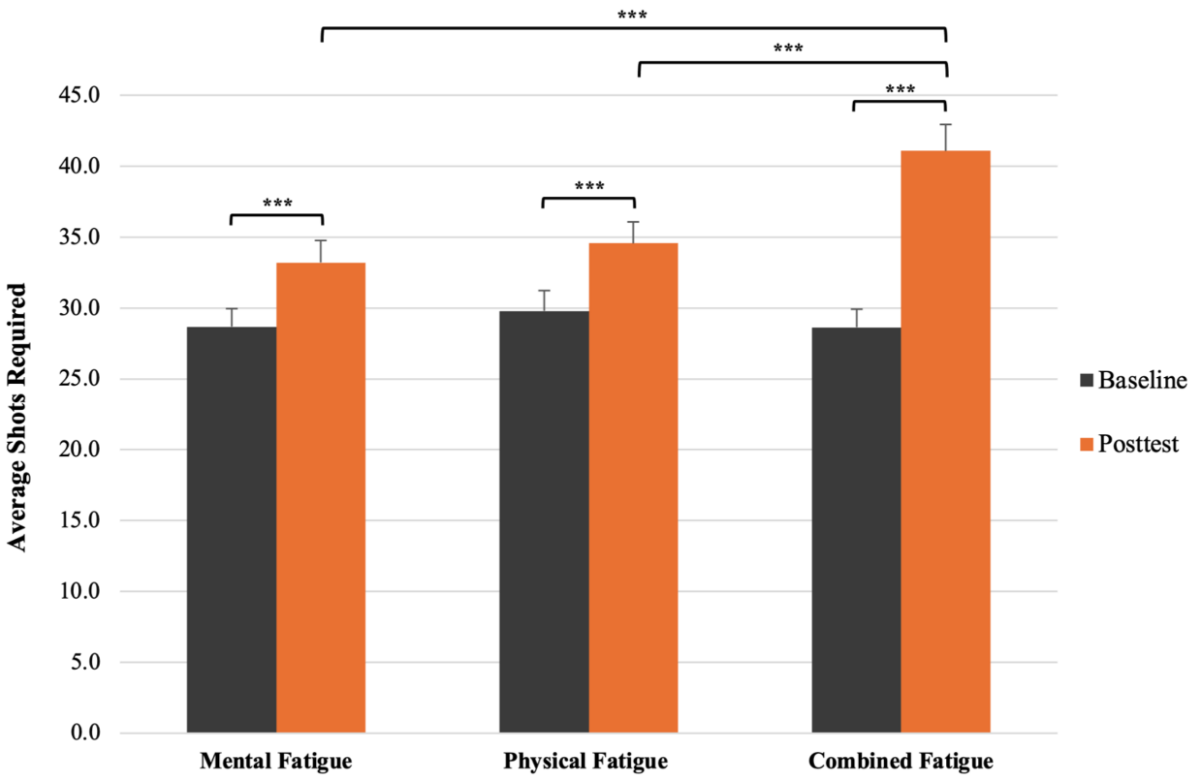


Figure 13. Average ammunition for completion between conditions and time.
*** *p* <.001.

compared to the mental (p=.037) and physical fatigue conditions (*p* =.028*)*. No differences were found between mental and physical conditions (*p* =1.00). For self-reported effort required, comparisons revealed that the physical and combined fatigue conditions required increased effort compared to the mental fatigue (*p*'s<.001). No differences were found between physical and combined conditions (*p* =*.836*). Comparisons of self-reported frustration revealed that combined fatigue increased frustration levels compared to the mental (*p*<.001) and physical fatigue (*p*=.003) conditions in isolation. No differences were found between mental and physical fatigue conditions (*p*=.184). Lastly, comparisons of the rate of perceived exertion indicated that the physical and combined fatigue conditions increased the perceived rate of exertion compared to mental fatigue in isolation (*p's* <.001). No significant differences were found between physical and combined fatigue (*p*=1.00).

Experiment 2 Brief Discussion

The results of this study provide meaningful insight into the isolated and combined effects of physical and cognitive fatigue on military marksmanship performance. These findings align with the growing body of literature demonstrating the negative effects of fatigue on both motor and cognitive performance. Furthermore, it extends the understanding of fatigue by highlighting the compounding effect of exposure to multiple simultaneous fatiguing tasks. The following section summarizes and interprets the present experiment's results.

Performance Variables

Isolated Motor and Cognitive Fatigue

As predicted, isolated motor, cognitive, and combined fatigue each independently impaired marksmanship performance. These findings support the negative impact of fatigue on marksmanship performance. The observed decrements in performance following isolated fatigue were evident across all measured variables and underscored the pervasive impact of fatigue regardless of origin. Corroborating previous research, our results demonstrate that exposure to physically demanding tasks impairs motor skills necessary for effective marksmanship performance (Jarorski et al., 2015). Additionally, exposure to cognitively fatiguing tasks (i.e., response inhibition, selective attention, visual tracking, scanning), similar to tasks found in this study, may deplete common resource pools of attention necessary for effective and efficient decision-making (Buckely et al., 2022). However, the results of the current study demonstrate decreased marksmanship performance (i.e., accuracy and precision), which is contrary to previous findings, which reported mental fatigue had limited to no effect on marksmanship accuracy, hit percentage, and precision compared to a control condition (Head et al., 2017).

Combined Motor and Cognitive Fatigue

The most notable finding of this study is the effect of combined motor and cognitive fatigue on marksmanship performance. These effects were most apparent in the marked decrease in marksmanship accuracy, prolonged response times, and substantial increase in total time to completion and shots required for task completion. These findings suggest that simultaneous exposure to motor and cognitive fatigue exacerbates deficits observed in the isolated fatigue conditions but, more importantly, introduces a performance deterioration greater than the sum of its parts. This compounded effect may be understood through the lens of resource depletion theories, which posits that motor and cognitive tasks compete for a limited, shared pool of attentional resources, and the number of available resources may be insufficient to meet the demands of each, resulting in a significant decline in overall performance (Kahneman, 1973; Marcora et al., 2009). The findings of this study suggest that structural or capacity interference occurred when competing demands (i.e., combined physical and mental fatigue) exceeded available attentional resources, resulting in deteriorated marksmanship accuracy, discriminatory reaction control, response time, and marksmanship efficiency.

Implications for Military Populations

Given the significant negative impact of combined fatigue exposure on marksmanship performance, military professionals may benefit from an integrated approach to nesting fatigue in training by integrating fatiguing protocols while executing military tasks that simulate the expected combat environment. While further research is needed to validate these findings, future training that simulates the combined demands of warfare could better prepare Soldiers for the realities of the battlefield, where exposure to numerous prolonged fatiguing events occurs regularly. Additionally, these results suggest that monitoring and managing fatigue in real time could be critical for prolonged military operations that require the maintenance of high-level performance. Technologies, surveillance tools, and effective screening protocols may help leaders and Soldiers prevent, recognize, or mitigate the effects of fatigue; tools that could prove invaluable in preserving motor and cognitive skills in demanding environments.

Limitations and Future Research

While the findings of this current study expand our knowledge of fatigue's impact on performance, it is important to acknowledge its limitations and how those limitations establish a need for additional research. While beneficial for safety and logistics, non-immersive virtual reality does not fully replicate the complexities and stressors of live-fire operations. Future research should utilize more ecologically valid methods and explore the effect of simultaneous, combined fatigue in live-fire and field operations to validate and expand these findings.

Moreover, the findings of this study are limited to the immediate effects of fatigue on performance, and a significant gap remains in research exploring the effect of combined fatigue on skill acquisition and transfer of learning. Future inquiries should investigate the short- and long-term impact of repeated exposure to combined fatigue conditions on skill acquisition and the transfer of learning to real-world environments. Continued use of STEs affords the opportunity to combine military-specific targets and tasks, allowing further investigation into the adaptability of what was learned during training and how it transfers to real-world environments such as close combat marksmanship (i.e., room cleaning) or response inhibition and selective attention (i.e., friendly vs. enemy discrimination).

Conclusion

The findings of this study demonstrate the independent and combined effects of motor and cognitive fatigue on military marksmanship performance. Furthermore, these findings highlight the need for comprehensive training programs across disciplines (e.g., sports, military, aviation, medicine) that address the challenges of combined fatigue while facilitating motor and cognitive performance, learning, and the transfer of learning to real-world environments. By integrating these results, leaders, educators, and Soldiers alike can prepare to perform effectively under the demanding conditions they must overcome in the field.

CHAPTER THREE: EXPERIMENT THREE:

EFFECT OF COMBINED ACUTE STATE MOTOR AND COGNITIVE FATIGUE ON MOTOR PERFORMANCE, LEARNING, AND TRANSFER IN A SIMULATED COMBAT ENVIRONMENT

Abstract

During sustained military operations, Soldiers experience high levels of physical, cognitive, operational, and environmental demands such as physical and mental fatigue, inherent danger, sleep deprivation, limited resources, and potentially stressful incidents. Research has established that physical and mental fatigue can negatively impact immediate marksmanship performance, affecting accuracy, decision-making, and movement efficiency. However, the effects of simultaneous combined fatigue (i.e., physical, mental) on skill acquisition and transfer of learning in military settings remain underexplored. Thus, this study aimed to explore the effect of combined fatigue on military marksmanship performance, learning, and transfer to a simulated combat environment. Twenty-eight participants (*M* age = 20.43 ± 0.92 years, male = 23) were randomly assigned to a fatigued or non-fatigued practice condition. The fatigue practice group completed a novel, combined fatigue task prior to marksmanship practice blocks. The non-fatigue practice group completed marksmanship practice following a seated rest period. Marksmanship performance was assessed in a non-immersive virtual reality platform (i.e., InVeris) across multiple phases, including baseline, immediate retention, delayed non-fatigue and fatigue retention tests, and a transfer task. Results from independent samples *t*-test s revealed statistically significant differences between practice groups, with the non-fatigue practice group demonstrating superior marksmanship accuracy during non-fatigued retention testing (*p*=.049). Furthermore, significant differences were found between practice groups, with the fatigue practice group demonstrating superior marksmanship accuracy (*p* =.006), faster response time (*p* =.008), and higher qualification scores (*p* =.009) at fatigued retention testing. Most notably, significant differences were found between practice groups, with the fatigue practice group

demonstrating superior marksmanship accuracy (*p* <.001) and response time (*p* =.010) during the fatigued transfer task. These findings suggest that training under conditions that mirror actual performance environments leads to superior outcomes across all measured objective performance metrics.

Introduction

In modern warfare, Soldiers are expected to perform under significant physical and mental strain, executing a wide range of complex tasks where the margin for error is slim. Previous research has demonstrated the negative effects of physical, mental, and combined fatigue on military marksmanship performance (Vrijkotte et al., 2016), particularly tasks requiring accuracy and precision (Ito et al., 1999), judgment and rapid decision-making (Head et al., 2017), and movement efficiency within a tactical setting (Gil-Cosano et al., 2019). Mental and physical fatigue have been identified as critical factors capable of compromising operational effectiveness. Despite extensive research on the effects of fatigue in isolation, relatively little is known about the combined effect of physical and mental fatigue on performance, skill acquisition, and transfer of learning of critical military tasks. Understanding how fatigue affects these domains is vital in developing training and practice to optimize Soldier performance on the battlefield.

One avenue capable of addressing these challenges lies in the development of training using well-established motor and cognitive behavior strategies. Research has consistently demonstrated that skill learning and transfer to real-world environments are highly specific to the conditions under which these tasks are practiced (Proteau, 1992). In order to maximize military skill acquisition and transfer, leaders and Soldiers alike must create training environments that incorporate the sensory, cognitive, and environmental conditions (Proteau, 1992; Lee, 1988; Wright & Shea, 1991) Soldiers will face in a contested environment. Additionally, training should integrate fatigue as a core element, as Soldiers rarely perform combat-related tasks in a fully rested state. In order to create positive transfer of learning (i.e., prior exposure improves the performance of a given task [Magill & Anderson, 2021]) to combat environments, training must incorporate similar characteristics in which the skill is being executed (Thorndike, 1914). Designing such environments provides an opportunity to investigate the flexibility and adaptability of skills acquired in practice and their transfer to real-world environments (Weiss et al., 2014; Wulf, 2007).

While live, real-world training is the gold standard of performance, learning, and transfer, numerous constraints (e.g., funding, safety, time, logistics, maintenance) inhibit consistent real-world practice of certain tasks. These constraints have prompted military entities to leverage emerging technologies to teach and evaluate military performance (Smith & Hagman, 2003). Advances in the development of virtual environments, such as synthetic training environments (STEs), enable military entities to overcome many of the inherent challenges of real-world training. Due to their controlled nature, STEs provide an opportunity to collect comprehensive data across multiple performance and learning domains (e.g., technical, tactical, physiological, cognitive) while significantly reducing the risk of injury and mitigating typical training constraints. More importantly, STEs offer the ability to merge virtually generated targets with the physically and mentally demanding tasks found in the performance conditions (Gray, 2017). Such capacity allows designing scenarios in a controlled, synthetic environment that optimizes training through evidence-based motor behavior principles while allowing for further investigation of how effective skills learned in these environments adapt and transfer to real-world combat scenarios (Weiss et al., 2014; Wulf, 2007).

While existing literature provides a promising future for this line of inquiry, a significant gap exists in the impact of combined fatigue on task performance, learning, and transfer to real-world environments. More specifically, to our knowledge, no study has explored the complex interplay of performing and learning under combined fatigue nor the transfer of learned skills to combat-specific environments. Thus, this study aimed to explore the effect of combined fatigue on military marksmanship performance, learning, and transfer to a combat-specific scenario. Based on previous research exploring the effect of combined fatigue on performance, the following hypotheses were tested:

1. Participants in the combined fatigue practice group will demonstrate decreased marksmanship performance, as measured by radial error, qualification scores, and response time during the immediate retention task, compared to the non-fatigued practice group.
2. Participants in the combined fatigue practice group will demonstrate decreased marksmanship performance compared to the non-fatigue practice group, as measured by mean radial error, total qualification scores, and mean response time during the non-fatigued delayed retention test.
3. Compared to the non-fatigue practice group, participants in the combined fatigue practice group will demonstrate increased marksmanship performance via measures of radial error, qualification scores, and response time during the fatigued delayed retention test.

4. Compared to the non-fatigue practice group, participants in the combined fatigue practice group will demonstrate superior marksmanship performance as measured by mean radial error and response time during the fatigued transfer task.
5. Compared to the non-fatigue practice group, combined fatigue practice group participants will report increased perceived exertion during practice and immediate retention tasks.
6. Participants in the combined fatigue practice group will report decreased perceived exertion during the non-fatigued and fatigued retention tests and the fatigued transfer task compared to the non-fatigue practice group.
7. Due to the novelty of the protocol and the lack of previous research to frame predictions, the NASA-TLX results will be exploratory, and no predictions will be made on the subscales.

Method

Participants

Participants, N+28 (*M* age = 20.42 ± 0.92 years, male = 23), were recruited from the Army and Air Force Reserve Officers Training Corps (ROTC) to participate in the study. Participants were informed that they would use a non-immersive virtual reality marksmanship simulator and complete a physical and mentally demanding task; volunteers of this experiment remained naïve to the purpose and goals of this study. Methods and documents were approved by the UTK IRB prior to study initiation. All participants completed a written informed consent prior to study initiation.

Task and Apparatus

The data collected during each testing phase occurred in a climate-controlled research laboratory with appropriate safety equipment.

InVeris Squad Advanced Marksmanship Trainer (SAM-T)

Similar to experiment 2, all marksmanship tasks were completed using the InVeris SAM-T. The United States Military commonly uses the InVeris SAM-T to conduct non-immersive marksmanship training to provide realistic practice in a safe and controlled environment. InVeris systems use infrared and wireless weapon technology (i.e., BlueFire) to deliver precise and robust data capture. Bluefire weapons replicate the form, fit, and function of live weapons used by the United States Military. Participants used Bluefire M4/M4A1 Rifles equipped with standard-issue iron sight optics. A ceiling-mounted projector and shot detection camera were set approximately 5.3 meters from the screen per the manufacturer's specifications.

Combined Fatigue Task

To induce simultaneous motor and cognitive fatigue, participants completed a 15-minute foot march while concurrently completing a novel 15-minute Stroop and Flanker Task. To induce motor fatigue, participants completed a weighted foot march on a powered treadmill. The treadmill speed was programmed at 6.5 km per hour at a two percent incline. Participants were outfitted with military uniforms and equipment, including a rucksack (20.4 kg), ammunition vest, helmet, eye protection, and gloves. Additionally, a Polar H10 chest heart rate monitor was used throughout. A maximum safe heart rate was calculated using an age-based formula (220 – age) for each participant, and participation was stopped immediately if the participant's heart rate exceeded the identified limit. To induce concurrent cognitive fatigue, participants completed a novel Stroop and Flanker task on a display situated at eye level, approximately 90 cm from the participant. Participants verbally responded to 300 trials (150 Stroop & 150 Flanker) over 15 minutes. Cues were presented on the screen for 1000 ms with a 2000 ms pause between trials. Identical to methods used in experiments 1 and 2, a color word (e.g., green, blue, yellow, red) was presented in a specified font color (e.g., green, blue, yellow, red) during the Stroop task. The trial was congruent if the meaning of the color word and the font color were identical, whereas the trial was incongruent if they differed. Participants were asked to identify and verbally respond to the font color (e.g., green, blue, yellow, red) of the color word on the screen. Identical to the methods used in experiment 2, five arrows were presented on the screen during the flanker task. Each cue consists of a target stimulus (i.e., center arrow direction) and two adjacent flanker arrows on the left and right of the target stimuli. The trial was congruent if the center arrow and adjacent arrows pointed in the same direction, whereas the trial was incongruent if the arrow directions differed. Participants were asked to verbally respond, trial by trial, to the direction of the center arrow and ignore the adjacent distractor flankers. For all Stroop and Flanker cues, the number and congruency of cues were set to 50%. The accuracy of responses was recorded for each Stroop and Flanker cue.

Marksmanship Task

The marksmanship tasks were completed in a controlled laboratory space (7.31 m x 7.31 m) using the InVeris SAM-T for each task phase during the experiment. The projected simulation mirrored Army specifications commonly used for indoor simulation-based training. Participants were provided verbal and written instructions prior to task initiation. The marksmanship task consists of two phases: (1) an accuracy task and (2) the Army Weapons

Qualification Course. The United States Army commonly uses each task to determine individual weapon proficiency. For the accuracy task, individuals were required to engage a standard Army A8 zeroing target (**Figure 14**). Five targets were engaged with one shot each for a total of five accuracy-based engagements. This was followed by the Army Weapons Qualification Course, consisting of 40 pop-up targets from five shooting positions (e.g., standing unsupported, prone unsupported, prone supported, kneeling supported, and standing supported. Target distances ranged from 50m to 300m and were exposed individually or in groups. Target type, exposure time, distance, and grouping can be found in the Appendix. Data was captured using InVeris Marksmanship Software. For the accuracy task, radial error (cm) was measured for each shot. For the Army Qualification Course, dichotomous (hit/miss) data were captured using the Army Qualification Score Sheet (See Appendix).

Figure 14. Army A8 zeroing target.

Transfer Task

The transfer task was completed in a controlled laboratory environment using the InVeris SAM-T to create a novel room-clearing scenario. The environment consisted of an entryway, an open corridor, and a wall projected simulation approximately 5.5 m from the entrance. Participants were equipped with military uniforms and equipment, including an ammunition vest, helmet, eye protection, wireless Bluetooth headphones, and gloves. Participants wore a Polar H10 chest heart rate monitor throughout the task. Prior to task initiation, participants were provided instructions on the task. Auditory stimuli (e.g., “Prepare to breach,” forceful door entry, gunfire, screaming) were played via an Aftershock wireless Bluetooth headset to simulate a combat environment. Following the forceful entry auditory stimulus (e.g., door kicked in), participants traversed the entryway and immediately engaged enemy targets while withholding fire from friendly or civilian non-targets within the simulation (see **Figure 15**). For each encounter, an image of two enemy targets and two civilian non-targets was projected on the screen (see **Figure 16**). Custom targets were created with embedded physical image overlays to capture response time, marksmanship accuracy (mean radial error), and total time to task completion.

Self-Report Measures

Workload

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) is a multi-dimensional workload measure comprised of six subscales (i.e., mental demand, physical demand, temporal demand, performance, effort, frustration) and has demonstrated good reliability, $\alpha = 0.71 – 0.81$ (Hart & Staveland, 1988). NASA-TLX was administered using the

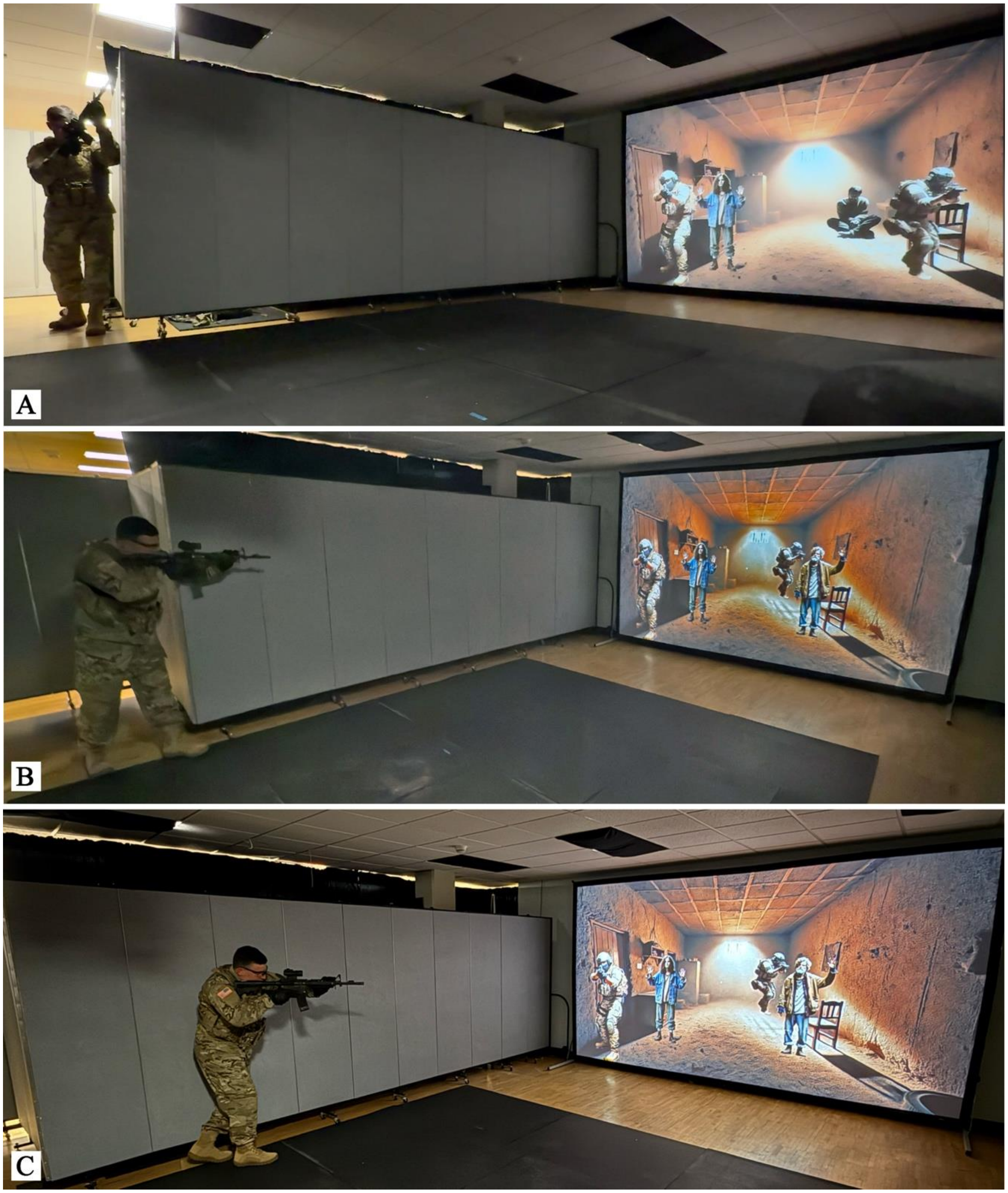


Figure 15. Transfer task sequence. A) Starting position. Initiation of the audio sequence marks the start of the transfer task; B) Following the breach audio, participants enter the room and engage with the targets; C) Transfer task completed following four engagements (i.e, shots).

Figure 16. Transfer task targets.

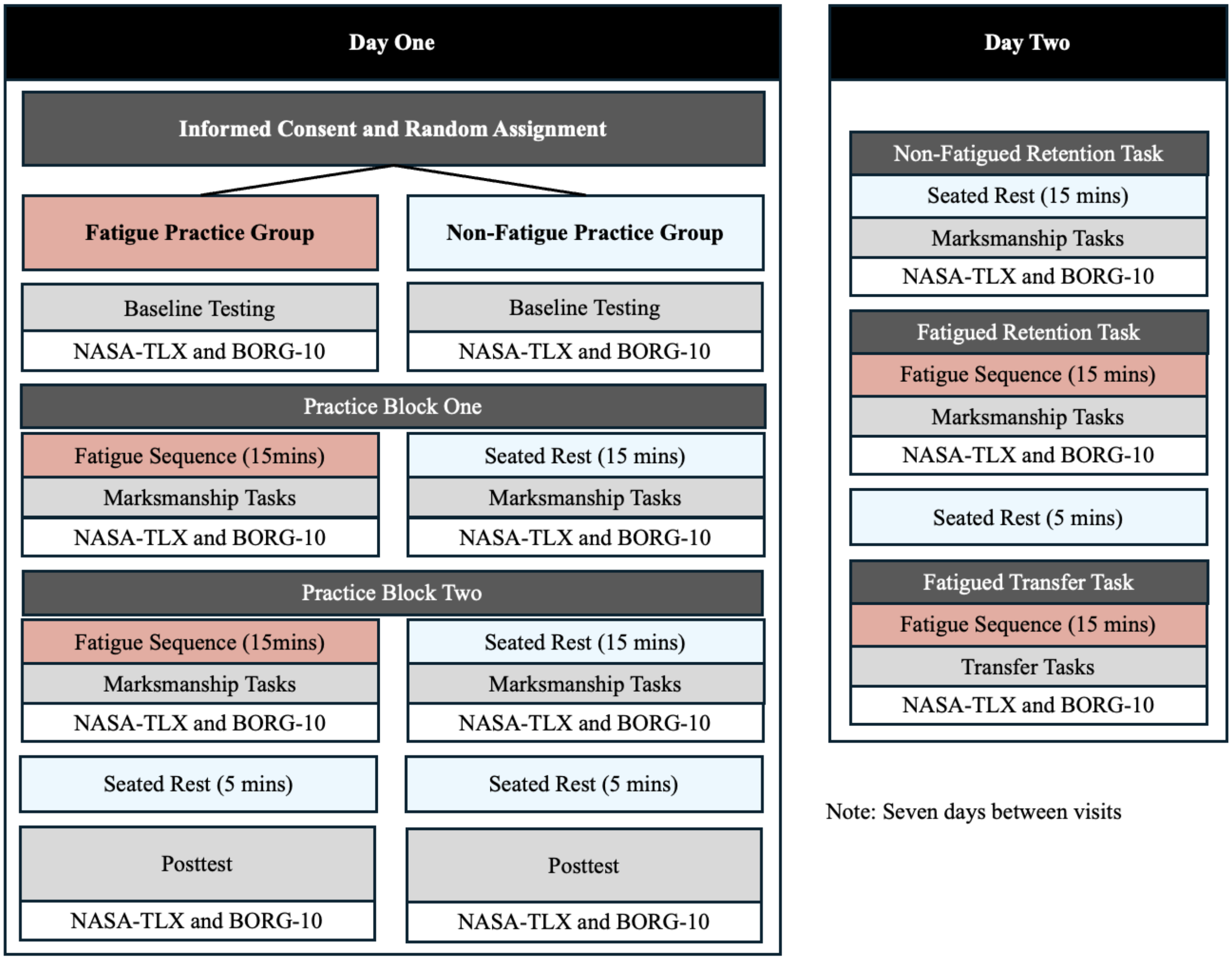
NASA-TLX iPad application. Participants were asked to rate their perceived workload on a scale of 0-20 anchored by bipolar descriptors (i.e., very low/ high). Each of the six subscale scores was digitally multiplied by five to transform data into a hundred-point scale for a possible total of 100 points.

Perceived Exertion

The Borg Rating of Perceived Exertion (RPE) Scale-10 (Borg CR-10) was used to measure Soldiers' perceived exertion during marksmanship tasks. Specifically, Soldiers rated their perceived exertion on a scale of 0 to 10, with 0 representing "no exertion at all" and 10 representing "maximal exertion."

Procedure

Participants were randomly assigned to one of two groups (i.e., non-fatigued practice, fatigued practice) using a blocked randomization approach with a block size of four. Each participant participated in the study for two days, with seven days between sessions (**Figure 17**).



Note: Seven days between visits

Figure 17. Schematic representation of the experimental design.

Day one consisted of a marksmanship pretest, marksmanship practice (i.e., normal, fatigued), and a post-test. Day two consisted of a non-fatigued marksmanship retention test, a fatigue marksmanship retention test, and a fatigued transfer marksmanship test. The following dependent measures were captured during the experiment: radial error (RE), Army Qualification Score (AQS), response time (RT), the National Aeronautics and Space Administration Task Load Inventory (NASA TLX), and the Borg Category-Ratio 10 (Borg CR-10).

On day one, participants completed an intake demographics survey before the marksmanship pretest. Following task instructions, participants completed the marksmanship pretest (i.e., accuracy and Army qualification) and the NASA-TLX. Participants were then assigned practice trials by group. The Fatigued Practice (FP) group completed two consecutive blocks of practice, which consisted of a combined fatigue task (i.e., 15-minute foot march while concurrently completing a novel 15-minute Stroop and Flanker Task), followed by a trial of the marksmanship task (i.e., marksmanship accuracy and Army qualification). The non-fatigued practice (NFP) group completed two consecutive blocks of practice. Each block consisted of a fifteen-minute seated rest followed by a trial of the marksmanship task (i.e., accuracy and Army qualification). Following a five-minute break, participants completed the post-test(i.e., marksmanship task) and the NASA-TLX and Borg CR-10. In order to ensure adequate recovery was achieved, a minimum of seven days was required between testing sessions. On day two, all participants completed a non-fatigued marksmanship retention test followed by the NASA-TLX and Borg CR-10. All participants then completed the 15-minute combined fatigue protocol, followed by a marksmanship retention task (i.e., accuracy and Army qualification) and NASA-TLX and Borg CR-10. Finally, all participants completed a fatigued transfer task and the NASA-

TLX and Borg CR-10. Upon completion, Participants were thanked for their participation and returned all issued equipment used during the experiment.

Data Analysis

All data validations and statistical analyses were performed with IBM SPSS Statistics (v29, IBM Corp., Armonk, NY). An a priori power analysis was performed using G*Power 3.1.9.6 to ensure the study was adequately powered. Based on the G*Power calculation with effects sizes from performance measures (i.e., accuracy; response time) from previous experiments, alpha = .05, power .90, the projected sample size required was approximately N=28 using a between-subjects comparison (test family = F; groups = 2; measurements = 5; correlation among repeated measures = 0.5; non-sphericity correction = 1). Before conducting the primary analyses, data were screened for irregular values and outliers. Assumptions of normality and heteroscedasticity were tested. When normality was violated, degrees of freedom were corrected using Greenhouse-Geisser estimates if necessary. To explore the effect of practice conditions on marksmanship performance (e.g., accuracy, response time), an independent samples *t*-test was conducted at baseline, post-test, non-fatigued retention test, fatigued retention test, and transfer test. For all *t*-test, all assumptions of normality and homogeneity of variance were tested. To explore rates of perceived effort during practice, a 2 (Time: practice block 1, practice block 2) x 2 (Group: non-fatigue, fatigue practice) repeated measures ANOVA was used. Bonferroni-corrected degrees of freedom were applied during post-hoc testing, and the statistical significance threshold was set at α=.05 for all analyses. We also determined partial eta-squared (η^2) effect size thresholds for omnibus ANOVAs and Cohen’s d thresholds for pairwise comparisons, defining small, medium, and large effects as 0.01, 0.06, and 0.14, respectively (Cohen, 1998).

Results

Performance Variable

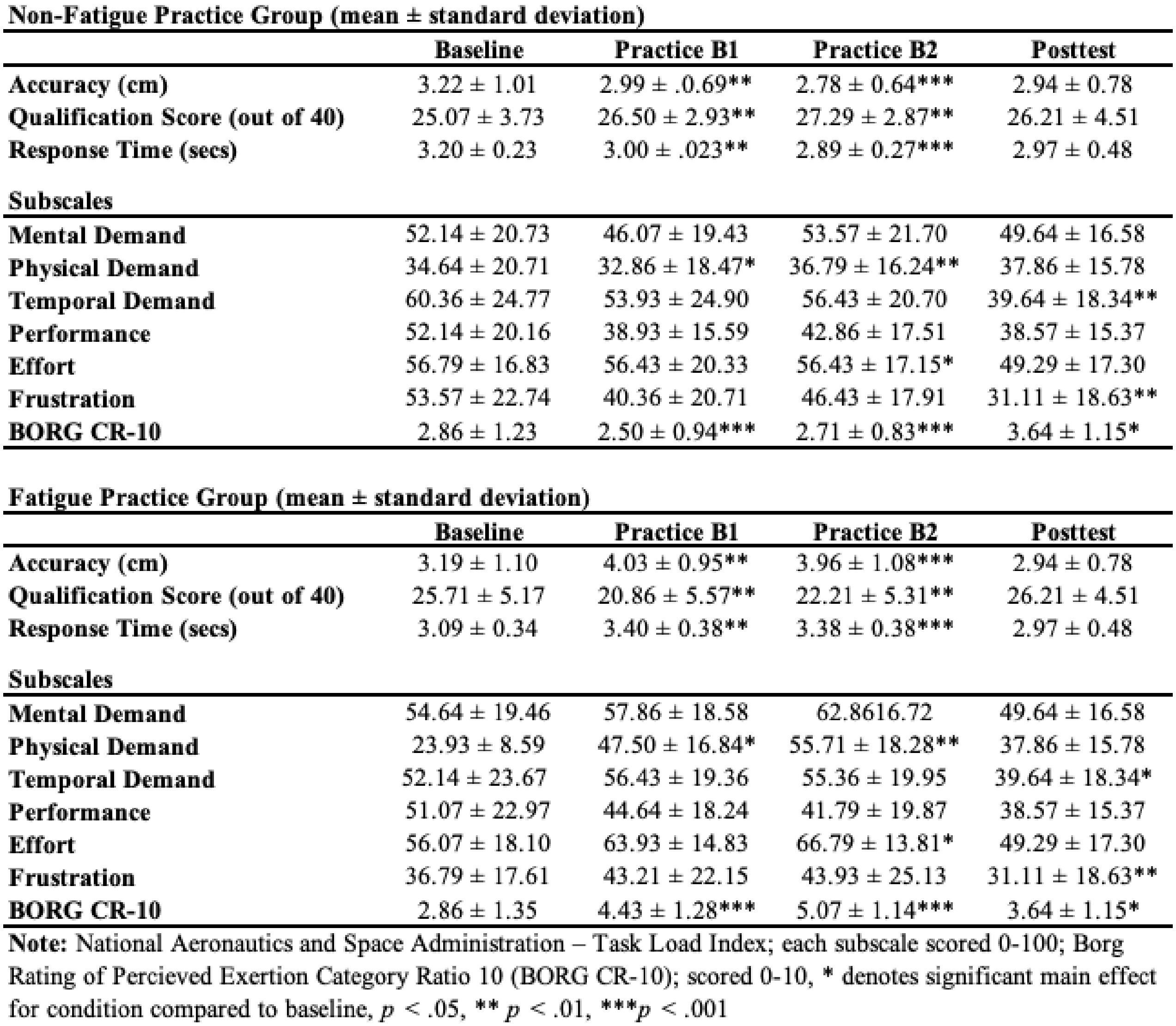
Baseline Marksmanship Performance and Workload Scores

Independent sample *t*-tests were conducted to assess the difference in marksmanship performance, self-reported workload, and rate of perceived exertion for the fatigue and non-fatigue practice groups. No differences were found for baseline marksmanship accuracy (p=.938), response time (p=.329*)*, or qualification scores *(*p=.709*).* Additionally, no significant differences were found for self-reported workload or rate of perceived exertion. Descriptive statistics (mean, standard deviation) for the marksmanship performance and workload data for NASA-TLX subscales are presented in **Table 3**.

Practice Performance, Rate of Perceived Exertion, and Workload Scores

Repeated measures ANOVA demonstrated a statistically significant main effect of practice group for marksmanship accuracy F(1,26)=484.31, p =.002, partial η^2 = .325; response time F(1,26) = 14.310, p <.001, partial η^2 =.355; total qualification score F(1,26) = 11.02, p=.003, partial η^2 = .298; and rate of perceived effort F(1,26) = 31.00, p <.001, partial η^2 = .544. Post-hoc decomposition indicated that the fatigue practice condition resulted in decreased accuracy (M_{diff} = 1.110, [.464, 1.750], d=1.00), slower response time (M_{diff} = .447, [.204, .690], d=1.01), lower total qualification scores (M_{diff} = 5.36, [2.041, 8.674], d=0.887), and increased reported perceived exertion (M_{diff} = 2.143, [1.352,2.934], d=1.488), when compared to the non-fatigue practice group. Additionally, independent sample *t*-tests were conducted to assess the

Table 3. Baseline, practice, and posttest performance and workload scores (mean + standard deviation) by time and fatigue condition.



Non-Fatigue Practice Group (mean ± standard deviation)

	Baseline	Practice B1	Practice B2	Posttest
Accuracy (cm)	3.22 ± 1.01	2.99 ± .0.69**	2.78 ± 0.64***	2.94 ± 0.78
Qualification Score (out of 40)	25.07 ± 3.73	26.50 ± 2.93**	27.29 ± 2.87**	26.21 ± 4.51
Response Time (secs)	3.20 ± 0.23	3.00 ± .023**	2.89 ± 0.27***	2.97 ± 0.48
Subscales				
Mental Demand	52.14 ± 20.73	46.07 ± 19.43	53.57 ± 21.70	49.64 ± 16.58
Physical Demand	34.64 ± 20.71	32.86 ± 18.47*	36.79 ± 16.24**	37.86 ± 15.78
Temporal Demand	60.36 ± 24.77	53.93 ± 24.90	56.43 ± 20.70	39.64 ± 18.34**
Performance	52.14 ± 20.16	38.93 ± 15.59	42.86 ± 17.51	38.57 ± 15.37
Effort	56.79 ± 16.83	56.43 ± 20.33	56.43 ± 17.15*	49.29 ± 17.30
Frustration	53.57 ± 22.74	40.36 ± 20.71	46.43 ± 17.91	31.11 ± 18.63**
BORG CR-10	2.86 ± 1.23	2.50 ± 0.94***	2.71 ± 0.83***	3.64 ± 1.15*

Fatigue Practice Group (mean ± standard deviation)

	Baseline	Practice B1	Practice B2	Posttest
Accuracy (cm)	3.19 ± 1.10	4.03 ± 0.95**	3.96 ± 1.08***	2.94 ± 0.78
Qualification Score (out of 40)	25.71 ± 5.17	20.86 ± 5.57**	22.21 ± 5.31**	26.21 ± 4.51
Response Time (secs)	3.09 ± 0.34	3.40 ± 0.38**	3.38 ± 0.38***	2.97 ± 0.48
Subscales				
Mental Demand	54.64 ± 19.46	57.86 ± 18.58	62.8616.72	49.64 ± 16.58
Physical Demand	23.93 ± 8.59	47.50 ± 16.84*	55.71 ± 18.28**	37.86 ± 15.78
Temporal Demand	52.14 ± 23.67	56.43 ± 19.36	55.36 ± 19.95	39.64 ± 18.34*
Performance	51.07 ± 22.97	44.64 ± 18.24	41.79 ± 19.87	38.57 ± 15.37
Effort	56.07 ± 18.10	63.93 ± 14.83	66.79 ± 13.81*	49.29 ± 17.30
Frustration	36.79 ± 17.61	43.21 ± 22.15	43.93 ± 25.13	31.11 ± 18.63**
BORG CR-10	2.86 ± 1.35	4.43 ± 1.28***	5.07 ± 1.14***	3.64 ± 1.15*

Note: National Aeronautics and Space Administration – Task Load Index; each subscale scored 0-100; Borg Rating of Percieved Exertion Category Ratio 10 (BORG CR-10); scored 0-10, * denotes significant main effect for condition compared to baseline, $p < .05$, ** $p < .01$, ***$p < .001$

difference in self-reported workload and rate of perceived exertion for the fatigue and non-fatigue practice groups. Results revealed a statistically significant difference between practice groups for physical demand during practice block one, t(26) = 2.192, *p* =038, d = 0.828, and practice block two, t(26) = 6.262, p=.008, d = 1.095, with the fatigue practice group reporting significantly more physical demand. Furthermore, significant differences between practice groups for the rate of perceived exertion were found during practice block one, t(26) = 4.534, *p*<.001, d = 1.714, and practice block two, t(26) = 6.262, *p*<.001, d = 2.367, with the fatigue practice group reporting increased perceived effort. Descriptive statistics for the marksmanship performance and NASA-TLX subscales are presented in **Table 3**.

Posttest Marksmanship Performance and Workload Scores

Independent sample *t*-tests were conducted to assess the difference in marksmanship performance, self-reported workload, and rate of perceived exertion for the fatigue and non-fatigue practice groups (**Figures 18, 19, 20**). No differences were found for posttest marksmanship accuracy (*p*=.460), response time (*p*=.749*)*, or qualification scores *(p=.199)* between practice condition groups. Additionally, no significant differences were found for self-reported workload or rate of perceived effort. See **Table 3** for descriptive statistics for marksmanship performance and NASA-TLX subscales.

Non-Fatigued Retention Marksmanship Performance and Workload Scores

Independent samples *t*-tests were conducted to assess the differences in marksmanship performance, self-reported workload, and rate of perceived exertion between the fatigue and non-fatigue practice groups (**Figures 18, 19, 20**). Results revealed a statistically significant difference between practice groups for marksmanship accuracy, t(26) = 2.067, *p*=.049, d = .588, with the

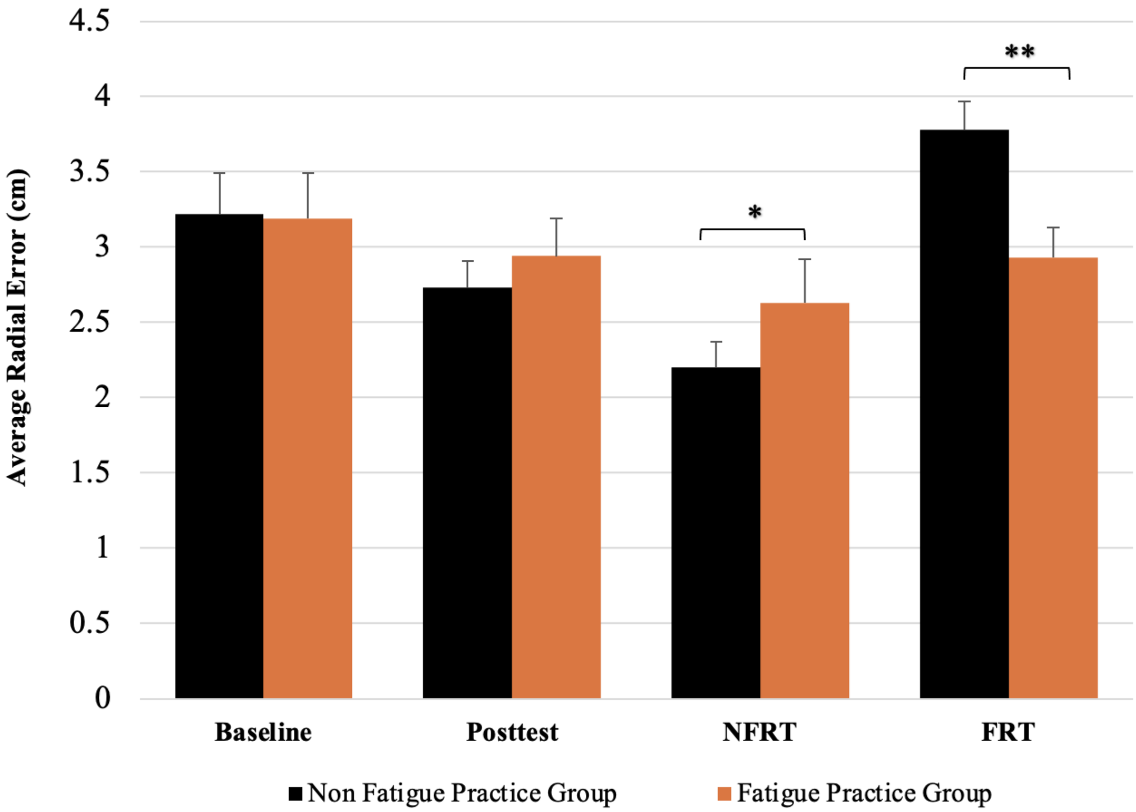


Figure 18. Average marksmanship accuracy (mean radial error) for practice conditions and time. NFRT = Non-Fatigued Retention Test. FRT = Fatigued Retention Test
** *p* <.01, * *p* <.05.

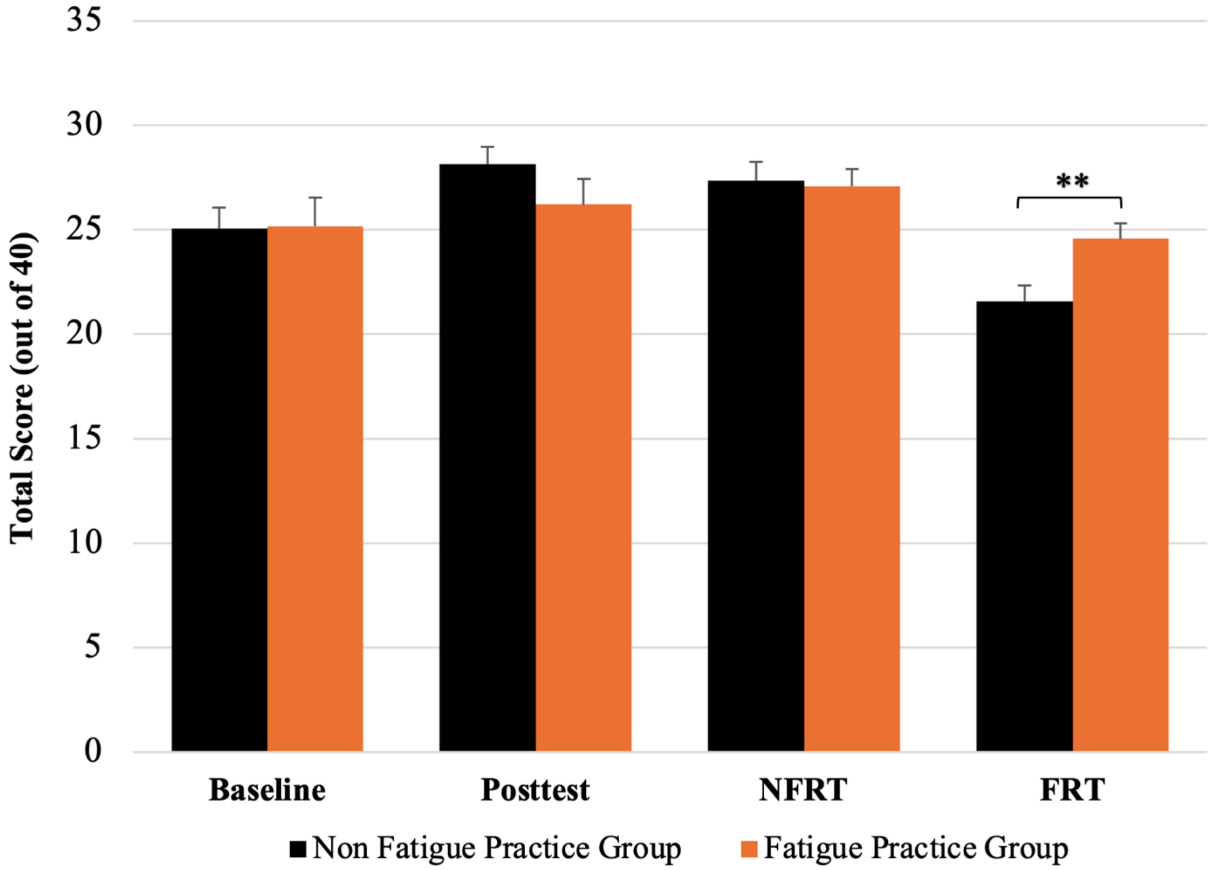


Figure 19. Average qualification scores for practice conditions and time.

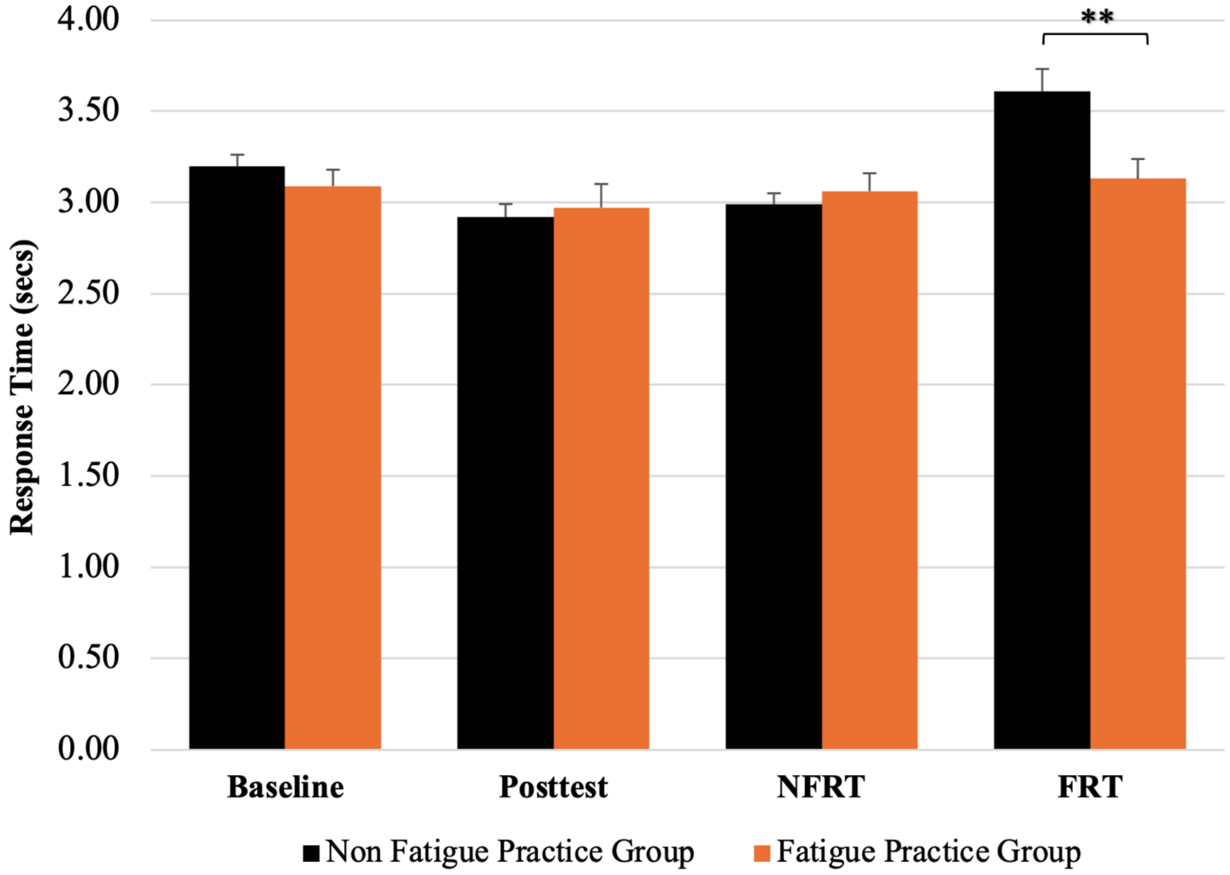


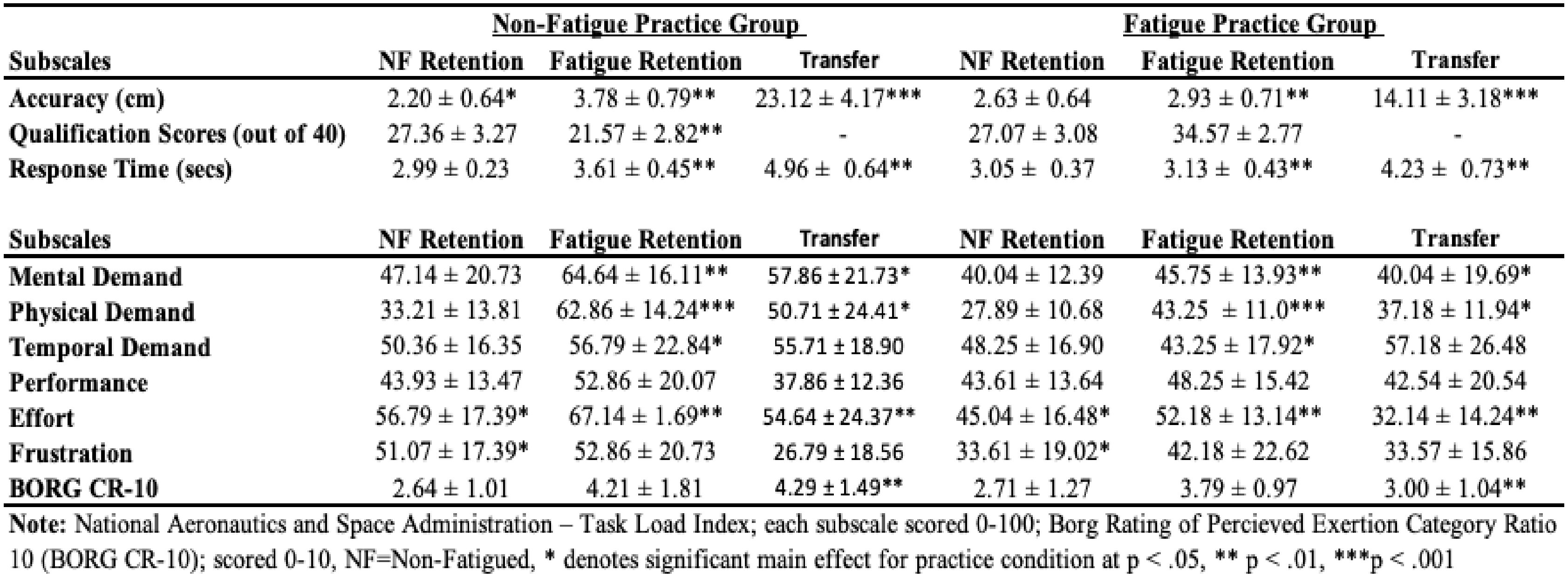
Figure 20. Average qualification task response time for practice conditions and time.

non-fatigue practice group demonstrating increased accuracy scores compared to the fatigue practice group. No differences were found for response time (*p*=.577) or qualification scores *(p=.814)*. For self-reported workload, a significant difference between practice groups for frustration, t(26) = 2.098, *p*=.046, d = 0.793, with the non-fatigue practice group demonstrating increased frustration compared to the fatigue practice group. Descriptive statistics for the marksmanship performance and NASA-TLX subscales are presented in **Table 4.**

Fatigued Retention Marksmanship Performance and Workload Scores

Independent samples *t*-tests were conducted to assess the difference in marksmanship performance, self-reported workload, and rate of perceived exertion for the fatigue and non-fatigue practice groups (**Figures 18, 19, 20**). Results revealed a statistically significant difference between practice groups for marksmanship accuracy, t(26) = 2.99, *p*=.006, d = 1.13l; response time, t(26) = 2.881, *p*=.008, d =1.089; and total qualification score, t(26) = 2.842, *p*=.009, d=1.074. The analysis indicated that the non-fatigue practice group demonstrated decreased accuracy, slower response times, and lower total qualification scores when compared to the fatigue practice group. For self-reported workload, a significant difference between practice groups for mental demand, t(26) = 3.319, *p*=.003, d = 1.255; physical demand, t(26) =4.078, *p*<.001, d = 1.541; and effort, t(26) = 3.306, *p*=.003, d = 1.249, with the non-fatigue practice group reporting increased mental demand, physical demand, and overall effort. Descriptive statistics for the marksmanship performance and NASA-TLX subscales are presented in **Table 4**.

Table 4. Retention and transfer testing performance and workload scores (mean ± standard deviation) by time and fatigue condition.



	Non-Fatigue Practice Group			Fatigue Practice Group		
Subscales	**NF Retention**	**Fatigue Retention**	**Transfer**	**NF Retention**	**Fatigue Retention**	**Transfer**
Accuracy (cm)	2.20 ± 0.64*	3.78 ± 0.79**	23.12 ± 4.17***	2.63 ± 0.64	2.93 ± 0.71**	14.11 ± 3.18***
Qualification Scores (out of 40)	27.36 ± 3.27	21.57 ± 2.82**	-	27.07 ± 3.08	34.57 ± 2.77	-
Response Time (secs)	2.99 ± 0.23	3.61 ± 0.45**	4.96 ± 0.64**	3.05 ± 0.37	3.13 ± 0.43**	4.23 ± 0.73**

Subscales	**NF Retention**	**Fatigue Retention**	**Transfer**	**NF Retention**	**Fatigue Retention**	**Transfer**
Mental Demand	47.14 ± 20.73	64.64 ± 16.11**	57.86 ± 21.73*	40.04 ± 12.39	45.75 ± 13.93**	40.04 ± 19.69*
Physical Demand	33.21 ± 13.81	62.86 ± 14.24***	50.71 ± 24.41*	27.89 ± 10.68	43.25 ± 11.0***	37.18 ± 11.94*
Temporal Demand	50.36 ± 16.35	56.79 ± 22.84*	55.71 ± 18.90	48.25 ± 16.90	43.25 ± 17.92*	57.18 ± 26.48
Performance	43.93 ± 13.47	52.86 ± 20.07	37.86 ± 12.36	43.61 ± 13.64	48.25 ± 15.42	42.54 ± 20.54
Effort	56.79 ± 17.39*	67.14 ± 1.69**	54.64 ± 24.37**	45.04 ± 16.48*	52.18 ± 13.14**	32.14 ± 14.24**
Frustration	51.07 ± 17.39*	52.86 ± 20.73	26.79 ± 18.56	33.61 ± 19.02*	42.18 ± 22.62	33.57 ± 15.86
BORG CR-10	2.64 ± 1.01	4.21 ± 1.81	4.29 ± 1.49**	2.71 ± 1.27	3.79 ± 0.97	3.00 ± 1.04**

Note: National Aeronautics and Space Administration – Task Load Index; each subscale scored 0-100; Borg Rating of Percieved Exertion Category Ratio 10 (BORG CR-10); scored 0-10, NF=Non-Fatigued, * denotes significant main effect for practice condition at p < .05, ** p < .01, ***p < .001

** $p < .01$. NFRT = Non-Fatigued Retention Test. FRT = Fatigued Retention Test

Transfer Task

Independent samples *t*-tests were conducted to assess the difference in accuracy, response time, self-reported workload, and rate of perceived exertion for the fatigue and non-fatigue practice groups during the fatigued transfer task. Results revealed a statistically significant difference in transfer task accuracy, t(26)=6.424, $p < .001$, 2.428, with the non-fatigue practice group demonstrating decreased accuracy performance compared to the fatigue practice group (**Figure 21**). Similarly, results indicated a statistically significant difference in transfer task response time, with the non-fatigue practice group demonstrating slower response time compared to the fatigue practice group, t(26) = 2.80, $p = .010$, d=1.058 (**Figure 22**). For self-reported workload and rate of perceived exertion, a significant difference between practice groups for mental demand, t(26) = 2.274, $p = .031$, d = 0.860; effort, t(26) = 2.982, $p = .006$, d = 1.127; and rate of perceived effort, t(26) = 2.650, $p = .014$, d = 1.001, with the non-fatigue practice group reporting increased mental demand, effort, and rate of perceived exertion. Descriptive statistics for the marksmanship performance and NASA-TLX subscales are presented in **Table 4**.

** $p < .01$. NFRT = Non-Fatigued Retention Test. FRT = Fatigued Retention Test

Experiment 3 Brief Discussion

This study investigated the effects of simultaneous, combined motor and cognitive fatigue on military marksmanship performance, learning, and transfer in a simulated combat environment. More specifically, the aim of study three was threefold: (1) investigate the effect of combined fatigue on marksmanship performance in a simulated combat environment, (2) assess the impact of training with and without fatigue on skill acquisition, (3) evaluate the transfer of learned skills

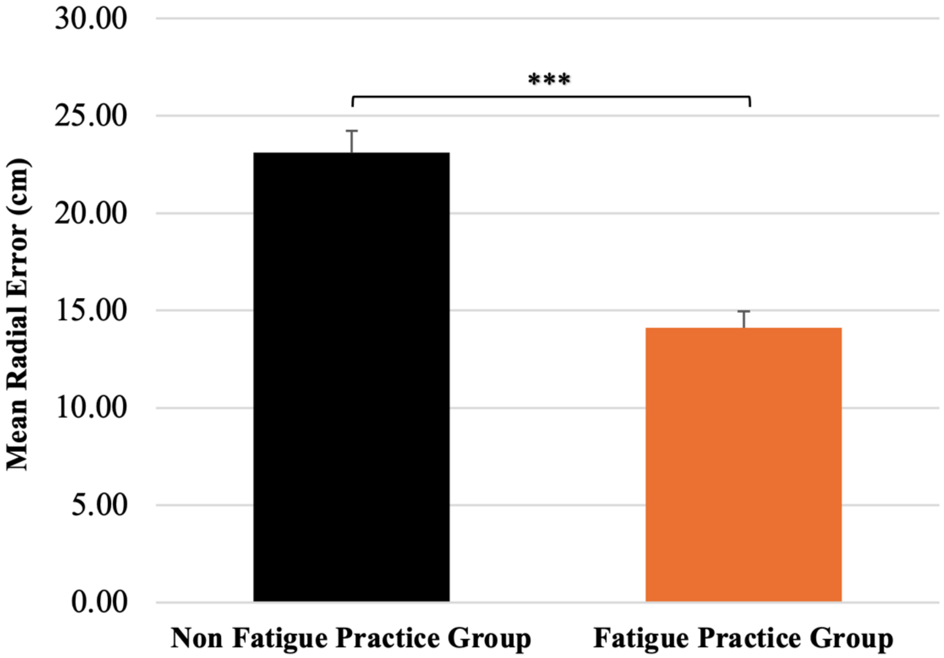


Figure 21. Average transfer task accuracy (radial error) for practice conditions.

*** *p* < .001

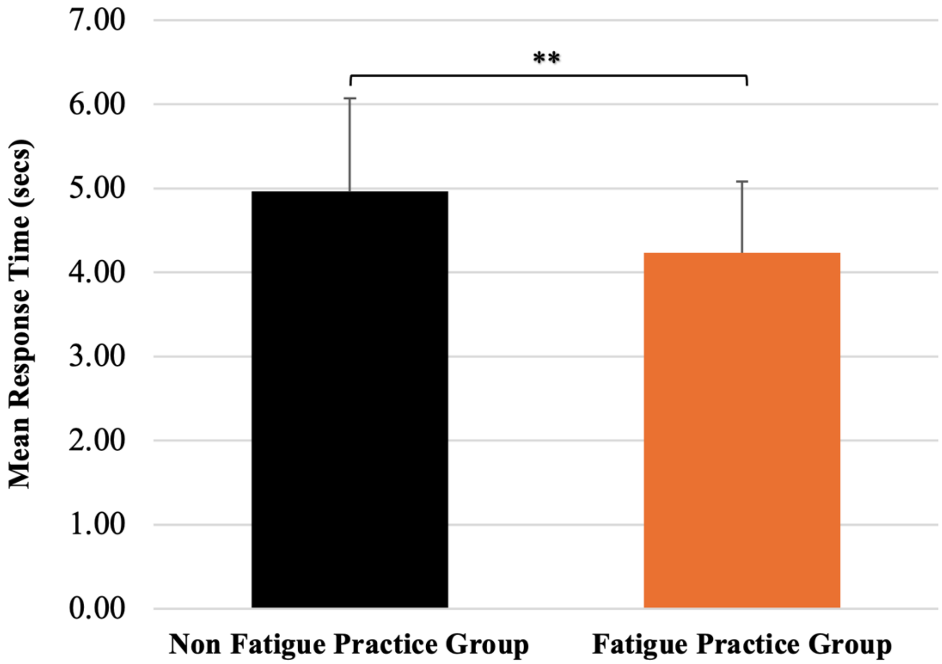


Figure 22. Average transfer task response time for practice conditions.

** *p* < .01

to combat-specific tasks. The results provide meaningful insight into the effects of combined acute state fatigue on immediate performance and skill acquisition, motor learning under various fatigue conditions, and transfer of acquired skills to demanding real-world environments. Furthermore, it extends the understanding of fatigue by highlighting the compounding effect of exposure to multiple simultaneous fatiguing tasks. The following section provides a summary and interpretation of the present experiment's results.

Motor performance, learning, and transfer under fatigue

Consistent with previous research (Lieberman et al., 2005: Springer S1; Springer S2), results demonstrate combined fatigue’s adverse, compounding effects on military performance. Throughout practice, the fatigue group consistently demonstrated lower rifle accuracy, lower overall qualification scores, and slower response time immediately following simultaneous motor and cognitive fatigue. Additionally, ratings of perceived exertion and workload further corroborate these results, as participants in the fatigue practice group reported increased perceived exertion, physical effort, and mental effort for task completion. Interestingly, despite immediate performance deterioration, no significant differences in marksmanship performance or response time were found between groups at post-test. This suggests that while fatigue negatively influences real-time performance, it does not inherently degrade short-term consolidation of motor performance when a rest period is given. The most notable contribution of this study is the evidence supporting task-adaptive training for motor skill learning and transfer. In support of hypothesis two, significant differences were found during non-fatigued retention testing in which participants who trained without fatigue demonstrated superior marksmanship performance and response times during the non-fatigued retention test. In support of hypothesis three, participants who trained with fatigue demonstrated superior marksmanship performance and response times during the fatigued retention test. As predicted, participants assigned to the fatigue practice group demonstrated superior marksmanship performance during the fatigued transfer test. As for self-reported exertion, participants in the combined fatigue group reported higher levels of exertion during practice and immediate retention testing in direct support of hypothesis five.

Lastly, in support of hypothesis six, participants who practiced with fatigue reported less physical and mental demand, lower overall effort, and decreased perceived exertion for task completion during fatigued retention and transfer tasks relative to the condition that practiced without fatigue. These findings support the idea that skill learning is highly context-dependent

(Proteau, 2009) and skill transfer is contingent on the similarity of training to applied environments (Thorndike, 1914).

Implications for Military Populations

The results of this study have significant implications for military training protocols and overall operational readiness. These results suggest that the traditional training programs that emphasize skill acquisition in rested conditions may not adequately prepare Soldiers for contested environments where they are expected to perform military-specific tasks successfully under various types of fatigue. By integrating combat-specific fatigue into training, military personnel will develop and execute the necessary skills for effective transfer to real-world combat environments. Additionally, Soldiers will gain additional exposure to the increased demands of combat, which may lead to an increased resistance to the perception of fatigue during extended military operations. The effective use of synthetic training environments further expands opportunities to execute safe yet effective training that can introduce task and fatigue variations to enhance long-term performance adaptation.

Limitations and Future Research

While this study provides meaningful insights into the effects of fatigue on military marksmanship performance, learning, and transfer of learning, several limitations must be acknowledged. First, the study was conducted in a controlled laboratory using a non-immersive virtual reality platform, which, although intended to replicate combat environments, does not fully replicate the complexity and unpredictability of live combat environments. The transferability of these findings warrants further investigation, particularly in environments where external elements (i.e., threat of death, team cohesion, environmental conditions) may influence performance. Second, the duration and intensity of fatigue may not entirely reflect the prolonged and cumulative effects of fatigue experienced during extended military operations. Future research should expand on the duration of fatigue within each practice session, as well as over multiple training days, to explore the potential impact of long-term skill retention and operational effectiveness. Lastly, despite using a representative sample of military trainees (i.e., ROTC cadets), future research should explore whether the observed effects persist across active-duty military populations. Due to their increased operational experience, task familiarity, and structured physical training, it is essential to further examine the effect of combined fatigue on motor performance, learning, and skill transfer. In doing so, training interventions can be appropriately tailored to meet the demands and capabilities of those serving in combat and operational roles.

Even with the aforementioned limitations, the present study contributes significantly to the growing body of research exploring the effects of combined fatigue on military performance, learning, and skill transfer. The findings highlight the detrimental effect of fatigue on immediate marksmanship performance while also demonstrating the potential downstream benefits of incorporating fatigue into military training paradigms. Most notably, Soldiers who trained under the combined fatigue condition demonstrated superior performance during the fatigue retention and transfer tasks, supporting the idea that skill learning is context-dependent (Proteau, 1992).

General Discussion

Understanding the mechanistic processes and behavioral influences of fatigue is crucial for preventing and mitigating performance deterioration across various disciplines. Additionally, the ability to transfer learned skills from practice to real-world environments is critical for military and high-performance occupations alike. The present series of studies aimed to inform these priorities by investigating the impact of motor, cognitive, and combined fatigue on motor and cognitive performance. Using theoretical frameworks encompassing attentional resource allocation models (Kahneman, 1973; Wickens, 2008), psychophysiological explanations (Noakes, 2012; Marcora, 2000), and overarching fatigue taxonomies (Enoka & Duchateau, 2016; Behrens et al., 2023), these studies provided a systematic approach to the evolving understanding of how different types of fatigue influence performance outcomes and individuals perceptions.

Due to the lack of evidence on the comparative effects of isolated and combined fatigue on performance, experiments one and two investigated how various types of fatigue influence motor performance, cognitive performance, and the perceptions of individual workload. As a foundational study, experiment one established the impact of isolated and combined fatigue on motor performance. Consistent with previous findings (Mockel et al., 2015; Rodrigues et al., 2022), isolated motor and cognitive fatigue negatively impacted subsequent motor and cognitive performance (i.e., anticipatory response time). More importantly, the novel comparison of isolated and combined fatigue revealed a significant increase in anticipatory reaction time, supporting the hypothesis of a compounding effect of fatigue on performance. Extending these results to a military-specific context, experiment two investigated the effects of isolated and combined fatigue on marksmanship accuracy, discriminatory reaction control, and efficiency. Similar to experiment one and previous work (Jaworski et al., 2015; Lieberman et al., 2005), the results of experiment two indicated that isolated fatigue conditions impaired subsequent military motor and cognitive performance. More significantly, the novel examination of isolated and combined fatigue resulted in a negative, additive decrement in military marksmanship performance. These findings suggest that real-world military operations, where various types of fatigues coexist, create an additive burden on a Soldiers' ability to execute mission critical tasks (Lieberman et al., 2005; Castellani et al., 2006). Further advancing these findings, experiment three of the present dissertation investigated the effects of combined fatigue on motor skill performance, retention, and transfer within a simulated combat environment. Findings revealed that prior exposure to fatigue during acquisition (i.e., practice or training) positively influenced performance and learning outcomes, reinforcing the established benefit of nesting keys characteristics of the transfer environment (i.e., combat) into practice (Proteau, 1992; Lee, 1988; Wright & Shea, 1991).

From a theoretical standpoint, the findings of this research line contribute significantly to the understanding of fatigue through the integration of multiple conceptual models. Kahneman proposed that attentional capacity is limited and thus flexibly allocated to meet various task demands (Kahneman, 1973). The findings from these studies, particularly the compounding effects of combined fatigue on motor and cognitive performance, support the idea that when multiple types of demands compete for attentional resources, the available capacity becomes strained, thereby reducing overall motor and cognitive performance. More specifically, in study one, combined fatigue resulted in slower subsequent anticipatory reaction time than isolated fatigue alone. Furthermore, results of study two revealed that combined fatigue resulted in decreased marksmanship accuracy, discriminatory reaction control, and overall efficiency when compared to isolated cognitive or motor fatigue. Contrary to Wickens (2008), which suggests that motor and cognitive tasks draw from separate, non-competing resource pools, these findings challenge this notion, indicating that overlapping demands (i.e., combined fatigue) create a negative, additive effect on motor and cognitive performance. Using a psychophysiological lens, the results support the idea that performance is regulated by a central governor (i.e., brain) in response to perceived fatigue, thus limiting overall output before reaching physiological failure where homeostasis is endangered (Noakes, 2012). Additionally, results support the notion that perception of effort, rather than physiological depletion alone, plays a critical role in task engagement and withdrawal (Marcora, 2009). Subjective workload scores reported in the dissertation support these views, as participants reported higher subjective fatigue under combined conditions, correlating with greater performance decline. Lastly, previous research has demonstrated that learning and retention are most effective when the practice environment incorporates similar sensorimotor representations (Proteau, 1992) and promotes processing activities (Lee, 1992) that are similar to the transfer test (i.e., combat). The observed learning and transfer effects indicate that incorporating motor and cognitive fatigue during practice (i.e., training) results in superior performance when testing under the same demands, as well as in novel environments requiring successful transfer of task-specific skills such as decision making and motor task execution.

While the present dissertation makes significant progress towards understanding the effect of fatigue on performance, several limitations warrant consideration and provide clear directions for future scholarly work. The artificiality of the environments and use of lab-based tasks may fail to capture the complexities found in real-world settings. Future research should explore the intricacies of field-based simulation, which is capable of offering a comprehensive understanding of fatigue’s real-world impact. Secondly, short-duration, moderate intensity fatigue was used throughout each study and may not replicate the prolonged demands experienced in military operations. Extending the duration of fatigue in future experimental designs will allow for investigating the cumulative cognitive, motor, and operational impairments experienced in operational military scenarios. In doing so, the ecological validity of fatigue's impact on mission performance will be enhanced. Third, the focus on short-term learning and transfer, coupled with the absence of longitudinal retention assessments, limits the understanding of skill retention over time. Future research should explore the dosage effect of fatigue, practice, and training in order to identify the necessary dose required for positive performance effects, while minimizing the adverse effects of excessive volume and intensity (i.e., musculoskeletal injuries). Lastly, future research should account for the heterogeneous nature of military personnel, where individual differences (e.g., fitness levels, operational experience) may moderate the impact of fatigue on motor and cognitive performance, learning, and transfer.

In sum, the collective findings reported in the present dissertation underscore the significant impact of motor, cognitive, and combined fatigue on military performance. Furthermore, the compounding effect of combined fatigue suggests that experiencing multiple fatigue types simultaneously yields further compromised performance beyond the effects of isolated fatigue. These findings and previous work have significant implications for military personnel and other professions requiring prolonged motor and cognitive performance in demanding environments. Understanding the complex interplay of combined fatigue and its impact on objective and perceived performance will be critical in the development of military-specific interventions, training platforms, and surveillance tools aimed at the mitigation of performance degradation over time. These results highlight the importance of integrating realistic training and immersive technological platforms within military training to improve skill performance, enhance learning, and ensure effective transfer to combat environments. Such advancements not only improve operational readiness but also offer a framework applicable to other occupational sectors that commonly experience fatigue. Emergency medical services and clinical training programs may benefit from the implementation of fatigue-based simulations to enhance decision making and procedural task performance. Rehabilitation professionals (e.g., occupational and physical therapy, athletic training) may explore embedding occupation-specific fatigue conditions into progression-based rehabilitation protocols in order to facilitate successful reintegration. Sports science researchers and practitioners may nest simultaneous fatigue into conditioning to facilitate greater transfer to competition. Furthermore, workforce development programs in critical industries (e.g., aviation, logistics) may benefit from training paradigms that integrate combined fatigue to achieve task and environment-specific performance and learning.

In conclusion, this body of research provides a foundation for the effects of isolated and combined fatigue on motor and cognitive performance, learning, and transfer. The findings enhance the understanding of the mechanistic impact of fatigue, illustrating its negative, additive effect on performance while highlighting the critical role of perceived workload in task performance. The demonstrated benefits of incorporating fatigue within various occupational training programs emphasize the necessity of implementing task-adaptive training for effective motor skill performance, learning, and transfer.

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APPENDIX

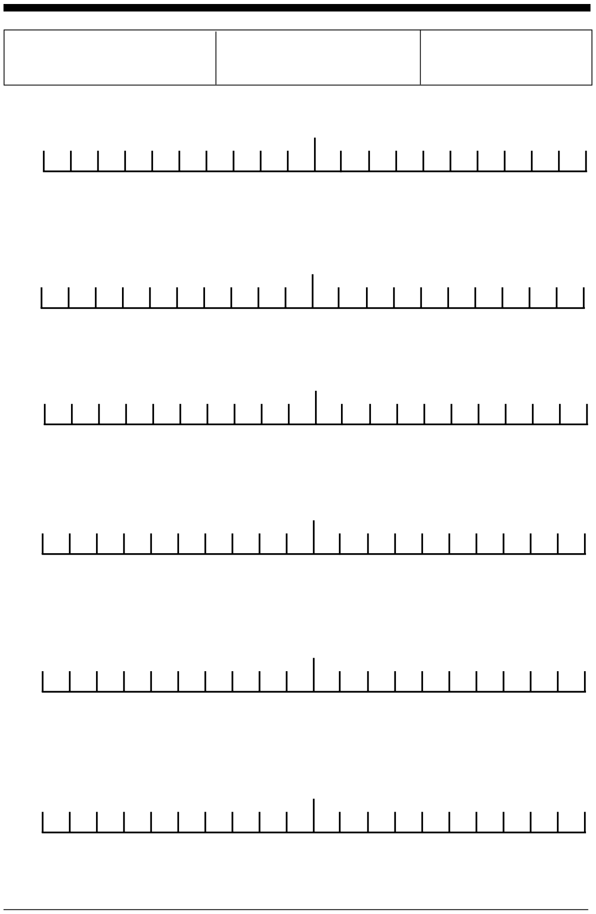


Figure A1. National Aeronautics and Space Administration Task Load Index (NASA-TLX).

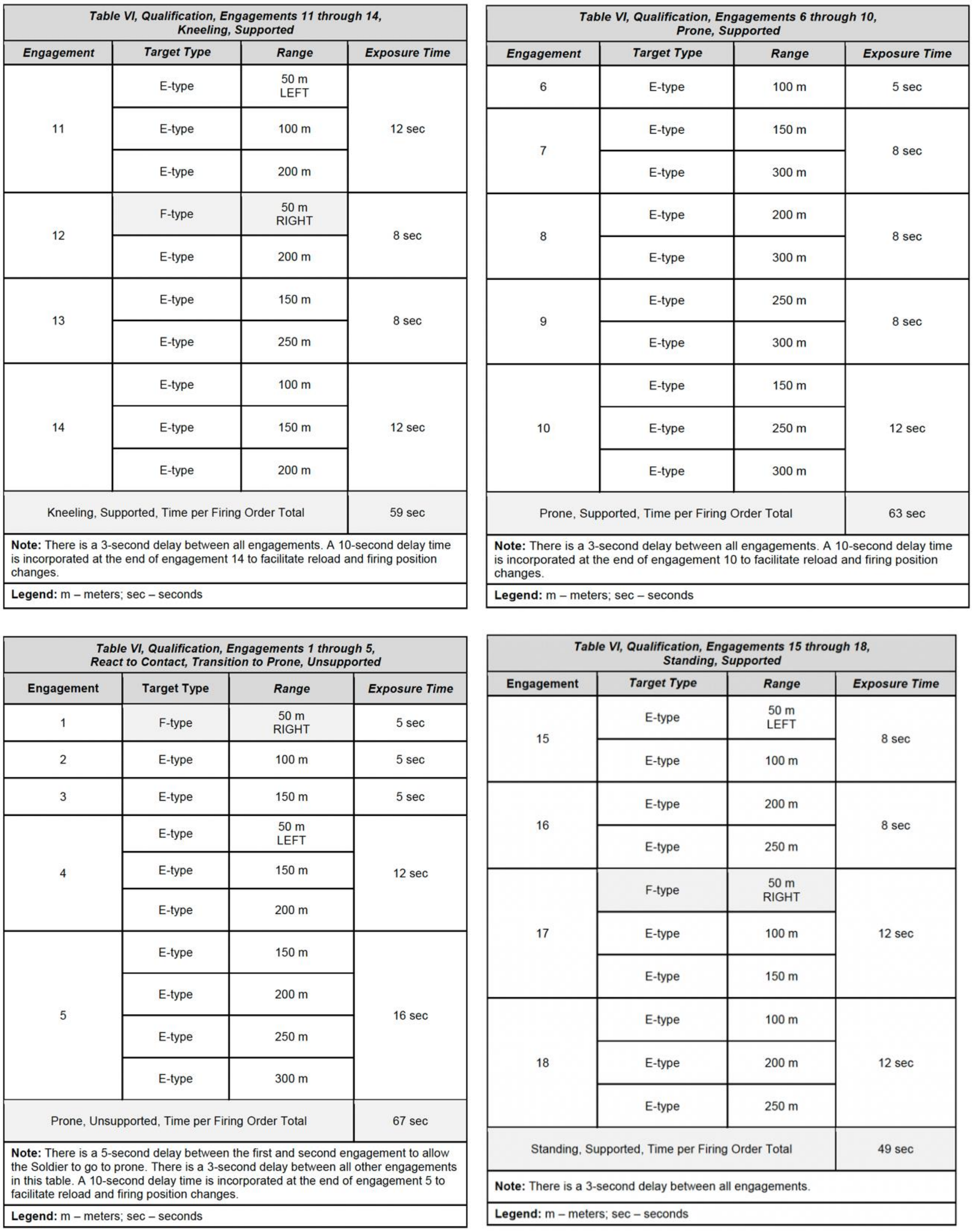


Table VI, Qualification, Engagements 11 through 14, Kneeling, Supported

Engagement	*Target Type*	*Range*	*Exposure Time*
11	E-type	50 m LEFT	12 sec
	E-type	100 m	
	E-type	200 m	
12	F-type	50 m RIGHT	8 sec
	E-type	200 m	
13	E-type	150 m	8 sec
	E-type	250 m	
14	E-type	100 m	12 sec
	E-type	150 m	
	E-type	200 m	
Kneeling, Supported, Time per Firing Order Total			59 sec

Note: There is a 3-second delay between all engagements. A 10-second delay time is incorporated at the end of engagement 14 to facilitate reload and firing position changes.

Legend: m – meters; sec – seconds

Table VI, Qualification, Engagements 6 through 10, Prone, Supported

Engagement	*Target Type*	*Range*	*Exposure Time*
6	E-type	100 m	5 sec
7	E-type	150 m	8 sec
	E-type	300 m	
8	E-type	200 m	8 sec
	E-type	300 m	
9	E-type	250 m	8 sec
	E-type	300 m	
10	E-type	150 m	12 sec
	E-type	250 m	
	E-type	300 m	
Prone, Supported, Time per Firing Order Total			63 sec

Note: There is a 3-second delay between all engagements. A 10-second delay time is incorporated at the end of engagement 10 to facilitate reload and firing position changes.

Legend: m – meters; sec – seconds

Table VI, Qualification, Engagements 1 through 5, React to Contact, Transition to Prone, Unsupported

Engagement	**Target Type**	*Range*	*Exposure Time*
1	F-type	50 m RIGHT	5 sec
2	E-type	100 m	5 sec
3	E-type	150 m	5 sec
4	E-type	50 m LEFT	12 sec
	E-type	150 m	
	E-type	200 m	
5	E-type	150 m	16 sec
	E-type	200 m	
	E-type	250 m	
	E-type	300 m	
Prone, Unsupported, Time per Firing Order Total			67 sec

Note: There is a 5-second delay between the first and second engagement to allow the Soldier to go to prone. There is a 3-second delay between all other engagements in this table. A 10-second delay time is incorporated at the end of engagement 5 to facilitate reload and firing position changes.

Legend: m – meters; sec – seconds

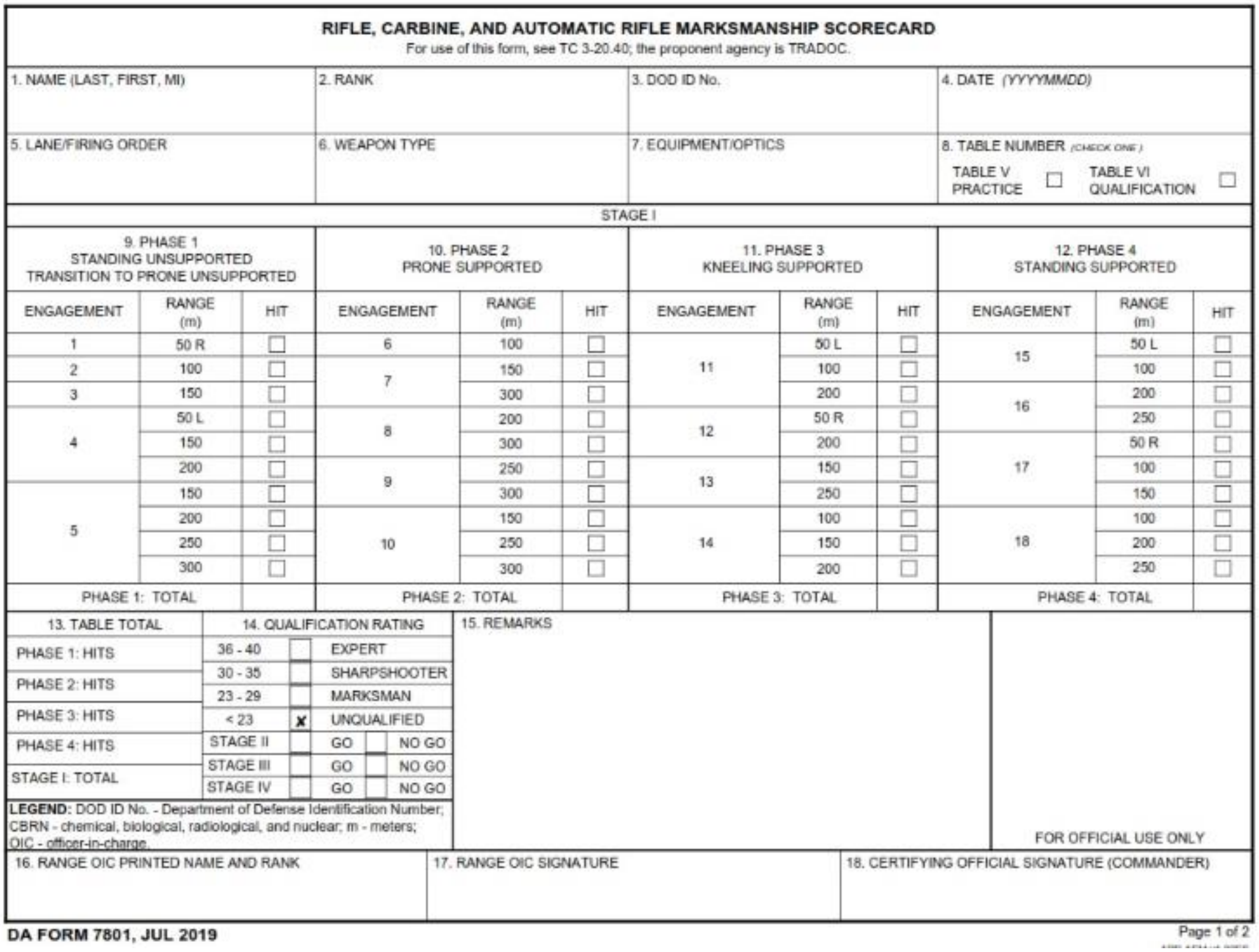
Table VI, Qualification, Engagements 15 through 18, Standing, Supported

Engagement	*Target Type*	*Range*	*Exposure Time*
15	E-type	50 m LEFT	8 sec
	E-type	100 m	
16	E-type	200 m	8 sec
	E-type	250 m	
17	F-type	50 m RIGHT	12 sec
	E-type	100 m	
	E-type	150 m	
18	E-type	100 m	12 sec
	E-type	200 m	
	E-type	250 m	
Standing, Supported, Time per Firing Order Total			49 sec

Note: There is a 3-second delay between all engagements.

Legend: m – meters; sec – seconds

Figure A2. Army qualification procedure with target type, distance, and target exposure time in sequence.



RIFLE, CARBINE, AND AUTOMATIC RIFLE MARKSMANSHIP SCORECARD

For use of this form, see TC 3-20.40; the proponent agency is TRADOC.

1. NAME (LAST, FIRST, MI)	2. RANK	3. DOD ID No.	4. DATE *(YYYYMMDD)*
5. LANE/FIRING ORDER	6. WEAPON TYPE	7. EQUIPMENT/OPTICS	8. TABLE NUMBER *(CHECK ONE)* TABLE V PRACTICE ☐ TABLE VI QUALIFICATION ☐

STAGE I

9. PHASE 1 STANDING UNSUPPORTED TRANSITION TO PRONE UNSUPPORTED			10. PHASE 2 PRONE SUPPORTED			11. PHASE 3 KNEELING SUPPORTED			12. PHASE 4 STANDING SUPPORTED		
ENGAGEMENT	RANGE (m)	HIT	ENGAGEMENT	RANGE (m)	HIT	ENGAGEMENT	RANGE (m)	HIT	ENGAGEMENT	RANGE (m)	HIT
1	50 R	☐	6	100	☐	11	50 L	☐	15	50 L	☐
2	100	☐	7	150	☐		100	☐		100	☐
3	150	☐		300	☐		200	☐	16	200	☐
4	50 L	☐	8	200	☐	12	50 R	☐		250	☐
	150	☐		300	☐		200	☐	17	50 R	☐
	200	☐	9	250	☐	13	150	☐		100	☐
5	150	☐		300	☐		250	☐		150	☐
	200	☐	10	150	☐	14	100	☐	18	100	☐
	250	☐		250	☐		150	☐		200	☐
	300	☐		300	☐		200	☐		250	☐
PHASE 1: TOTAL			PHASE 2: TOTAL			PHASE 3: TOTAL			PHASE 4: TOTAL		

13. TABLE TOTAL	
PHASE 1: HITS	
PHASE 2: HITS	
PHASE 3: HITS	
PHASE 4: HITS	
STAGE I: TOTAL	

14. QUALIFICATION RATING				
36 - 40	☐	EXPERT		
30 - 35	☐	SHARPSHOOTER		
23 - 29	☐	MARKSMAN		
< 23	☒	UNQUALIFIED		
STAGE II	☐	GO	☐	NO GO
STAGE III	☐	GO	☐	NO GO
STAGE IV	☐	GO	☐	NO GO

15. REMARKS

LEGEND: DOD ID No. - Department of Defense Identification Number; CBRN - chemical, biological, radiological, and nuclear; m - meters; OIC - officer-in-charge.

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16. RANGE OIC PRINTED NAME AND RANK	17. RANGE OIC SIGNATURE	18. CERTIFYING OFFICIAL SIGNATURE (COMMANDER)

DA FORM 7801, JUL 2019

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Figure A3. Army qualification score sheet.

VITA

Joshua Springer was born and raised in Clayton, Ohio. He completed his undergraduate education at The Ohio State University, earning his Bachelor's of Science in Human Ecology and Family Science. He continued his education at Thomas Jefferson University in Philadelphia, Pennsylvania, where he completed his Master of Science in Occupational Therapy in 2013. In 2014, he commissioned into the United States Army as a First Lieutenant. In 2016, he completed his post-professional Doctor of Science in Occupational Therapy from Baylor University. In 2025, he will earn his Doctor of Philosophy degree in Kinesiology with a specialization in Sport Psychology and Motor Behavior.